SUB-COMMITTEE ON BULK LIQUIDS AND GASES
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Agenda item 5

BLG 11/INF.3
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REVIEW OF MARPOL ANNEX VI AND THE NO_x TECHNICAL CODE

Allocation and forecasting of global ship emissions

Submitted by the Friends of the Earth International (FOEI)

SUMMARY

Executive summary:	The annex to this document is a new report entitled "Allocation and Forecasting of Global Ship Emissions" authored by James J. Corbett, Chengfeng Wang, James J. Winebrake and Erin Green
Action to be taken:	Paragraph 2
Related document:	BLG 11/5/5

1 The annex to this document contains a recent report and analysis of global and regional inventories of emissions of air pollution from international shipping entitled "Allocation and Forecasting of Global Ship Emissions". The report also projects the growth of those emissions over the next several decades. The report was commissioned by the Clean Air Task Force, summarizing research led by James J. Corbett of the University of Delaware, USA. An introduction to and a summary of the report can be found in document BLG 11/5/5.

Action requested of the Sub-Committee

2 The Sub-Committee is invited to note the information provided in the attached final report by the Clean Air Task Force in its work on prevention of air pollution from ships and the revision of MARPOL Annex VI and the NO_x Technical Code.

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ANNEX

Allocation and Forecasting of Global Ship Emissions

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1 Introduction and Summary

1.1 This report presents updated global inventories of emissions from international shipping using best practices, and projects future shipping emissions. More specifically, in this report we:

1. Summarize recent work with regard to global ship emissions inventories.
2. Describe how growth in trade activity affects fleet energy and emissions trends.
3. Present updated global ship emission inventories at high resolution (0.1 degree latitude by 0.1 degree longitude).
4. Present a business-as-usual (BAU) forecast of fleet energy and emissions trends consistent with the correlation between increased oceangoing trade and required power.

We believe this inventory represents the most complete and accurate global inventory of air emissions from international shipping prepared to date. As such, the global ship emissions presented in this report will facilitate analyses of shipping's contribution to ambient concentrations of these pollutants and their secondary atmospheric products. Combined, these inventories and pending atmospheric modeling will support analyses and improved understanding of the impacts to human health due to ship emissions.

1.2 This study was conducted to improve the understanding of the International Maritime Organization (IMO) and other environmental regulatory authorities regarding air pollution emitted from global shipping activity and to inform IMO deliberations on potential revisions to standards for air pollution from ships set forth in Annex VI to MARPOL 73/78 *(1-3)*. It should also inform IMO deliberations regarding greenhouse gas (GHG) emissions from ships, as reflected in the *IMO Study on Greenhouse Gas Emissions from Ships (4, 5),* related resolution *(6)* and subsequent documents. IMO has conducted significant work to evaluate fleet environmental impacts from propulsion emissions over more than a decade, as Annex VI was drafted, ratified, and entered into force. Presently, IMO delegates are discussing revisions to Annex VI to better achieve environmental stewardship goals for international shipping *(7, 8)*, partly by continuing or expanding its focus on reducing oxides of nitrogen (NOx), sulfur emissions (SOx and sulfate aerosol formation), and related particulate matter (PM). These efforts include consideration of the fate of particulate and aerosol emissions emitted by ships on major trade routes *(9)*, industry assessments of feasibility and benefits from expanded fuel-switching to lower-sulfur fuels through additional SOx Emissions Control Areas (SECAs) and/or globally *(10, 11)*, and consideration of geographically non-uniform NOx standards that would reduce land-side exposure *(12)*. Work currently supporting IMO deliberations includes updated studies in Europe on the air quality, health, and environmental impacts attributed to shipping by peer-reviewed experts published in leading journals *(13, 14)*. This work is part of European efforts to identify cost-effective abatement measures to reduce emissions of air pollution from ships *(15)*, and to implement a new Thematic Strategy on Air Pollution that was adopted by the European Commission in September 2005 *(16)*.

1.3 IMO submittals by Friends of the Earth International (FOEI) have contributed information related to air pollution from ships and assessments that show a number of operational and technical measures for reducing such emissions from ships, feasible in both short- and long-term contexts *(17, 18)*. FOEI's submittal to MEPC 53 (MEPC 53/4/1) discussed potential health impacts and growth in fleet emissions, citing data showing that increased international shipping emissions will overwhelm sulfur reductions in IMO-compliant SECAs and that emissions in European sea areas will exceed total land-based emissions in the EU25 countries by as early as 2020.

1.4 In terms of assessments, IMO has received analyses of local and regional inventories and impacts, and more qualitative global evaluations of potential costs and mitigation strategies. Global inventories and forecasts are needed to enable larger scale assessment of impacts and mitigation measures. The IMO-commissioned *Study on Greenhouse Gas Emissions from Ships (4, 5)* used an activity-based inventory approach to better understand total energy use by ships, fleetwide trends, and potential GHG reductions from technical and operational measures *(19)*.

1.5 This report describes global ship activity data and best-practice methodologies for producing emissions inventories. These best-practices include identification and use of installed power characteristics, current power-based emissions factors, engine load service corrections, and engine operating time *(19-21)*. Improved spatial resolution is presented as well, updating global representation of shipping in the *IMO Study on Greenhouse Gas Emissions from Ships* as well as updating emissions estimates. The report uses ICOADS data, the source with the greatest spatial detail and longest publicly available time series, to produce 2002 (baseline) inventories for ship SOx, PM, and black carbon emissions. However, ICOADS data are improved by trimming over-reporting vessels, by using multiple-year data, and by weighting ship observations with ship installed power; these steps mitigate sampling bias, augment sample data set, and account for ship heterogeneity. The report adopts updated emissions inventory values reported and confirmed in peer-reviewed articles, reflecting total ship fuel use.

1.6 Using a power-based approach consistent with baseline inventory practices, we construct a business-as-usual (BAU) forecast scenario that reveals faster growth rates for total energy requirements in recent decades than previously reported *(5, 22)*. We discuss and consider a range of economic and energy trends that support this BAU forecast, demonstrating that the updated forecast trends may be more conservative than direct extrapolation from the past three decades.

1.7 **This forecast confirms that current IMO policy does not reduce emissions even in a short-term context.** Furthermore, emission reductions in the 60% range will do little more than offset through 2030 emissions growth accompanying projected increases in future shipping activity. New-engine NOx reductions resulting from IMO-compliant fleet turnover since 2000 are less than increased NOx emissions over this period. In other words, controls reducing fleetwide shipping emissions by at least 60% would need to be fully implemented for both new and existing engines within the next two decades to maintain 2002 shipping pollution levels.

1.8 This study's results provide a global context within which other IMO submittals focused on regional fate and transport and human health can be considered. The inventories can be used to model BAU impacts with atmospheric models, and can be adjusted to represent certain policy controls (e.g., future SECAs). This context enables insightful consideration by IMO and member nations of areas where air quality, human health effects, and environmental impacts may support revision of MARPOL Annex VI, the NOx Technical Code and related guidelines. Given that more aggressive technology and operational measures are necessary to offset increasing emissions of greenhouse gases and air pollution, this report may also help guide the choice of those technologies and strategies that have the potential to achieve necessary emissions reductions.

2 Inventory Development

2.1 Overview

2.1.1 Approaches applied in previous studies to produce spatially resolved ship emissions inventories can be categorized as either top-down or bottom-up. Top-down methods apply non-spatial estimates to a spatial domain using some proportionality assumptions; bottom-up methods develop estimates directly from spatially resolved detail and aggregate this activity to represent the inventory domain. Both of these types of approaches have strengths and weaknesses. A top-down approach is capable of producing multi-scale inventories perhaps in a quicker and less costly way and is less resource-demanding. However, the accuracy of a top-down approach is limited by the "representativeness" of the spatial proxy of ship traffic and the accuracy of the global inventory *(20, 23-26)*. On the other hand, a bottom-up approach faces problems associated with large numbers of ship movements and potentially dynamic shipping routes that are time-dependent *(26-28)*. Both methods have been applied in service of IMO policy development. In our work, a global shipping network has been developed and applied to data for North America; this hybrid approach combines the best of the bottom-up and top-down approaches *(26, 29-32)*.

However, additional time is needed to build worldwide data sets to produce this type of hybrid approach for global ship emissions inventories. Nevertheless, atmospheric modelers and policy makers need a global inventory in the interim. After comparing statistically and geographically two spatial proxies to produce top-down global ship emissions inventories, we use the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) to improve representativeness of the top-down approach by addressing potential statistical and geographic sampling bias caused by over-reporting and non-responding ships.

2.1.2 Representing spatial (and temporal) activity of commercial shipping is fundamentally similar to modeling any mobile source: the location and intensity of the fleet activity must be depicted. This can be done using sampled data representing fleetwide spatial activity and its temporal dynamics. Ideally, the reporting ship fleet would be representative of the world fleet pattern in terms of ship type, size, installed power, operating profiles, etc. The number of ships reporting should be statistically large or at least approximate a randomly sampled subset of the world fleet, and locations should be reported regularly at equal intervals. For emission estimating purposes, ship load or speed data are useful; in addition, a ship identifier can be used to adjust ship reporting frequencies with related ship attributes. Two global ship reporting data sets, ICOADS and the Automated Mutual-assistance Vessel Rescue system (AMVER) data set *(33)*, have been previously used as proxies of ship traffic to geographically resolve the global emissions inventories *(23, 34, 35)*.

2.1.3 Emissions inventories for oceangoing ship are calculated using activity-based methodologies referenced above. There are, however, significant differences among various global ship emission inventories; inventories estimated by one approach may be 50% higher than inventories estimated by another *(20, 24, 25)*. A reliable and up-to-date global ship emission inventory is also critical to the accuracy of the spatially resolved inventory. In this work, we adopted the updated inventories produced by Corbett and Koehler *(20)*, generally confirmed by Eyring et al *(36)*. The methodology is as follows *(20)*:

Step 1: Identify the vessel(s) to be modeled, and engines in service
Step 2: Estimate the engine service hours for the voyage or voyage segment
Step 3: Determine the engine load profiles, including power and duty cycle

Step 4: Apply emissions or fuel consumption rates for specific engine/fuel combinations
Step 5: Estimate emissions or fuel consumption for the voyage or voyage segment
Steps 6+: Assign emissions spatially and temporally both in and out of port regions

2.1.4 These efforts yield a total value for the fleet emissions included in the scale of the estimate (e.g., port-based, national, regional, global). Figure 1 presents a summary of recent activity-based estimates for NOx (as elemental nitrogen), SOx (as elemental sulfur), and particulate matter (PM_{10}). The inventory by Corbett and Fischbeck *(35)* used international marine fuels and fuel-based emissions factors; Endresen et al *(23)* also used fuel-based emissions factors, but included activity-based data such as operating hours, engine load, and specific fuel consumption.

Ranges depicted in Figure 1 suggest that NOx and SOx pollution from oceangoing ships represent some 15-30% of global NOx emissions and 5-7% of global SOx emissions, while fuel usage ranges 2-4% of world fossil fuels. Spatial representation is required to fully understand environmental impacts at regional and local scales, especially for aerosols and particulate matter (PM).

2.2 Spatial Proxies

2.2.1 Mapping emissions requires additional steps. Global ship emissions inventories are allocated to each geographic grid cell proportional to the activity level in that cell represented by spatial proxies. Emissions in each grid cell can be calculated with equation (1):

$$e_i = \frac{e_g \times w_i}{w_g} \qquad (1)$$

Where $\boldsymbol{e_i}$ represents emissions of one mass unit of pollution (in tons, kilograms, or grams) from cell $\boldsymbol{i}$ in one period; $\boldsymbol{e_g}$ as the global ship emissions inventory (in tons, kilograms, or grams) for that pollutant in that period; $\boldsymbol{w_i}$ is the value of cell $\boldsymbol{i}$ represented by a global spatial proxy; and $\boldsymbol{w_g}$ is the sum of the value of all the grid cells of the proxy in that period.

2.2.2 ICOADS is the world's largest data set for global marine surface observations voluntarily reported by the Voluntary Observing Ships (VOS) fleet and taken from moored and drifting buoys (only data reported by marine vessels were used for ship traffic and emissions analysis purposes) *(37, 38)*. Ships are recruited by Members of the World Meteorological Organization (WMO) on the basis of the willingness of the ships' officers to perform the observations and the regular route followed by the ships. Ships are asked to make observations at the standard synoptic hours four times a day and send to a meteorological service as soon as possible. However, analysis shows that many ships reported only once a year and the majority of ships reported less than 280 times per year while a few ships reported more 6,000 times a year *(39)*. Due to changes in the global ocean observational systems, the number of ships on the Voluntary Observing Ships (VOS) fleet list, which is the main source of ship observations for ICOADS, has declined from a peak of 7,700 in 1984-1985 to about 4,000 ships worldwide in 2003, which, by number, is about 13.8% of the world fleet of ships of 1,000 gross tons and greater, or about 4.4% of the world fleet *(37, 40-42)*. ICOADS data is publicly available from http://dss.ucar.edu/pub/coads/. This work is based on the analysis of 20-year of ICOADS data (1983-2002). Figure 2 illustrates ship traffic intensity derived from ICOADS data.

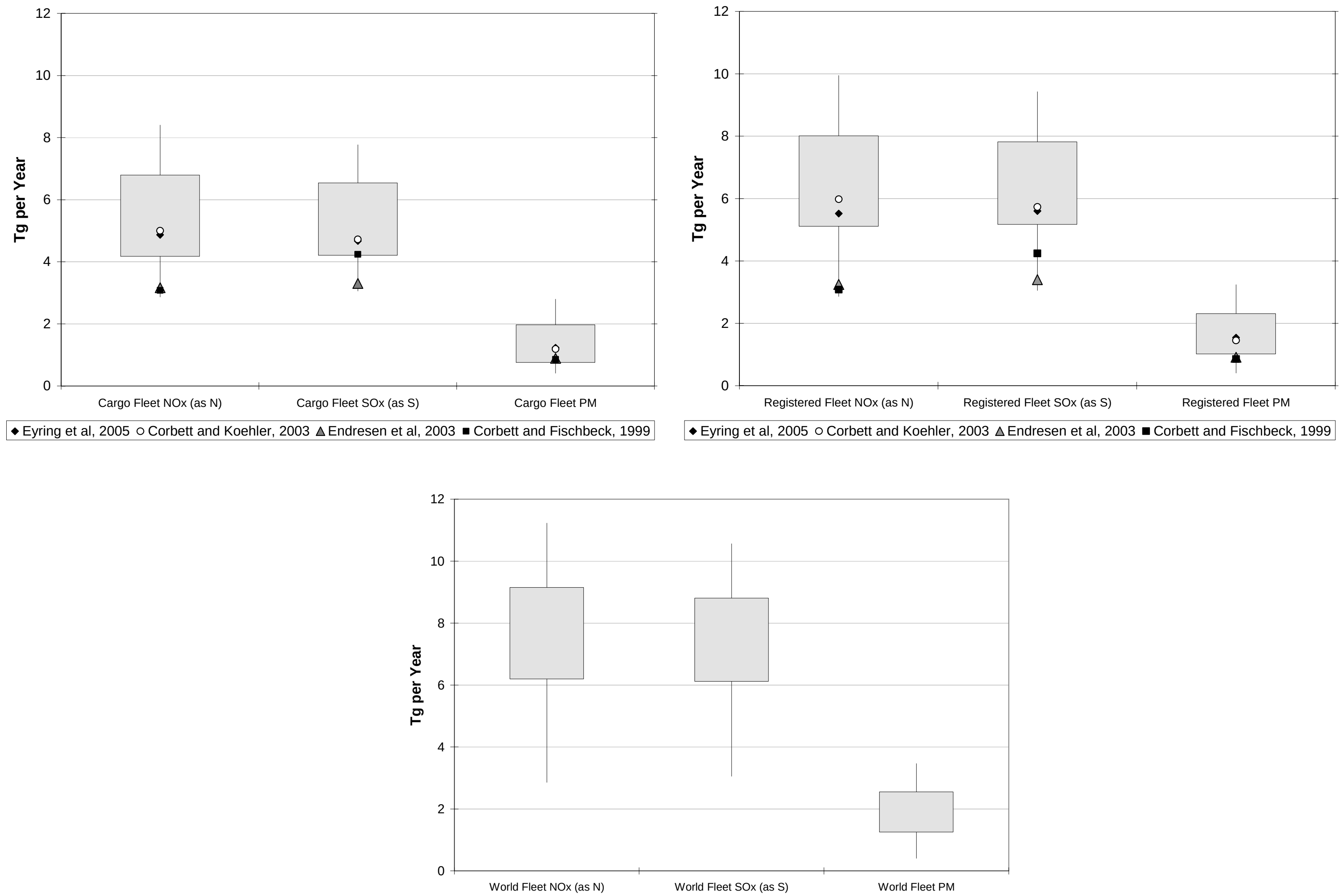

Figure 1. Summary of ship emissions point estimates *(20, 23, 35, 36)*. Box-plots represent the 5th and 95th percentile results from uncertainty analysis; whiskers extend to lower and upper bounds *(20, 25)*.

2.2.3 AMVER, sponsored by the United States Coast Guard (USCG), is a global ship reporting system used worldwide by search and rescue authorities to arrange for assistance to ships and persons in distress at sea. Participation is free, voluntary, and open to merchant ships of all flags, but, until recently, had been limited to ships over 1000 gross tons, on a voyage of 24 hours or longer. Enrollment now has been expanded to accommodate vessels outside the traditional criteria, such as cruise ships, research vessels and fish processors. AMVER vessels are requested to report their position every 48 hours at sea and as soon as voyage information changes (voyage deviation). At the discretion of the master, reports may be sent more frequently than requested *(43)*. Apparently, many ships report much less than requested and around 4,000 vessels with at least 128 days on the AMVER plot in a calendar year are eligible for an award *(44)*.Although there are about 12,000 vessels from more than 100 nations in the AMVER database *(23)*, around 4,000 vessels have actively participated in the AMVER system in recent years *(44)*. The number of unique vessels reporting to AMVER in a given year appears to vary from year to year, but appears to demonstrate similar consistency to ICOADS data. AMVER is strictly confidential and used only in a bona fide maritime emergency *(45)*. Only a few researchers have been given access to limited AMVER data under special agreement, and this data does not include ship identities.

2.2.4 The number of observations made by one type of ship is a function of number of vessels, operating profile (e.g., time at sea), and reporting frequency of that type of ship. Both ICOADS and AMVER are statistically and spatially biased. Neither of the two data sets perfectly represents the world fleet and its activity. An examination of ICOADS reveals that it over-samples container ship traffic, and, to a lesser extent, refrigerated cargo ship (i.e., reefer) traffic, and under-samples general cargo ship and tanker traffic, particularly general cargo ship traffic. These vessels more typically require weather routing information than bulk vessels due to their liner schedules, which may explain their increased participation in ICOADS. In contrast, AMVER over-samples bulk carrier, tanker, and container ship traffic, especially bulk carrier and tanker traffic and significantly under-samples general cargo ship, RO-RO, and reefer traffic. AMVER's sampling bias is consistent with its participating criteria, and apparently attracts greater participation of vessels that operate outside of set liner schedules. Consequently, these two proxies allocate the intensity of ship activity differently (as expected by routing differences among ship types) and produce emissions inventories with significant differences in some regions. These differences could significantly affect regional accuracy of atmospheric modeling of ship emissions. Figure 3 shows how the two proxies will allocate global ship emissions differently.

Efforts have been taken to improve the two proxies *(23, 31, 32)*. When ICOADS observations are weighted by installed power, more emissions will be assigned to 0°-40° north and less will be assigned to 40°-90° north, 0°-20° south and 40°-90° south than unweighted ICOADS. In contrast, weighting AMVER data by gross tonnage matters less. This also implies that AMVER covers a less broad range of vessels by size. ICOADS, whether weighted by ship installed power or not, will assign significantly more emissions than AMVER to the region between 40°-60° north and assign significantly fewer emissions to the region between 0°-20° north.

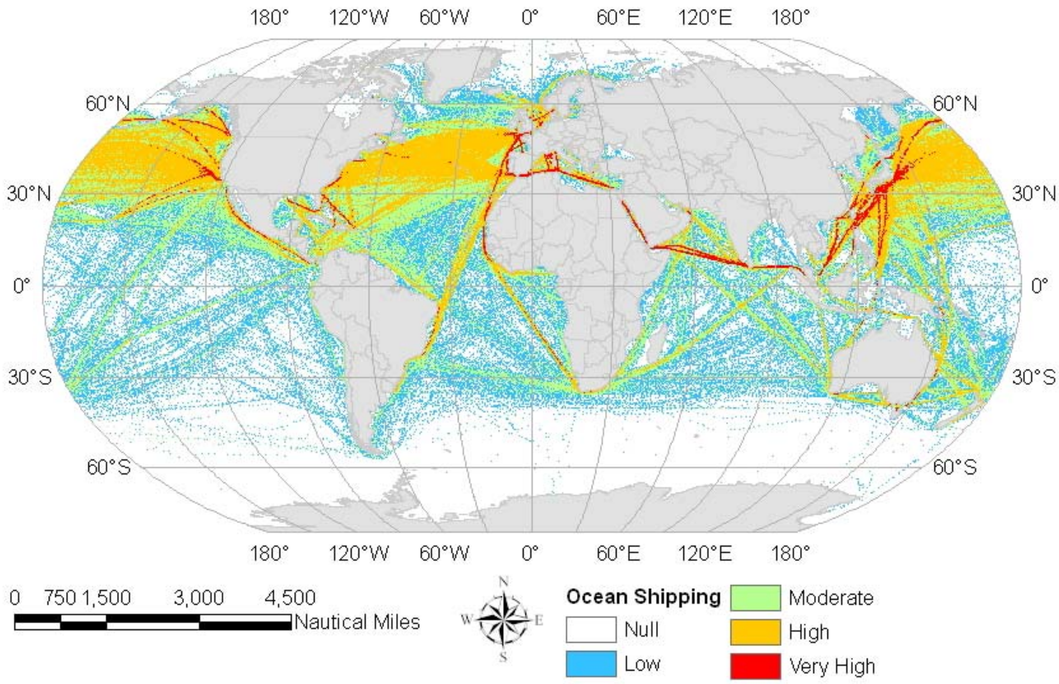

Figure 2. Illustration of oceangoing ship traffic, based on 2000-2002 ICOADS proxy.

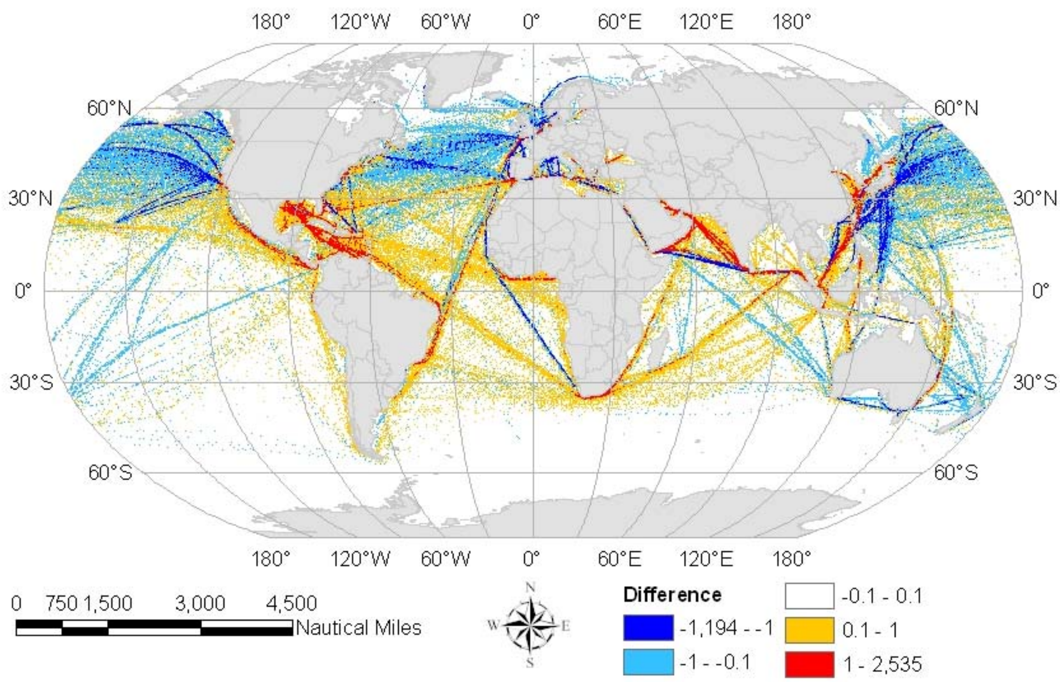

Figure 3. Comparison of ship emissions spatial proxies derived from power-weighted AMVER 2005 and improved ICOADS 2000-2002; value of each 0.1° by 0.1° grid cell represents the difference between the two proxies (in millionth of global emissions); grid cells with warm color have more emissions allocated by AMVER while grid cells with cool color have more emissions allocated by ICOADS.

2.2.5 We chose ICOADS as the spatial proxies for allocating ship emissions for this work for three reasons:

- ICOADS is free to researchers and has maintained a historical data set for temporal analysis, while AMVER can be obtained only under special agreement and does not maintain a historical data set;
- ICOADS covers a wider range of ships in terms of ship type, size, and engine power (132 – 74,640 kW), and thus it may better represent the world ship traffic *(46)*, while AMVER focuses on larger vessels due to its participation criteria; and
- Individual ships reported to ICOADS can be identified to improve the proxy.

2.2.6 The three most recent years, 2000-2002, ICOADS data were used to augment the sample size and to mitigate non-uniform response bias. Lloyd's ship registry data set was used to identify ships made ICOADS reports *(46)* based on unique ship identifiers, and only observations made by ships with valid installed power were selected. The number of observations made by each ship was examined and outliers were trimmed. Each observation was weighted by ship installed power which is a more direct of indicator of ship emissions than with ship size *(20, 21, 26)*. Power-weighted method increases emissions assigned to ocean-shipping lanes while decreasing the emissions to coastal routes.

2.3 Baseline Inventory, Comparison, and Validation

2.3.1 Global emissions inventories were evaluated and validated by comparing with studies at regional and port scales. Figure 4 presents the comparison of a top-down approach using ICOADS, AMVER, and a combination of the two as spatial proxies with STEEM, a bottom-up network model recently applied to estimate North America coastal emissions *(30)*. STEEM empirically routed more than 170,000 voyages and estimated emissions from activity-based characteristics of ships using these routes; the spatial distribution from STEEM has no sampling bias since it represents all available port call activity for oceangoing ships in international service. As shown in Figure 4, ICOADS, AMVER, and their combination are each biased around North America. None produces better inventories in all areas than the other two.

2.3.2 Accuracy of the ICAODS-based inventory was also examined by comparing it with results of previous regional studies. Results of different reference years for different vessel groups were extrapolated and/or projected to the same reference year, 1990, to enable the comparison. Table 1 summarizes the comparison of our approach with the results from regional studies by Lloyds Register and ENTEC, both using a bottom-up approach.

The Baltic Sea is defined in the Lloyds Register study as "the Gulf of Bothnia and the Gulf of Finland" and the entrance to the Baltic Sea bounded by the parallel of the Skaw in the Skagerrak at 57˚44.8'N" *(27)*. The North Sea is defined as in MARPOL 73/78 ANNEX VI (regulation 5(1)) *(47)*. The Mediterranean and Black Sea area is defined in the Lloyds Register's study as "including the gulfs and seas there in, bounded to the west by the Straits of Gibraltar at the meridian 5˚36'W" and the Black Sea *(28, 48)*.

Our estimates for SO_2 for the Mediterranean/Black Sea agree very well with the Lloyds study; our SO_2 results are about 10% higher than Lloyds'. Results for NO_2 and SO_2 for other regions, except the Baltic Sea, agree fairly well with other studies. The discrepancies for the Baltic Sea are significant, with our results about 50% lower than Lloyds Register study;

however, our results for all shipping in the Baltic/North Sea combination fall in the range of the results derived from ENTEC, Lloyds, and IIASA studies *(22, 27, 28, 47, 49)*.

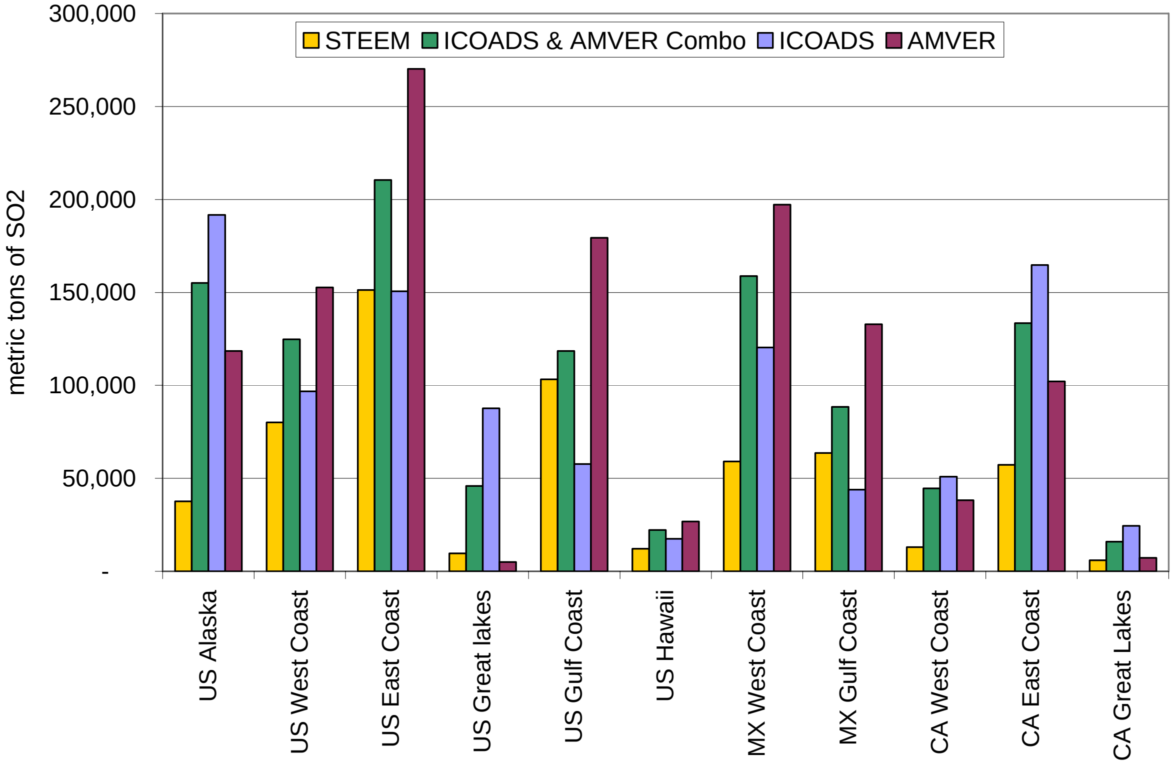

Figure 4. Comparison between the results of STEEM, top-down approach using ICOADS, AMVER, and the combination. Coastal zones resemble the 200 nautical miles Exclusive Economic Zone (EEZ). Canadian West Coast includes northwest of Canada; and Canadian East Coast includes the northeast of Canada.

Table 1. Emissions Comparison with Different Regional Estimates ('000 metric tons)

Region	Source	NOx (NO_2)	SO_2	Year and fleet represented
Mediterranean/Black Sea	This work	958	550	International cargo fleet, 2002
		2,387	1,391	Estimated for all shipping, 1990
	Lloyds *(28)*	1,725	1,246	All shipping movements, 1990
Baltic/North Sea	This work	502	287	International cargo fleet, 2002
		1,601	929	Estimated for all shipping, 1990
	ENTEC *(22)*	1,074	763	All shipping movements, 2000
		1,074	763	Extrapolated for all shipping, 1990[1]
	Lloyds, IIASA *(27, 47, 49)*			
		N/A	1,400	Estimated for all shipping, 1990
North Sea	This work	445	255	International cargo fleet, 2002
		1,421	826	Estimated for all shipping, 1990
	IIASA *(27, 49)*	N/A	439	International shipping, 1990
		N/A	1,171	Extrapolated for all shipping, 1990[1]
Baltic Sea	This work	56	32	International cargo fleet, 2002
		179	104	Estimated for all shipping, 1990
	Lloyds *(27)*	353	229	All shipping movements, 1990

1. Extrapolations to common years for comparison are based on the cited sources.

2.3.3 Some discrepancies identified in Table 1 may be due to a number of factors, including sampling bias, assignment of emissions by ship type, and inconsistent definition of terms. Additionally, emissions from hotelling activity in and near ports are likely under-represented in this work for at least two reasons. First, the top-down approach allocates a calculated global inventory to the ICOADS (or other ship activity proxy) proportionally - with adjustments for installed power, etc., as described above. Second, ship reporting frequencies may decrease as operators prepare for arrival and/or departure, and ships may not report locations to ICOADS or AMVER while at dock. Additionally, port-based inventories would typically include emissions from related harbor craft activity (e.g., vessel-assist tugs) and may allocate ship activity along more resolved local navigation routes. For these reasons, this global context may support but not replace detailed local inventories using bottom-up methods.

2.3.4 Taking the foregoing into consideration, we do not consider this work to contradict the inventory, fate and transport, and health effects estimates provided in other studies for this region *(13-15)*, and we conclude that our results either agree very well or fall in the range of previous studies.

2.4 Results

2.4.1 Our final inventory results for various pollutants are shown in Table 2 with monthly global ship emissions inventories produced using ICOADS 2000-2002 power-weighted spatial proxy.

Table 2. Global ship emissions (Unit: metric tons)

Month	Monthly %	NOx (N)	SOx (S)	CO2 (C)	HC (CH4)	PM (PM10)	CO	BC
1	7.81%	390,743	368,861	13,754,144	44,857	92,997	84,400	5,580
2	7.33%	366,634	346,103	12,905,531	42,090	87,259	79,193	5,236
3	8.20%	410,136	387,168	14,436,788	47,084	97,612	88,589	5,857
4	8.10%	404,813	382,143	14,249,414	46,473	96,345	87,440	5,781
5	8.25%	412,597	389,492	14,523,415	47,366	98,198	89,121	5,892
6	7.87%	393,421	371,389	13,848,421	45,165	93,634	84,979	5,618
7	8.55%	427,683	403,733	15,054,458	49,098	101,789	92,380	6,107
8	8.68%	434,240	409,923	15,285,248	49,851	103,349	93,796	6,201
9	8.50%	424,797	401,008	14,952,847	48,767	101,102	91,756	6,066
10	8.90%	445,173	420,244	15,670,102	51,106	105,951	96,157	6,357
11	8.99%	449,502	424,330	15,822,462	51,603	106,981	97,092	6,419
12	8.81%	440,261	415,606	15,497,171	50,542	104,782	95,096	6,287
Total	**100.00%**	**5,000,000**	**4,720,000**	**176,000,000**	**574,000**	**1,190,000**	**1,080,000**	**71,400**

Note: We use Corbett and Koehler emissions inventory (base case) with 2000-2002 ICOADS monthly variation.-

3 Forecasting Trends

3.1 Overview

3.1.1 Forecasts can differ depending on their purposes and scales. Some forecasts look to reveal where timely investment and action at a local scale or by a single firm can produce the most benefit (e.g., profit). Other forests are intended to be conservative or aggressive; that is, they intend to be biased to serve the decision makers' value and tolerance for risk and surprise. This may describe large scale forecasts such as emissions or trade trends. One challenging class of forecasts may be considered "*difference*" forecasts, where alternative scenarios illustrate how "*a path taken*" may differ from "*a path not taken*" rather than to determine which is most probable. These kinds of forecasts are common in policy domains, such as energy, environment, and economics (e.g., IPPC scenarios). Certainly, ship emissions forecasting presents one challenging example, especially at the international or multinational scales, and especially when considering policy actions like a SOx Emissions Control Area (SECA) under IMO MARPOL Annex VI *(2)*.

3.1.2 Previous studies available to IMO have described global growth rates for maritime shipping, based on fleet size, trade growth, and/or cargo ton-km, mostly calibrated to linear or conservative extrapolations of historic data. The *IMO Study on Greenhouse Gas Emissions from Ships (5)* used fleet growth rates based on two market forecast principles, validated by historical seaborne trade patterns: 1) World economic growth will continue; and 2) Demand for shipping services will follow the general economic growth. The IMO study correctly described that growth in demand for shipping services was driven by both increased cargo (tonnage) and increased cargo movements (ton-miles), and considered that these combined factors make extrapolation from historic data difficult. Nonetheless, their forecast for future seaborne trade (combined cargoes in terms of tonnage) was between 1.5% and 3% annually. The IMO study applied these rates of growth in trade to represent growth in energy requirements.

The ENTEC study *(22)* adopted growth rates from the IMO study. Eyring et al. *(50)* estimated "future world seaborne trade in terms of volume in million tons for a specific ship traffic scenario in a future year" using a linear fit to historical GDP data. Interestingly, this represents one of the only studies to forecast growth in seaborne trade for energy and emissions purposes at rates faster than GDP. The TREMOVE maritime model *(51, 52)* estimates fuel consumption and emissions trends derived from forecast changes in ship voyage distances (maritime movements in km) and the number of port calls. According to the TREMOVE report, maritime "fleet and vehicle kilometres grow annually by 2.5% for freight and 3.9% for passengers," while "port callings grew by 8% compared to the previously used input figures."

3.1.3 Except for the Eyring et al. work, these linear extrapolations appear to present growth rates slower than the economy. Linear extrapolations are likely biased on the low side, because shipping growth rates have actually grown faster than the economy. Freight transportation, particularly international cargo movement, is an important and increasing contributor to global and national economic growth, as well as state and regional economic growth in and around major cargo ports. If growth in GDP and trade volumes is compounded as forecast by economic and transportation demand studies, then growth in energy requirements should be non-linear also. The U.S. Bureau of Transportation Statistics (BTS) recently released a report that describes North American freight activity and trends *(53)*. This document reports growth rates for North America above 7.4% for international trade and above 7.2% across all measures of value, and states that:

> "*Since 1994, the value of freight moved among the three countries has averaged almost 8 percent annual growth in both current and inflation-adjusted terms, compared with about 7-percent growth for U.S. goods trade with all countries (table 1). In 2005, both goods trade and gross domestic product (GDP) grew in*

inflation-adjusted terms. Except in 2001 and 2002, during the past decade, U.S. trade with Canada and Mexico has increased at a faster rate than U.S. GDP."

Growth in goods movement by dollar value may be expected to differ from growth in the volume of goods moved, and in the change in activity by the multimodal fleets (ships, trucks, trains, and aircraft) moving cargo. We confirmed that the contribution of international trade is increasing as a proportion of U.S. gross domestic product (GDP) – i.e., freight transportation is growing faster than U.S. GDP *(53, 54)*. Economic activity related to imports and exports together contribute about 22% of recent U.S. GDP in recent years; whereas, goods movement contributed only about 10% of GDP in the 1970s. Moreover, the dominance of containerized cargoes in seaborne trade suggests that truck and containerized shipments may double by 2025 or sooner *(55)*. GDP in the U.S. is growing at ~3.7% CAGR since 1980, and the freight sector is growing at ~6.4% CAGR over the same period *(54)*. This freight-sector growth rate in terms of dollar value is reflected in the observed ~6.3% to 7.2% annual growth rates of "high-value" containerized trade volumes, particularly from Asia *(56)*.

Studies for Southern California (San Pedro Bay) ports agree that growth in cargo volumes equivalent to 6-7% compounding annual growth rates is expected *(57-60)*. However, increased cargo may not produce a corresponding increase in port calls, as some studies interpret *(58)*. Historic data on port calls to San Pedro Bay have shown the number of ship calls remained between 5,000 and 7,000 calls per year since the 1950s *(61)*.

3.1.4 Freight energy use is correlated to increased goods movement, unless substantial energy efficiency improvements are being made within a freight mode (e.g., U.S. rail) or across the logistics supply network. Even assuming that efficiency improvements from economies of scale reduce energy intensity and emissions rather than being directed to larger and faster ships (e.g., containerships), compounding increases in trade volumes outstrip energy conservation efforts unless technological or operational breakthroughs in goods movement emerge. Furthermore, proportional relationships between environmental impacts and goods movement trends are reflected in recent port and regional studies of economic activity and goods transportation, particularly those focused on Southern California ports *(57, 62-64)*.

3.2 Ship Installed Power as Emissions Trend Indicator

3.2.1 Given that energy used and emissions produced during goods movement increases at a rate correlated to growth in activity, a number of proxies may be used to estimate inventory growth rates. These include: economic activity (GDP and imports/exports value), trade activity (tons and ton-miles), and fuel usage (sales and estimates). All of these are indirect proxies (second or higher order) of the activity that produces emissions. Except for fuel usage statistics, none directly describe power requirements for shipboard power plants (propulsion and auxiliary engine systems). Best practices for ship emissions inventories typically use power-based (or fuel-based) emissions factors, because of the implicit proportionality between engine load and pollutant emissions – especially for uncontrolled sources *(20, 21)*. Therefore, we derive emissions trends directly from installed power data for cargo ships in the world fleet.

3.2.2 Assumptions we must make to use trends in installed power are rather simple: 1) international vessels in cargo service generally design power systems to satisfy trade route speed and cargo payload requirements; in other words, there is no economic reason to design propulsion systems for containerships, tankers, etc., with more power than their cargo transport operation requires; 2) international vessels operate under duty cycles that are well understood, especially at sea speeds, which for most vessel types utilize the majority of installed power as reflected in best practice methodologies for activity based inventories of energy and emissions from ships; and 3) ships in commercial cargo service on major trade routes reflect the best fit of ship design to service requirements; in other words, the trends revealed in installed power of ships reveals fleet trends in speed and size. With these assumptions, trends in installed power reveal the correlated trend in energy use by ships.

3.2.3 We considered the trend in average installed power by year of build covering 1970 to 2003 for the world fleet of ships. Where data were missing in the installed power field for some vessels, we used linear regression statistics within each vessel type associating gross registered tonnage (GRT) and rated power to fill data gaps. That describes one homogeneous world-average growth rate, which will result in underestimating future emissions where trade increases strongly and overestimating emissions in declining trade routes.

Observed trends in average installed power by year-of-build are shown in Figure 5. The compound annual growth rate (CAGR) for installed power since 1985 is ~10.7% per year, more than twice the rate of world seaborne trade growth, driven by increases in containership power which grew at more than 16% CAGR over these two decades. While the slope before 1980 appears similar to the slope after 1985, one can observe the significant fleet restructuring (particularly for tankers) during the economic recession in the early 1980s. Choosing a period since 1970 inclusive of the shipping recession, the rate of installed power growth for the world fleet ~5.1% CAGR; even so, power growth rates for the liner fleet over this period were still greater than 9% CAGR.

3.3 Growth Forecast Discussion

3.3.1 Admittedly, the quality of forecasts of maritime shipping and trade is somewhat limited *(66)*, and thus forecasting of environmental impact from shipping is constrained by the quality of shipping and trade forecasts. This section compares results of alternative measures of growth at multiple scales, demonstrating general similarity among power-based and other ocean shipping trends. At the global scale, we evaluate available trends in energy use and/or emissions from published literature with the seaborne cargo and trade data discussed earlier. Eyring et al estimate fuel usage and emissions over a historical period from 1950 to 2000 and forecasts for 2020 and 2050 using an activity-based approach describing a BAU scenario and a number of alternate scenarios combining different ship traffic and technology assumptions *(36, 50)*. For comparison purposes, we use their BAU scenario for a diesel-only fleet.

3.3.2 We compare world fleet trends in installed power (derived from average power by year of build) with energy trends (Eyring work and fuel sales), with trade-based historical data (tons and ton-miles). Activity-based energy results for similar base-years (2001 or 2002) are within close agreement *(20, 25, 36)*.[1] This allows us to index trends to nearly the same value and year, to index trade-based trends similarly, and to compare these with trends in installed power, as summarized in Figure 6.

3.3.3 Three insights emerge from this global comparison.

1) Extrapolating past data (with adjustments) produces a range of BAU trends that is bounded and reveals convergence around a set of similar trends; in other words, while the range of growth may vary within bounds of a factor of two, one cannot get “any

[1] An exception is work by Endresen et al, that tends to adjust parameters to agree with international marine fuel sales statistics; their results are within uncertainty ranges described in other work (23, 24, 67).

forecast they want" out of the data. If we consider that global trade and technology drivers mutually influence future trends, then we may interpret convergence within the bounds as describing a likely forecast of global shipping activity.

2) World shipping activity and energy use are on track to double from 2002 by about 2030 (~2015 if one considers seaborne trade since 1985, ~2050 if one considers Eyring's BAU trend). Growth rates are not likely to be reduced without significant changes in freight transportation behavior and/or changes in shipboard technology.

3) Confirming earlier discussion, trends in installed power are clearly coupled with trends in trade and energy. This reinforces the analysis of installed power as a proxy for forecasting growth, not only for use in baseline inventory estimates.

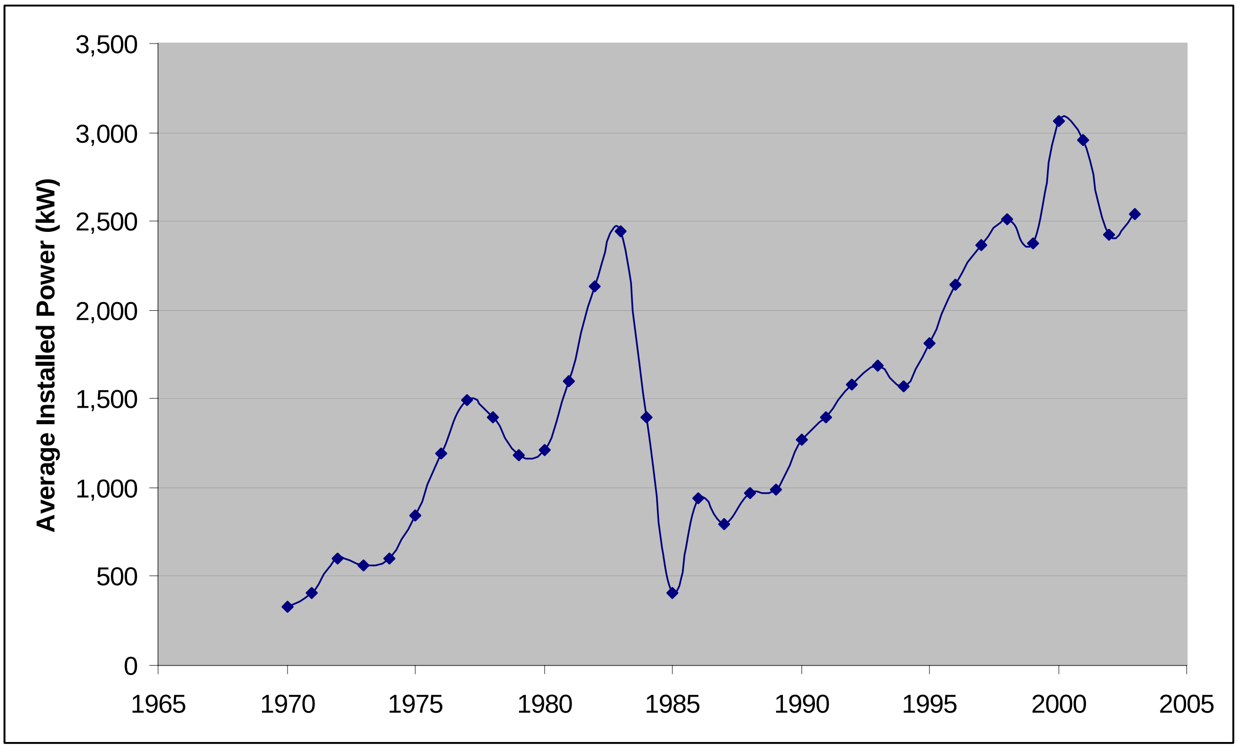

Figure 5. Average installed power in the world fleet by year-of-build *(65)*.

3.3.4 An important question is whether forecasts that directly apply seaborne trade growth rates to energy and emissions trends should assume any change in the fleet-average energy intensity over the coming decades. A common belief is technological change improves energy efficiency in ocean freight transportation (i.e., reduces energy intensity) over time; rationale for this belief may extend from two historical facts about shipping and energy use: 1) shipping has traditionally been less energy intensive than other freight modes (especially trucking), and 2) marine propulsion engineering developments over the past century produced what are arguably the most fuel-efficient internal combustion (diesel) engines in the world *(68)*.

Depending on change in energy intensity and/or emissions through investments in economies of scale, fuel conservation measures, or emissions control measures, the rate of change in energy and emissions could be a modified growth curve from the growth in cargo activity. If so, one indication would be different rates of change for installed power on ships providing goods movement compared to changes in cargo volume. In other words, if a fleet of ships can carry more cargo without a proportional increase in installed power, then it must be adopting improved technologies (e.g., hull forms, engine combustion systems, plant efficiency designs) or innovating its cargo operations (e.g., payload utilization).

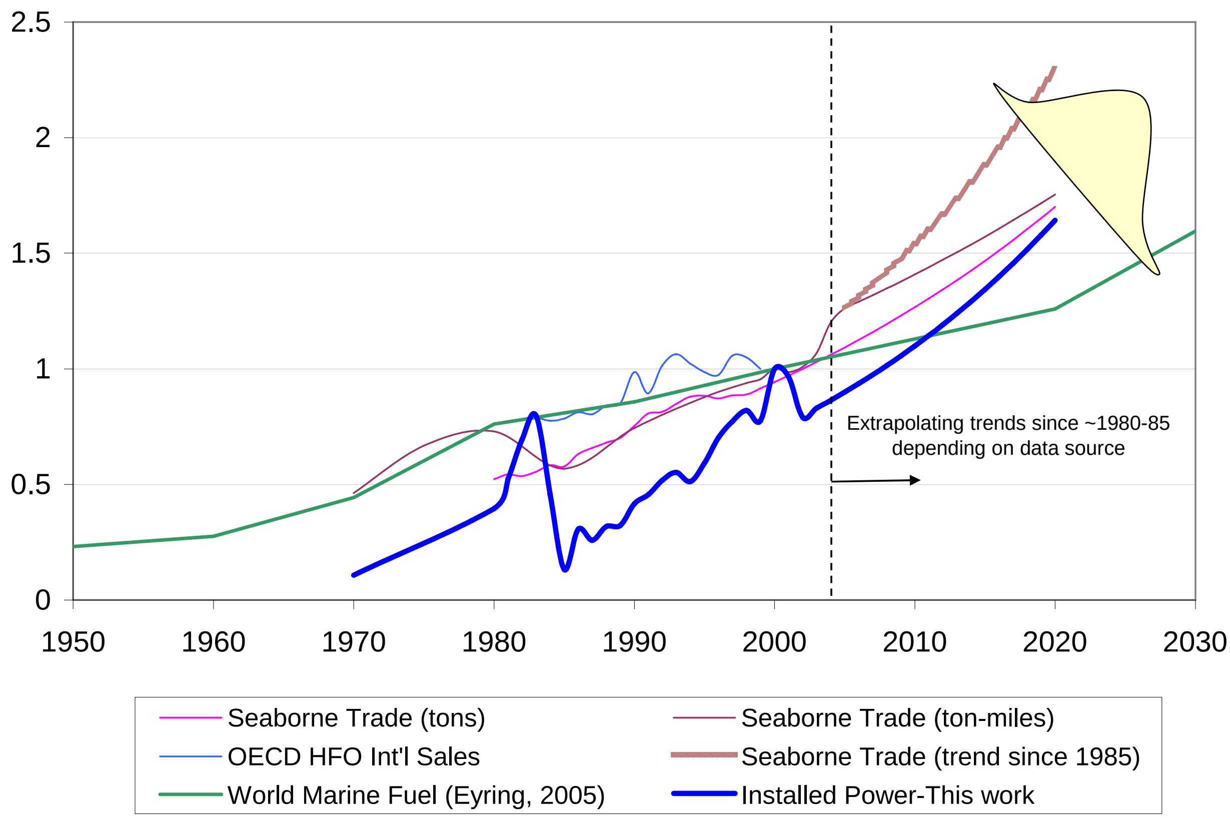

Figure 6. Global indices for seaborne trade, ship energy/fuel demand, installed power.

3.3.5 In fact, the opposite trend is observed over the past 20 to 30 years, where fleet installed power has grown at rates faster than global trade growth. Rephrasing, ***ocean shipping may have become more energy intensive, not more energy conserving***. This seemingly counter-intuitive observation is typical of other transportation modes, particularly onroad freight and passenger vehicles, and readily explainable in terms of trade globalization and containerization of international trade. Globalization produced longer shipping routes, and containerization serves just-in-time (or at least on-time) liner schedules; both of these drivers motivated economic justification for larger and faster ships which require greater power to perform their service. Introduction of the fastest, largest ships first occurred on the most valuable trade routes (e.g., serving North America and Europe) where economics most justified the higher performing freight services. Increasingly over the past two decades, ships serving all routes became faster and larger through intentional expansion and aging fleet transition from prime routes to secondary markets.

3.3.6 However, technological change can offset this trend, if fleets can achieve greater efficiencies while increasing installed power. In other words, if fuel economy (energy input) is not directly proportional over time to energy output (proportional to rated power), then improved propulsion technologies can explain the decoupling of increased power and fuel use. Ship diesel engines have achieved substantial improvements in thermal efficiency since the 1970s *(69-71)*, and fleet turnover has introduced more efficient ships into the world fleet. Using thermal efficiency as an indicator of this, we construct a sensitivity table that illustrates the potential for engine designers to offset trade-driven energy requirements through more efficient fleet modernization. Table 3 shows that replacing an old ship with inefficient engine with a new ship using the most efficient engine of equivalent power has potential to double fuel economy.

Table 3. Sensitivity analysis of potential improvement in thermal efficiency (fuel economy)

		Max	High-high-bound	High-bound	High	Low	Low-bound	Low-low-bound
	Thermal Efficiency	55%	50%	45%	40%	35%	30%	25%
Low-low-bound	25%	2.20	2.00	1.80	1.60	1.40	1.20	0.00
Low-bound	30%	1.83	1.67	1.50	1.33	1.17	0.00	
Low	35%	1.57	1.43	1.29	1.14	0.00		
High	40%	1.38	1.25	1.13	0.00			
High-bound	45%	1.22	1.11	0.00				
High-high-bound	50%	1.10	0.00					
Max	55%	0.00						

In practice fleet modernization is not as extreme as the illustration in Table 3; fleetwide average gains in efficiency occur slowly over time because operators replace vessels according to other economic factors in addition to fuel economy. For example, if one were to assume for illustration that every new ship replaced the least efficient ship in the fleet since 1970, an upper bound improvement in energy efficiency can be illustrated (Table 4). Emphasizing that this over-estimates fleetwide improvements, Table 4 would suggest that growth rates in installed power may be adjusted downward by no more than 3% to 4% per year, and with fleet-average adjustments for fuel economy improvements between 0.5% and 2% more likely given fleet turnover rates.

The average technology in the fleet may not change that much from its current path over the next 35 years without strong policy incentives or substantial changes in fleet energy pricing and supply. A linear growth rate does not match known or expected technology changes relative to cargo growth; a linear trend in energy use would imply less power required to achieve cargo throughput – where compounded growth is forecast for cargo volumes. In a BAU context, fleet propulsion technologies will remain more similar than different to the current profile at least through 2040. Moving more cargo will require more power and more energy, even with anticipated thermal efficiency improvements for new engines.

If the economics of globalization and containerization sustained the high rate of growth in installed power over the past decades, one could expect growth over the next decades more similar to growth in trade as smaller, slower ships are scrapped thereby reducing variation among the world fleet characteristics. In other words, the prime routes will continue to attract ship designs best suited to the balance between freight performance and operating economy. Even so, energy intensity is (at best) holding constant with increasingly globalization and containerization of trade logistics. If fuel prices remain high or continue to increase, and if the pace of liner freight continues to be satisfied by ship speeds ranging between 20-27 knots, then technical improvements in propulsion and hull design may again be devoted to improving energy intensity.

Table 4. Matrix of maximum annual percent fuel economy gain over from 1970 to 2005, comparing thermal efficiencies in new versus replaced engines.

		Max	High-high-bound	High-bound	High	Low	Low-bound	Low-low-bound
	Thermal Efficiency	55%	50%	45%	40%	35%	30%	25%
Low-low-bound	25%	6.29%	5.71%	5.14%	4.57%	4.00%	3.43%	0.00%
Low-bound	30%	5.24%	4.76%	4.29%	3.81%	3.33%	0.00%	
Low	35%	4.49%	4.08%	3.67%	3.27%	0.00%		
High	40%	3.93%	3.57%	3.21%	0.00%			
High-bound	45%	3.49%	3.17%	0.00%				
High-high-bound	50%	3.14%	0.00%					
Max	55%	0.00%						

Note: Obtained by dividing the Table 3 matrix by 35, representing 1970 to 2005. Actual fleetwide average improvements in engine efficiency are smaller.

3.3.7 We believe that the unconstrained exponential trend and the linear trend define bounding limits for expected change in ship installed power and energy use due to expected trade growth and fleet technology improvements. Averaging these curves defines an arbitrary middle-growth trend, which implicitly describes a mix of positive and negative drivers for ship energy requirements without articulating a detailed scenario of conditional events. After adjustment, we estimate a world growth trend ranging between 3.8% and 4.5% CAGR. This averaging conservatively forecasts energy and emissions trends; it implicitly combines two assumptions: 1) transition to containerization followed by larger, faster containerships will level-off as the world market scraps older ships; and 2) improvements in propulsion and engine efficiency may continue, more clearly decoupling energy demand from cargo service than has been observed over recent decades.

3.3.8 Coincidentally, averaging bounding extrapolations yields between 3.8% and 4.5% CAGR growth in installed power, nearly the same 4.1% CAGR as observed for past world seaborne trade. In other words, this explains and confirms the use of seaborne trade growth to project ship fuel use and emissions, as other studies have done. Therefore, we consider this BAU forecast to be informed by observed past trends and consistent with adjustments intended to avoid overly aggressive growth estimates. **Consistent with the market-forecast principles reflected in the IMO study, and given the strong relationship observed between cargo moved (work done) and maritime emissions (fuel energy used), we adopt for our forecasts the world average growth rate of 4.1%**.

3.4 Emissions Adjustments

3.4.1 While we grow each pollutant inventory by this 4.1% annual rate, we also make several adjustments for existing IMO regulatory requirements for NOx and sulfur. First, we adjust for IMO NOx standards and fleet modernization rates introducing cleaner IMO-compliant engines. Pursuant to MARPOL Annex VI, engines installed on ships constructed on or after 1 January 2000 or engines which undergo a major conversion on or after 1 January 2000 should meet the requirements of the Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines *(2)*. This means that after that date, the increase and replacement of the fleet should be IMO-compliant for NOx. Using the U.S. EPA estimate that IMO compliant engines will emit about 17% less NOx emissions than uncontrolled emissions *(72)*, we adjust NOx emissions for fleet scrapping and new ship orders. This results in a downward adjustment from uncontrolled projections; for 2012 this adjustment is 3.6% of total NOx emissions. Other studies suggest the downward adjustment may be greater, perhaps ranging from 5.5-5.6% in 2012 to 8.3-8.4% in 2020. We accept that there can be a range of NOx reductions attributed to IMO MARPOL Annex VI, and consider the difference in these estimates to be small.

3.4.2 We also adjust future inventories spatially to reduce forecast emissions in SECA regions to comply with IMO SECA standards of 1.5% fuel. (The Baltic Sea SECA was implemented and operational since 19 May 2006; the North Sea SOx Emission Control Area (SECA) comes into effect on 22 November 2007.) To do this, we forecast emissions globally under the assumption that world residual fuel sulfur levels remain constant (~2.7% world average), and multiply emissions in SECA regions by 0.66, representing an average 44% reduction in fuel-sulfur content. Adjustments are implemented for both the Baltic and North Seas for IMO-SECA inventories for 2012.

4 Conclusions

4.1 These results help reveal insights important for future policy:

1. There are emissions reductions from an IMO-compliant (1.5% fuel-sulfur SECA) over BAU trends; and
2. Shipping emissions and resultant health effects and/or other impacts that may be offset in a base year by implementing a SECA will return to base-year levels within one or two decades.
3. An estimation of benefits from reducing ship emissions can be made using the global data set we report here, or using more refined regional and local data sets.

4.2 These insights appear robust, regardless of the range in possible forecasts. Using the forecast trend derived in this work, trade growth offsets baseline (2002) SOx emissions under a global 1.5% marine fuel-sulfur cap before 2017. Using the range of growth rates reported by Eyring et al. (2.6%, 3.1%, 3.4%, and 4.0%, annually), emissions within a SECA return to 2002 levels by 2025, 2022, 2020, and 2017, respectively; this range captures the 3% growth rate in the IMO study on GHGs from ships *(4, 5)*, and is consistent with findings for North America *(29)*.

4.3 Figure 7 and Table 5 illustrate projected global sulfur emission trajectories under a number of different scenarios (for illustration, we assume global reductions take effect in 2010):

- business as usual (4.1% growth), with existing IMO ANNEX VI regulations in place;
- BAU using 3% growth, consistent with IMO GHG study;
- global marine-fuel reduction to 1.5% fuel-sulfur, for both 4.1% and 3% growth rates;

- global marine-fuel reduction to 1.0% fuel-sulfur (for 4.1% growth); and
- global marine-fuel reduction to 0.5% fuel-sulfur (for 4.1% growth).

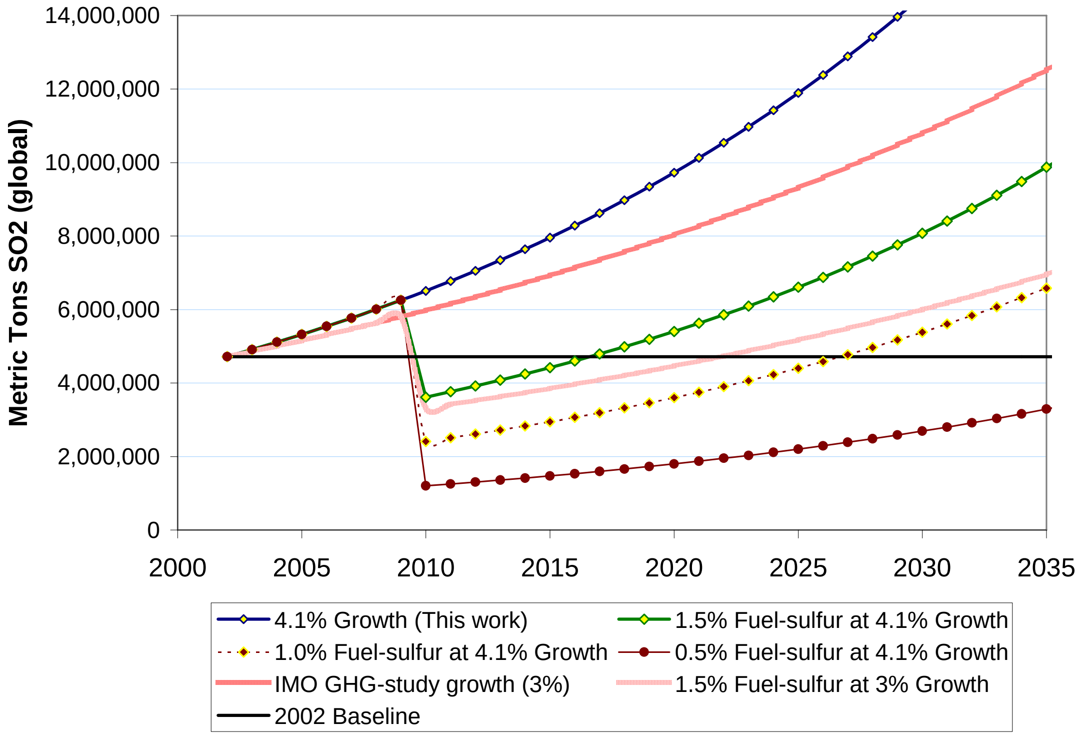

Figure 7. Comparison of BAU SOx trends with global sulfur controls at 1.5%, 1%, and 0.5%.

Table 5. Projected SOx emissions under BAU and various global sulfur-control scenarios.

	2002	2010	2015	2020	2025	2030
BAU: 4.1% Growth (This work)	4.72	6.51	7.96	9.73	11.89	14.54
1.5% Fuel-sulfur at 4.1% Growth	4.72	3.62	4.42	5.40	6.61	8.08
1.0% Fuel-sulfur at 4.1% Growth	4.72	2.41	2.95	3.60	4.40	5.39
0.5% Fuel-sulfur at 4.1% Growth	4.72	1.21	1.47	1.80	2.20	2.69
BAU: IMO GHG-study growth (3%)	4.72	5.98	6.93	8.04	9.32	10.80
1.5% Fuel-sulfur at 3% Growth	4.72	3.32	3.85	4.46	5.18	6.00

Note: Implementation of global controls assumed to begin as early as 2010 for illustration. Shaded cells represent uncontrolled BAU growth rates (this work or IMO GHG study)

4.4 This illustrates that more substantial emissions reductions will last longer into the future under reasonable growth assumptions. Thus, policies requiring a global 0.5% fuel-sulfur limit or control technologies achieving equivalent reductions would offset trade growth continuing to the early 2040s under a 4.1% CAGR. However, a 2010 global sulfur limit of 1.5% would offset trade growth only until approximately 2017 to 2022, depending on whether a 4.1% or a 3% growth rate is applied.

4.5 With respect to NOx, growth in emissions has exceeded expected new-engine NOx reductions resulting from IMO-compliant fleet turnover since application of the existing Annex VI NOx standards to year 2000 and later ships. This is primarily due to the low scrappage rates of the vessel fleet; in other words, new engine standards take along time to be fully incorporated into the fleet due to the lengthy fleet turnover time.

To take a hypothetical example, a 20% reduction in emissions for a fleet that has a 2% scrappage rate would imply only a 0.4% (20% x 2%) reduction of annual fleet emissions; this per-year reduction is an order of magnitude smaller than annual emissions growth (~4%) due to increased seaborne trade activity. Even a 50% reduction in emissions from new vessels leads to only a 1% overall annual reduction under a 2% scrappage rate scenario. Controls reducing fleetwide shipping emissions by at least 60% would need to be fully implemented for both new and existing engines within the next two decades, in order to maintain 2002 global shipping pollution levels. Achieving fleetwide reductions will involve more aggressive reductions “per ship” if part of the fleet is left uncontrolled during transition or phase-in years, and reductions of this magnitude cannot be achieved through new-engine standards alone.

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