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ARTICLE *in* ENVIRONMENTAL SCIENCE AND TECHNOLOGY · JUNE 2007

Impact Factor: 5.33 · DOI: 10.1021/es060752e · Source: PubMed

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Modeling Energy Use and Emissions from North American Shipping: Application of the Ship Traffic, Energy, and Environment Model

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The waterway network ship traffic, energy, and environment model (STEEM) is applied to geographically characterize energy use and emissions for interport ship movement for North America, including the United States, Canada, and Mexico. STEEM advances existing approaches by (i) estimating emissions for large regions on the basis of nearly complete data describing historical ship movements, attributes, and operating profiles of individual ships, (ii) solving distances on an empirical waterway network for each pair of ports considering ship draft and width constraints, and (iii) allocating emissions on the basis of the most probable routes. We estimate that the 172 000 ship voyages to and from North American ports in 2002 consumed about 47 million metric tonnes of heavy fuel oil and emitted about 2.4 million metric tonnes of SO_2. Comparison with port and regional studies shows good agreement in total estimates and better spatial precision than current top-down methods. In quantifying limitations of top-down approaches that assume existing proxies for ship traffic density are spatially representative across larger domains, we find that International Comprehensive Ocean-Atmosphere Data Set (ICOADS) proxy data are spatially biased, especially at small scales. Emissions estimated by STEEM for ships within 200 nautical miles of the coastal areas of the United States are about 5 times the emissions estimated in previous studies using cargo as a proxy.

Introduction

Air pollutants from marine vessels account for a non-negligible portion of the emissions inventory and contribute to air quality, human health, and climate change problems at local, regional, and global levels (*1*−*23*). Better emissions estimates and improved spatial representation are needed for atmospheric scientists, pollution modelers, and policy makers to evaluate and mitigate ship emissions impacts on the environment and human health. The principal existing approaches for producing spatially resolved ship inventories generally can be categorized as either top-down or bottom-up. Their fundamental difference is that in bottom-up approaches emissions are directly estimated within a spatial context, whereas in top-down approaches emissions are calculated without respect to location at an aggregate level and may later be associated with spatial characteristics. Strengths and weaknesses of each approach are discussed in the Supporting Information.

Using a top-down approach, Corbett et al. produced the first global spatial representation of ship emissions using a proxy derived from the Comprehensive Ocean-Atmosphere Data Set (COADS) (*1*, *10*). They assumed that the reporting ship fleet is representative of the world fleet, that the spatial distribution of ship reporting frequencies represents the distribution of ship traffic intensity, and that emissions are proportional to traffic intensity. Endresen et al. improved the global spatial representation of ship emissions by weighting reporting frequencies using ship size (gross tonnage) from automated mutual-assistance vessel rescue (AMVER) system data (*3*). They implicitly assumed proportionality between ship size and ship energy consumption and emissions (*3*), although this is not uniformly valid for all ship types. Wang et al. addressed the potential statistical and geographical sampling bias of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS; current version of COADS) and AMVER data set, the two "best" global ship traffic intensity proxies (*24*). These two proxies draw self-reported samples from the global fleet and produce traffic intensity representations that differ significantly across regions; for example, AMVER represents more tanker traffic, and ICOADS represents more container ship traffic.

Bottom-up approaches were applied by Lloyd's Register and Entec UK Ltd. to produce regional ship emissions inventories for the EMEP (European Monitoring and Evaluation Programme) area, the Baltic Sea, and the Mediterranean Sea (*15*, *22*, *23*). Bottom-up approaches estimate ship- and route-specific emissions based on historical ship movements, ship attributes, and ship emissions factors. The locations of emissions are determined by the locations of the most probable navigation routes, often simplified to straight lines between ports.

Streets et al. estimated emissions from international shipping in Asian waters on the basis of commodity flow associated with major sea routes (*5*, *6*). The accuracy of this method, which can be categorized as a bottom-up approach using trade as a proxy for emissions, is limited by the assumed relationships between the volume of trade flow and emissions, which are more closely related to ship installed power, load profile, etc., and by the aggregation of individual voyage routes into major shipping lanes.

In this paper, we introduce a new framework, the waterway network ship traffic, energy, and environment model (STEEM), which was developed to quantify and geographically represent interport vessel traffic and emissions as contrasted with in-port activities which have been well-characterized in other studies (*27*−*31*). STEEM applies advanced GIS technology and solves routes automatically at a global scale, following actual shipping routes. This model can be used to characterize ship traffic, estimate energy use, and assess environmental impacts of shipping, etc. This paper focuses on the application of STEEM for geographically characterizing ship emissions for North America, including the United States, Canada, and Mexico. Other applications of STEEM are reported elsewhere and/or reserved for future work (*32*−*34*).

Description of STEEM

STEEM adopts the strengths of both top-down and bottom-up approaches and improves ship emissions inventories. First, the model builds an empirical waterway network based

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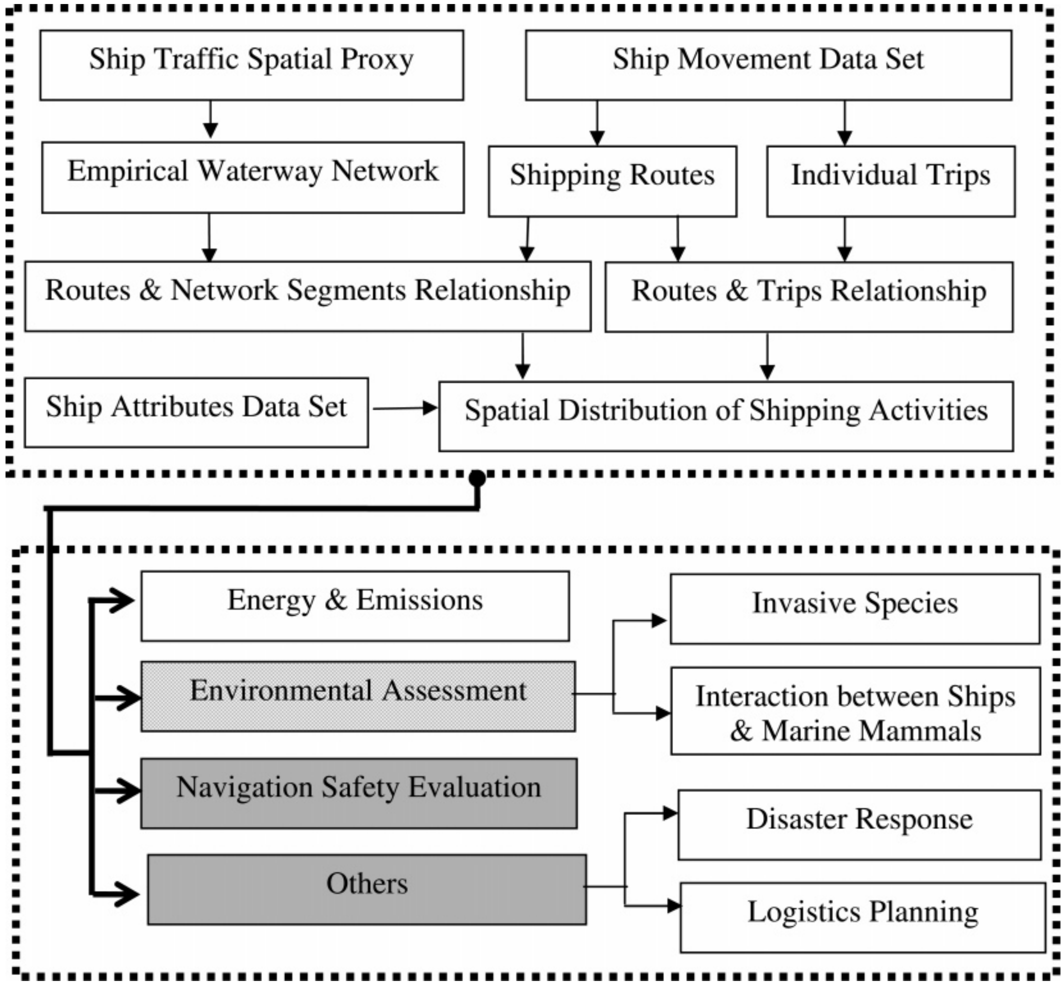

FIGURE 1. Illustration of STEEM.

on shipping routes revealed from observed historical ship locations. The spatial allocation is more accurate than approaches that assign speculative routes or that apply biased spatial proxies. Second, as in a bottom-up approach, this model estimates energy use and emissions using complete historical ship movements, ship attributes, and the distances of routes. Calculations based on actual activity are more accurate than a top-down approach assigning emissions by global proxy. Third, the automation of repetitive processes on a global routing network makes this method capable of producing global energy and emissions inventories. Fourth, since the network can be updated, modified, reused, and shared among users, STEEM is potentially more cost-effective than both the top-down and the bottom-up approaches. Figure 1 shows the STEEM model framework.

The upper part of Figure 1 illustrates the ship traffic module of STEEM, used to geographically and temporally characterize ship traffic on the basis of an empirical waterway network, historical ship movement data, and a ship attributes data set. The lower part shows applications of STEEM including producing spatially resolved energy and emissions inventories, assessing the impacts of shipping activities on the environment, e.g., invasive species carried by ballast water and encounters between ships and marine mammals, evaluating navigation safety, and other potential uses, e.g., logistics planning and disaster response planning. Research applying STEEM to estimate interaction probabilities between ships and whales is under way (*32*, *35*). Application of STEEM to navigation safety evaluation and other uses (boxes in gray) is reserved for future research. See the Supporting Information for a complete description of model elements and calculations.

Energy and SO_2 Emissions from North American Shipping

In this section we describe the application of STEEM to estimate energy use and SO_2 emissions from North American shipping. Inventory results for other pollutants are provided in the Supporting Information and are available at http://coast.cms.udel.edu/NorthAmericanSTEEM.

STEEM improves the North American shipping emissions inventory in the following ways: (1) STEEM employs an emprical global waterway network derived from 20 year ICOADS data. (2) The model estimates emissions from nearly complete historical North American shipping activities (172 000 trips in the U.S. Foreign Commerce Entrances and Clearances data set and Lloyd's movement data set) and individual ship attributes. (3) The model is constructed using advanced GIS network analysis to solve the most probable route for each individual trip on a global scale. (4) STEEM establishes explicit mathematical relationships among trips, ships, routes, pairs of ports, and segments of the waterway network using a matrix approach. (5) STEEM uses the actual lengths of routes, together with service speeds of individual ships, to calculate hours of operation. (6) STEEM follows the best practices to estimate emissions on the basis of ship installed power, service speed, and traveling distance for each trip. (7) STEEM assigns emissions on the basis of the locations of solved routes. (8) STEEM captures transit traffic which contributes to local air quality problems in areas such as Santa Barbara, CA.

Shipping Activities and Shipping Routes Data Sets. We derived ship movements from two data sets, the U.S. Army Corps of Engineers (USACE) Foreign Traffic Entrances and Clearances data set and the ship movement data set from Lloyd's Maritime Intelligence Unit (LMIU). Together, these two data sets include nearly all ship movements carrying North American waterborne commerce, excluding U.S. domestic commerce data, which were not part of these data sets. We assigned a unique trip ID to each of about 172 000 unique trips described in the North American shipping activities data set for 2002, which are defined as nonstop movements from origin ports to destination ports. We define a route as an actual nonstop voyage between one origin and one destination port. We derived shipping routes from the shipping activities data set, which includes prior and next ports of call. Each route received a unique ID that established the one-to-many relationships between trips and routes (a trip can be assigned to one route, while one route can have many trips). North American shipping activities for 2002 included voyages on ~21 000 unique routes.

Port Characteristic Data Set. We built a data set which includes all ports appearing in the shipping activities data set for 2002. We assigned each port a unique port ID, used to link the shipping activities data set to the waterway network. Most geographic port locations (longitude and latitude) come with the activities data set. Four databases contribute missing data, including Geographic Data for International Cities, Landmarks (http://earth-info.nga.mil/gns/html/cntry_files.html), Geographic Data for U.S. Cities, Landmarks (http://geonames.usgs.gov/geonames/stategaz/index.html), the United Nations Code for Trade and Transport Locations (UN/LOCODE at http://164.214.12.145/pubs/pubs_j_wpi_sections.html), and the World Port Index—Digital Navigation Publication of the U.S. National Geospatial-Intelligence Agency (http://www.unece.org/cefact/locode/service/main.htm). About 400 U.S. ports and about 1300 non-U.S. ports are in the 2002 U.S. Entrances and Clearances data set; about 950 ports are in the 2002 Lloyd's movement data set. These ports are located by longitude and latitude and connected to the network in ArcMap.

Ship Attributes Data Set. We built a ship characteristic data set, which includes all ships appearing in the shipping activities data set. Ship attributes in this data set include the unique ship ID, ship type, gross registered tonnage (GRT), installed power, and cruise speed. We group ships into nine major ship types including container ships, bulk carriers, tankers, general cargo ships, RO—RO ships, passenger vessels, reefers, fishing vessels, and miscellaneous vessels.

We combined ship attributes data sets that come with the shipping activities data sets with ship registry data sets that are commercially available. Where ship power data are missing, the values were estimated for each vessel type from statistical relationships between the GRT and the net register tonnage (NRT) and between power and the GRT. Regression results are shown in Table SI1 in the Supporting Information. Where speed data are missing, the average service speed of a given type of ship in the data set is used. Table SI2 in the Supporting Information summarizes the average speed we used, the average speed used by Lloyd's Register in the Baltic Sea study, and the average speed used by Entec UK Ltd. in the study conducted for the European Commission (*15*, *23*, *36*).

The ship attributes data set also includes the ship size and dimensions, including the length, width, and draft for determining whether a specific ship can pass canals or restricted waters. In this work, ships are divided into three groups by size including (1) ships small enough to use both the Panama Canal and the Suez Canal, (2) ships too big to pass Panama but small enough to pass the Suez Canal, and (3) ships too big to pass either of the two canals. We did not consider the potential conditions where a loaded vessel cannot transit a canal, but may meet draft restrictions on empty or backhaul voyages.

Building the Empirical Waterway Network. The empirical waterway network, which aligns the shipping lanes with actual shipping activity, is composed of ports, which are origins and destinations of shipping routes, junctions, where shipping routes intersect, and segments (edges), which are shipping lanes between two connected junctions or ports. Each segment can have only two junctions or ports, and ship traffic flow can enter and leave a segment only through a junction or a port. Since shipping lanes are not lines in reality but have a certain width which can be hundreds of nautical miles wide in the ocean (*41*), polygons are more representative of the shipping lanes than polylines. In this work, we assigned each polyline segment a width, which was obtained by measuring the width of the shipping lanes in the spatial proxy of ship traffic.

Two global ship reporting data sets, ICOADS and AMVER, have been used as proxies of ship traffic to geographically resolve the global emissions inventories (*3*, *10*, *37*). ICOADS is a data set of global marine surface observations collected by the voluntary observing ships (VOS) fleet, which has about 4000 ships worldwide (*3*, *38*). AMVER, sponsored by the United States Coast Guard, is a global ship reporting system for ship search and rescue. Participation in AMVER is free, voluntary, and open to merchant ships of all flags, but had been limited to ships over 1000 gross tons, on a voyage of 24 h or longer (*39*). A total of 8587 different vessels reported to AMVER in 2004.

By studying the spatial and temporal dynamics of global ship traffic patterns derived from historical locations where ships reported to ICOADS and AMVER, we confirmed that ships travel along well-established shipping lanes (*3*, *10*, *37*, *40*). We compared traffic patterns revealed from ICOADS and AMVER data sets and confirmed the consistency of the traffic lanes from these two independent sources. Figure SI1 in the Supporting Information shows the similarity of the structure of the lanes from 20 years (1983—2002) of ICAODS data and about 1 year (part of 2004 and part of 2005) of AMVER data. The consistency of the two data sets further confirms the stability of the shipping network and justifies efforts to build an empirical network for repetitive use with updates and modifications when needed.

We used 20 years (1983—2002) of ICOADS data and about 1 year (2004—2005) of AMVER data to identify shipping lanes of the empirical waterway network. The network for North American waterborne commerce is comprised of about 9000 segments, and each segment has a unique segment ID number. Attributes were added to the network to open and close certain segments, such as the Panama Canal and the Suez Canal, for certain sizes of ships.

Figure SI2 in the Supporting Information illustrates the empirical waterway network we built and a sample of routes solved with ArcGIS Network Analyst. The network can be updated and modified by adding new lines or by plugging more refined regional network data into this global network. The network also can be enhanced by differentiating lanes into seasonal lanes, weather lanes, and lanes for different ship types and sizes. Small-scale (local or regional) networks can achieve precision similar to that of port-based inventories with regard to the spatial distribution of ship traffic.

Establishing Relationships between Routes and Segments. Using ArcGIS tools, we established the many-to-many relationships between routes in the shipping activities data set and segments of the empirical waterway network. A route can be composed of many segments, and a segment can be part of many routes. ArcGIS Network Analyst solves the most probable path on the network between each pair of ports for a certain size of ship. We assumed that ships take the least-energy path, which is the shortest distance in most cases unless prevented by weather or sea conditions, water depth, channel width, navigation regulations, or other constraints. By conforming the shortest route to empirical shipping lanes (i.e., historically observed navigable routes for ships), the network approach intrinsically addresses these factors better than previous straight-line route assumptions. We wrote Visual Basic for Application (VBA) and Python scripts to automate the process of solving 21 000 routes.

Summary of the Relationships among the Elements of the Model. We established the relationships among the elements of the network including ship ID, trip ID, port ID, route ID, and segment ID. Figure SI3 in the Supporting Information illustrates the relationships. The one-to-many relationships between ship ID and trip ID means that one ship can have many trips while one trip can be associated with only one ship. The many-to-one relationships between trip ID and port ID pairs means that one trip can be assigned to only one pair of port IDs while there can be many trips between one pair of port IDs. The one-to-one relationship between port ID pair (considering ship size) and route ID means that each route corresponds to one pair of ports for one group of ships of a certain size. The many-to-many relationships between route ID and segment ID means that a route can be composed of many segments and one segment can be part of many routes.

Estimating Fuel Demand and SO_2 Emissions. The installed power of individual ships was used to estimate the ship energy and emissions for each trip. We adopted the at-sea main engine load factors used by Corbett and Koehler for the updated emissions inventory for international shipping (*2*). On the basis of engine manufacturer data used in other global analyses, we assumed that 55% of the passenger vessel total main engine power is devoted to propulsion and 25% of the remaining power serves the auxiliary engine (AE) power (*2*, *25*). We used a maneuvering load profile (lower engine load factor and slower ship speed) for the first and last 20 km of each trip when a ship is entering or leaving a port. If the trip was shorter than 20 km, we assumed that ships were maneuvering for the whole trip, although this assumption may underestimate emissions from some short-sea routes. We assumed that the main engines operate at 20% of the installed power during maneuvering, the same number used by Entec UK Ltd. (*15*).

Since most of the auxiliary engine data for ships are missing in the ship attributes data set, the average auxiliary power of each ship type was used to estimate the energy and emissions from auxiliary engines. The average auxiliary engine power and percent in-use marine distillate of auxiliary engines was adopted from the California Air Resources Board (ARB) survey (*42*). ARB survey results indicate that "29 percent of the auxiliary engines used marine distillate and 71 percent used HFO, except for passenger vessels that use approximately 8 percent marine distillate and 92 percent HFO" (*42*). These numbers were adopted to adjust the SO_2 emissions factors for auxiliary engines. Table SI3 in the Supporting Information summarizes engine power and at-sea load profiles.

Considering the emissions factors used in previous studies, we used a composite SO_2 emissions factor of 10.6 g/(kW h) to estimate main engine SO_2 emissions (*2*, *15*). The SO_2 emissions factors for auxiliary engines using marine distillate and heavy fuel oil are 4.3 and 12.3 g/(kW h), respectively. A composite SO_2 emissions factor was adopted for each type of ship, weighted by the percent of marine distillate used by that type of vessel (*42*). For passenger vessels and miscellaneous ships, we used SO_2 emissions factors of 11.66 and 4.3 g/(kW h), respectively. For other types of ships, we used 9.98 g/(kW h). For estimating fuel consumption, 206 g/(kW h) was used as the specific fuel oil consumption (SFOC) for transport ships and 221 g/(kW h) for nontransport ships, including fishing and factory vessels, research and supply ships, and tugboats, as adopted in other studies (*2*).

We estimated that the global interport transport of North American commerce consumed more than 44.7 million metric tonnes of heavy fuel oil and emitted about 2.3 million metric tonnes of SO_2 in 2002, about 16.5% of the SO_2 emissions from all sources in the U.S. in the same year (*21*). Given that in-port emissions are about 2−6% of the total emissions, as reported by Streets et al. and Entec UK Ltd. (*5*, *15*), total heavy fuel use and SO_2 emissions from North American shipping are approximately 47 million and 2.4 million metric tonnes, respectively. North American shipping fuel use and SO_2 emissions are between 18% and 20% of the world commercial fleet totals estimated by Corbett and Koehler and between 28% and 34% of the world cargo and passenger fleet totals estimated by Endresen et al. (*2*, *3*).

We estimated that global waterborne transport of U.S. foreign commerce consumed about 38 million metric tonnes of fuel in 2002. This number agrees well with Energy Information Administration statistics that estimate that ships consumed about 44 million metric tonnes of fuel in 2002. U.S. domestic waterborne commerce, which we did not include in this work, may be partially responsible for the difference. Moreover, we only route North American voyages between prior and next ports; multiport logistics, common to commercial shipping (especially container ships), are not modeled. This means that ships may be traveling much longer distances than estimated by this version of STEEM.

Container ships, bulk carriers, and tankers account for about 35%, 22%, and 17% of SO_2 emissions from North American shipping, respectively. The top 10 maritime countries collectively account for about 71% of the 2.3 million metric tonnes of SO_2 emissions. Panama, the largest flag of convenience country, accounts for 23% of the SO_2 emissions. Liberia, the Bahamas, and the U.S. account for 13%, 8%, and 5% of the emissions, respectively. The Norwegian International Register, Singapore, Greece, Cyprus, Malta, and Hong Kong each account for between 3% and 4% of the emissions. The other 111 countries account for the remaining 29% of the emissions. Energy use is proportional to the SO_2 emissions profile.

Producing a Spatially Resolved SO_2 Emissions Inventory. On the basis of the relationships among trips, routes, and segments of the network, we allocated total SO_2 emissions onto the waterway network. We buffered the waterway network with the width of each segment and calculated the area of the segments. We calculated the average of SO_2 emissions per square kilometer by dividing the total SO_2 emissions in each segment by its area. We converted the buffered network to a raster file with a resolution of 4 km × 4 km, and the value of each grid is the amount of SO_2 emissions from this 16 km^2 area. We adjusted the emissions within a 20 km radius circle of ports with maneuvering load profiles. Figure 2 illustrates the resulting estimate of the spatial distribution of SO_2 emissions from North American shipping.

Using this inventory, we estimated emissions and fuel use for North America coastal areas as illustrated in Figure SI4 in the Supporting Information. The coastal zones are 200 nautical miles buffer zones from shore resembling the 200 nautical mile exclusive economic zone (EEZ), but the division among countries is for illustration purposes only.

Comparison with Other Emissions Studies

We compared the STEEM emissions inventories with our top-down approach using ICOADS as the spatial proxy (*24*). In Figure 3a, U.S. coasts are 200 nautical miles buffer zones approximating the 200 EEZ as defined by NOAA (*43*), the

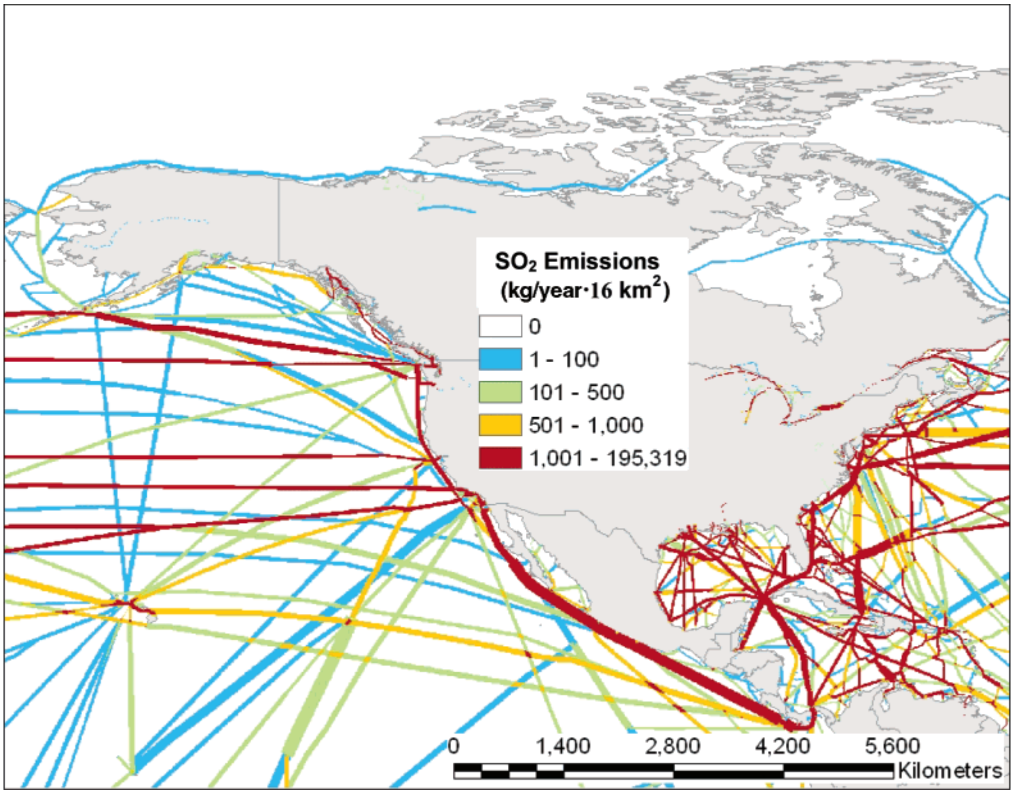

FIGURE 2. Illustration of the spatial distribution of annual SO_2 emissions from North American shipping.

TABLE 1. Summary of 2002 Emissions and Fuel Use for North America (metric tonnes/yr)[a]

	NO_x as NO_2	SO_2	CO_2	HC	PM	CO	fuel use
United States EEZ[b]							
West Coast	135 000	80 200	4 817 000	4 470	11 300	10 500	1 480 000
East Coast	255 000	151 000	9 095 000	8 440	21 300	19 900	2 800 000
Gulf Coast	174 000	103 000	6 201 000	5 750	14 500	13 600	1 910 000
Great Lakes	16 200	9 620	578 000	540	1 350	1 260	178 000
Alaska	63 300	37 600	2 260 000	2 100	5 300	4 940	697 000
Hawaii	20 500	12 200	732 400	680	1 720	1 600	226 000
Canada EEZ[b,c]							
West Coast	21 900	13 000	781 000	720	1 830	1 700	241 000
East Coast	96 200	57 200	3 440 000	3 190	8 050	7 500	1 060 000
Great Lakes	10 100	5 980	359 000	330	840	800	111 000
Mexico EEZ[b]							
West Coast	99 400	59 100	3 550 000	3 290	8 320	7 800	1 090 000
Gulf Coast	107 000	63 700	3 827 000	3 550	8 970	8 000	1 180 000
total coastal regions	998 000	593 000	35 640 000	33 100	83 500	77 900	10 980 000
noncoastal regions[d]	1 740 000	1 040 000	62 200 000	57 700	146 000	136 000	19 170 000
total in domain	2 740 000	1 630 000	97 800 000	90 800	229 000	214 000	30 160 000

[a] Values are rounded to three significant figures for presentation; sums may vary as a result of rounding. [b] National estimates of EEZ boundaries are approximate, using an ArcGIS buffer of 200 nautical miles and informal divisions between nations. [c] Western Canada summaries include emissions in the northwestern part of the domain; eastern Canada summaries include emissions in the northeastern part of the domain. [d] Noncoastal regions are areas in the domain not within the EEZ of Canada, the United States, or Mexico.

Great Lakes include Lake Superior, Lake Michigan, Lake Huron, Lake Erie, Lake Ontario, and connecting waters on both the U.S. and Canadian sides.

Figure 3a shows that SO2 emissions estimates from these two approaches differ to varying degrees for the U.S. coasts and for the Great Lakes (both U.S. and Canadian sides). Annual network estimates of SO2 emissions within the Gulf Coast EEZ are ~128% higher but ~90% lower for the Great Lakes than emissions estimated with ICOADS; the network estimates for the West Coast are ~18% lower and ~14% higher for the East Coast than those of the ICOADS approach. Discrepancies between the two inventories can be explained by geographic sampling bias of ICOADS, which significantly oversamples the Great Lakes and undersamples the Gulf of Mexico (*24*). This suggests that STEEM is more accurate than top-down approaches.

We compared our results with the inventories from other regional and port emissions inventory studies (*29−31*, *44*, *45*). Figure SI5 in the Supporting Information illustrates the domains of the ports and regions we compared. Figure 3b shows variability among regional/port air emissions inventories. The emissions inventory produced with the top-down approach using ICOADS as a spatial proxy is significantly higher for the Great Lakes on the Canadian side, but significantly lower for the western Canada region, the port of Los Angeles, and the port of New York and New Jersey. We observe that small-scale emissions inventories produced with ICOADS as the top-down proxy may be greatly distorted

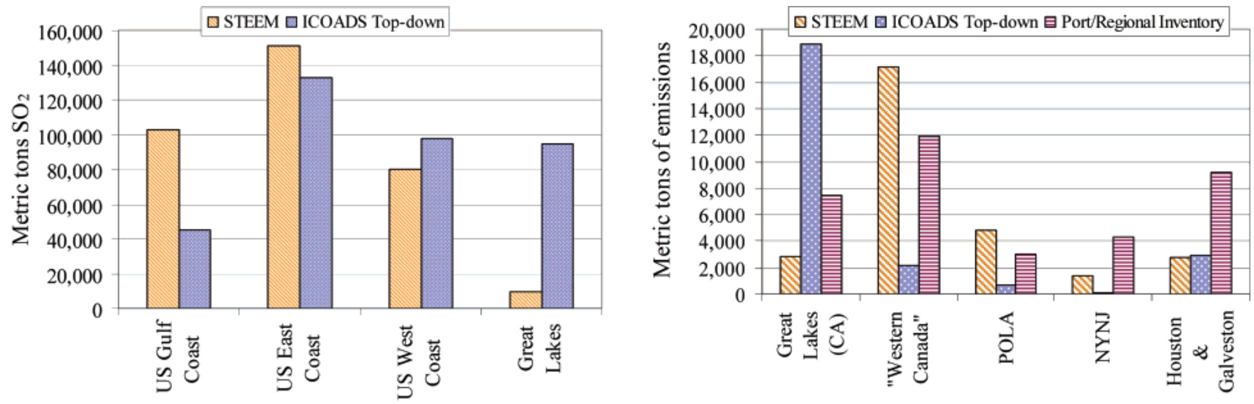

FIGURE 3. Comparison of inventories produced with STEEM with the (a) top-down approach using ICOADS and (b) top-down approach using ICOADS and port/regional approaches. Emissions for Houston and Galveston are NO_x, and emissions for the other areas are SO_2.

(*3*, *24*). Figure 3b also shows STEEM estimates achieve closer agreement (better precision) with most port studies than top-down estimates.

We understand the following: (1) STEEM captures transit traffic, possibly ignored in the portwide studies that used arrivals and departures of the specific ports (e.g., the port of Los Angeles study does not include shipping activity to other San Pedro Bay ports). (2) Portwide studies used more complete arrival and departure data for the Great Lakes, the port of New York and New Jersey, and Houston and Galveston. (3) Emissions from dockside hotelling included in the portwide studies for the port of New York and New Jersey and Houston−Galveston are not included in the STEEM results (hotelling emissions increase proportionately when the domain becomes smaller around the terminals and when ships spend less time in transit). (4) The motivation behind the creation of STEEM was to improve the emissions inventories describing interport movements; emissions around ports can be adjusted by either inserting the portwide inventories or modifying STEEM to include the dockside emissions. (5) Comparisons showing both higher and lower port and regional estimates suggest there is no systematic error in STEEM. (6) Our assumption that ships generally maneuver within 20 km of ports may represent some port regions better than others.

We also observe that emissions from ships carrying foreign cargo within the 200 nautical miles of coastal areas of the United States estimated by STEEM are about 5 times higher than results estimated by Corbett and Fischbeck using cargo as a proxy (*8*). STEEM is superior to the method used by Corbett and Fischbeck, consistent with prior uncertainty analyses and with the upward correction of Northwest United States emissions also published previously in *Environmental Science and Technology* (*7*).

Discussion

Precision can be refined by improving the waterway network, using a more complete activities data set, and improving the characterization of operating profiles of ships. Improved accuracy will be achieved as bottom-up input data improve, similar to port-based inventory improvements. Also, the localized structure of the network may be better modeled; the constraints of shipping channels, including depth, width, regulatory limitations, and even the weather and sea conditions, can be incorporated into the algorithm in solving the most probable shipping routes for individual trips. Weather routing behavior can be simulated by probabilistically favoring alternate segments in ocean routing. In the energy and emissions context, emission estimates for each trip can be improved by better characterizing engine duty cycles, updating emissions factors, and accessing superior ship data.

This model will help scientists and policy makers understand the ship emissions issue better by improving spatially resolved energy and emissions inventories and can subsequently help policy makers evaluate the "best set" of policy instruments to control ship emissions in an effective and efficient manner.

Acknowledgments

This work was partly funded by California Air Resources Board Contract 04-346, Council on Environmental Cooperation Project Number 113.111, and NOAA Contract NA04NMF-4720399. We thank John Callahan of the Research & Data Management Services of the University of Delaware for his help in applying the GIS tools.

Supporting Information Available

Additional rationale for the network model, mathematical manipulation of STEEM elements, three tables, and five figures. This material is available free of charge via the Internet at http://pubs.acs.org.

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Received for review March 29, 2006. Revised manuscript received February 19, 2007. Accepted February 23, 2007.

ES060752E