TECHNICAL PROPOSAL

Improved Geospatial Forecasting of Commercial Marine Vessels

Principal Investigator:
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Official Authorized to Bind this Proposal:

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Table of Contents

Statement of Significance

Emissions research and atmospheric modeling studies have shown that ship emissions contribute significantly to pollution in remote ocean areas, along coastlines, and in ports *(1-5)*. The California Air Resources Board (ARB) has been involved in the inventory, analysis, and regulation of air pollution from waterborne shipping for more than two decades *(6, 7)*. Recent efforts to understand environmental implications of goods movement in California require an understanding of oceangoing shipping as a direct source of emissions and as a primary generator of multimodal truck and rail freight transportation within and through the state.

A recently completed ARB project applied a GIS-based network model, the Waterway Network Ship Traffic, Energy and Environment Model (STEEM), to quantify and geographically represent inter-port vessel traffic and emissions for North America, including the United States, Canada, and Mexico *(8, 9)*. The model estimates main and auxiliary engine emissions from nearly complete historical North American shipping activities and individual ship attributes, applying activity-based emissions estimates in a GIS platform using an empirically derived network of shipping routes. North American shipping consumed about 47 million tons of heavy fuel oil and emitted ~2.4 million tons of SO_2 in 2002, with approximately 30 million tons fuel and 1.6 million tons SO_2 within the North American domain for this project.

In addition to 2002 baseline emissions, the project forecast emissions growth through 2020 using change in energy demand correlated to port-based data describing installed power on ships. Under current IMO legislation, our results show that emissions from ships bringing global trade to and from North America will double by or before 2020. Under a *with-SECA* scenario, assuming IMO-compliant reductions in fuel sulfur for all shipping within the North American Exclusive Economic Zone (200 nautical miles) future SOx emissions are offset by more than 700 thousand metric tons (~44%) from what they may otherwise grow to be in 2020. However, even *with an IMO-compliant SECA* this represents an increase of more than 2 million metric tons over 2002 emissions throughout the North American domain.

Trade-driven growth in shipping differs among vessel types, with increased containership activity leading growth in energy and emissions at 6-9% per year while trends in tanker growth are between 1-2% per year. The baseline inventory identified that Containerships contributed more than 35% of total North American shipping emissions, with bulk carriers and tankers contributing ~20-22% and ~17%, respectively. Applying a common growth rate, the previous work ignored differences among port traffic profiles and asymmetric growth among vessel types. Routes dominated by faster growing containership traffic would result in higher emissions in future years than routes that do not serve containerized shipping.

Vessel-specific growth must be modeled to adequately describe the spatial assignment of future emissions. This project will re-run 2002 base year data by vessel type and by month, and will apply vessel-specific growth rates to base-year ship inventories. This will produce more detailed North American inventories for 2002, 2010 and 2020, and help California better understand the impact of freight transportation in both air quality modeling and climate change impact assessment. Moreover, these results will advance STEEM capabilities to link with multimodal/intermodal models for freight transportation, providing both the most advanced waterway network and a source from which to estimate the numbers of truck and rail trips generated by imports and exports through California ports. This work supports California's regulatory and policy priorities regarding West Coast shipping and contributes to better regional inventories of commercial marine emissions for U.S, Canadian, and Mexican coastal waters.

Abstract

This proposal describes a project to update geographically resolved commercial marine emissions inventories and forecasts for cargo traffic in shipping lanes serving U.S. continental coastlines. Using the recently developed GIS-based methodology for estimating CMV emissions in coastal waters, a set of vessel-specific inventories will be produced that describe air emissions both spatially and temporally for a baseline year (2002) and forecast years (2010 and 2020). Activity-based emissions inventories will be provided separately for Containerships, Bulk carriers, Tankers, General cargo vessels, Roll-on/Roll-off vessels, and Refrigerated cargo ships. These ship types account for more than 90% of the current inventory of North American port arrival/departure data for ~170,000 voyages in 2002; moreover, other vessel types (passenger, miscellaneous, and fishing) are less associated with multimodal goods movement. This work will provide greater detail and improved spatial forecasts of commercial marine emissions for North American coastal waters that supports the California Air Resources Board (ARB), western regional states, federal and international efforts to quantify and evaluate potential air pollution and climate impacts from shipping.

Background

With previous support partially provided by ARB, we applied best practices for marine vessel emissions inventories to spatially and temporally describe North American interport shipping activity. (Interport shipping is ship activity voyaging between ports; it does not include dockside hotelling.) We use a network model, the Waterway Network Ship Traffic, Energy and Environment Model (STEEM), to quantify and geographically represent inter-port vessel traffic and emissions for North America, including the United States, Canada, and Mexico. The model estimates main and auxiliary engine emissions from nearly complete historical North American shipping activities and individual ship attributes, applying activity-based emissions estimates in a GIS platform using an empirically derived network of shipping routes. We produced a baseline (2002) emissions inventory for ships engaged in foreign commerce arriving at U.S. ports, and for ship activity in Canada and Mexico by commercial cargo and passenger vessels (excluding ferries).

We forecasted inventories for business-as-usual (BAU) and for a hypothetical SOx Emission Control Area (SECA) including the Exclusive Economic Zone (EEZ) of North American nations (i.e., 200 nautical miles). Based on evaluation of various sources of growth projections for commercial marine activity and energy use, we chose an adjusted extrapolation scenario from historic trends in installed power on ships calling on North American ports. Use of installed power trends depends on the following assumptions: 1) commercial marine vessels in cargo service design power systems to satisfy trade route speed and cargo payload requirements; 2) commercial marine vessels operate under duty cycles that are well understood, especially at sea speeds; 3) installed power trends for ships calling on North American ports directly reveals the trend in speed and size for these routes. Trend extrapolations for installed power reveal the correlated trend in energy use by ships, although different extrapolations approaches yield different forecasts. An unconstrained exponential fit may be overly optimistic given economic cycles in shipping and technological change in the fleet; a linear fit may be unrealistic with regard to fundamental work-energy principles and economic drivers for global trade. These define bounding limits for expected change in ship activity. We averaged these to describe a BAU growth trend that implicitly reflects a mix of positive and negative drivers for ship energy requirements.

Previous Results for Baseline Inventory: North American shipping consumed about 47 million tons of heavy fuel oil and emitted ~2.4 million tons of SO_2 in 2002, with approximately 30 million tons fuel and 1.6 million tons SO_2 within the North American domain for this project. Comparison of our results with port and regional studies shows good agreement, and improved accuracy over existing top-down methods. Table 1 summarizes the interport inventory estimates for the baseline year of 2002. The table presents results for coastal regions (defined as the 200 nautical mile EEZ) by nation, and the total for all domain areas outside coastal regions. Comparison of our results with five inventories from other regional and port emissions inventories studies (including Great Lakes, Western Canada, the Port of Los Angeles, Houston & Galveston area, and the Port of New York and New Jersey) showed no bias and better accuracy using STEEM than top-down emissions inventories.

Previous Results for Forecasts: We estimated a growth trend for North America (including United States, Canada, and Mexico) of about 5.9%, compounded. We produced two classes of forecasts: 1) a *business as usual (BAU)* forecast applying a common growth trend without sulfur controls (but with existing IMO NOx requirements); and 2) a *with-SECA* scenario assuming IMO-compliant reductions in fuel sulfur to 1.5% by weight for all activity within the Exclusive Economic Zone (200 nautical miles) of North American nations. Our BAU scenario compares reasonably well with available energy and fuel usage trends and with trends describing growth in trade volume; our growth trends are lower than have been reported since 2002 by major US ports. Various trends agree under BAU scenarios that energy used by ships bringing global trade to and from North America will double by or before 2020. Forecasts show that implementing a North American SECA region reducing fuel-sulfur content from 2.7% to 1.5% (whether through fuel changes or through control technology) will reduce future SOx emissions (as SO_2) by more than 700 thousand metric tons (~44%) from what they may otherwise grow to be in 2020. However, our 2020 inventory *with an IMO-compliant SECA* represents an increase over emissions in the 2002 base-year of more than 2 million metric tons of SOx emissions throughout the North American domain. At a growth rate of 5.9% from the baseline year 2002, trade growth offsets emissions under a 1.5% fuel-sulfur SECA by 2012; using alternative growth rates of 3.6% (separate work presented to the West Coast SECA team), emissions within a North American SECA return to 2002 levels by 2019.

Baseline (2002) inventory results are being used by ARB, the U.S. Environmental Protection Agency (U.S. EPA), Environment Canada, and others to model atmospheric fate and transport of pollution, evaluate air quality impacts, and assess potential health effects attributed to ships. The base-year inventory and forecasts assist the California Air Resources Board (ARB) in evaluating air quality and health impacts in California, and help evaluate national impacts, providing part of the required information to request a North American SECA (or SECAs) on behalf of the United States, Canada, and Mexico at the International Maritime Organization (IMO).

Table 1. Baseline 2002 inventory of emissions and fuel use in North American Domain (metric tonnes)[1]

	NOx as NO_2	SO_2	CO_2	HC	PM	CO	Fuel Use
United States EEZ[2]							
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[2,3]							
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[2]							
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
Non-coastal regions[4]	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**

1. Values are rounded to three significant figures for presentation; sums may vary as a result of rounding.
2. National estimates of EEZ boundaries use an ArcGIS buffer of 200 nautical miles and informal national divisions.
3. Western Canada summaries include emissions in the Northwestern part of the domain; Eastern Canada summaries include emissions in the Northeastern part of the domain.
4. Non-coastal regions are areas in the Domain not within the EEZ of Canada, United States or Mexico.

Project Objectives

A primary objective of this project is to produce improved CMV emissions inventories by applying activity-based methods for estimating CMV emissions in coastal waters to different vessel-types. There are several other objectives that rely upon an explicit understanding of emissions by ship type, including:

1. To update the baseline inventory of CMV emissions consistent with current North American ship inventories, in which differences among vessel characteristics can be evaluated within a spatial and temporal context. Inventories need to be appropriate for modeling impacts relevant to potential regulatory and economic mitigation strategies, including SECA designation.
2. To better forecast how baseline emissions for different vessel-types may change in future years. Future emissions depend in part upon changes in emission factors (due to MARPOL Annex VI, other policy, and other changes in engine characteristics), changes in fuel quality (especially sulfur content), changes in vessel size and number. However, prior work demonstrated that asymmetric growth among different types of ships will produce changes in vessel activity patterns in coastal and port regions. These changes respond to commodity-specific changes in cargo trade routes and to innovation in vessel design to meet global logistics demand.
3. To develop freight transportation information for international arrival/departure of ships that can improve understanding of the relationship between international cargo transport and domestic multimodal goods movement. This is particularly important for California where containerized cargoes discharged and loaded in major ports generates significant intrastate and interstate truck and rail transport serving North America.

Technical Plan

Task 1: Produce ship emissions inventories by vessel type

This task will apply the activity-based methodology developed in STEEM to produce CMV emissions inventories for different vessel types. In at least three important ways, STEEM advances the quality of large-scale CMV inventories: (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. STEEM estimated 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, about 16.5% of SO_2 emissions from all sources in the U.S. in the same year *(10)*. Comparison with port and regional studies shows good agreement in total estimates and better spatial precision than current top-down methods. North American shipping fuel use and SO_2 emissions are between 18-20% of the world commercial fleet estimated by Corbett and Koehler and between 28-34% of the world cargo and passenger fleet estimated by Endresen et al. *(11, 12)*.

Containerships, bulk carriers, and tankers account for about 35%, 22%, and 17% of SO_2 emissions from North American shipping, respectively. Other types of ships jointly account for the remaining 26%. This information was available from post-hoc analysis of the STEEM results and input data, but the routing was not performed in batches that corresponded to vessel type. This task responds to interest in vessel-specific routes by ARB, U.S. EPA, and other SECA team partners.

We will prepare vessel-specific gridded inventories for the following six pollutants: Sulfur (SOx as S or SO2), Nitrogen (NOx), Carbon dioxide (CO2), Particulate Matter (PM), Hydrocarbons (HC), and Carbon monoxide (CO). Products of this task include ***36 gridded annual inventories*** (six for each vessel type to be included), ***monthly inventories for the best estimate inventories for each pollutant***, and ***a technical memorandum***.

Resources: This work extends the analysis previously funded by the California Air Resources Board under ARB Contract Number 04-346 *(9)*. Materials for this work include the STEEM model developed at the University of Delaware *(8, 13)*, vessel activity data for the United States from the U.S. Army Corps of Engineers *(14)*, LMIU-derived vessel movement data for Canada and Mexico provided by Environment Canada and the Commission for Environmental Cooperation, respectively *(15, 16)*. Ship characteristics are also obtained from Lloyd's ship registry data *(17)*. As part of this work, we will review updated vessel movement data captured by the Canadian Coast Guard for Eastern Canada and the Great Lakes, and California data obtained from the California State Lands Commission to evaluate whether these sources can improve the quality of STEEM output by augmenting or substituting for previously used data; if so, we will identify whether these data can be input into STEEM with existing resources or through collaboration with ARB and Environmental Canada. Inventory assumptions and other model inputs were derived from earlier ARB reports and published work *(11, 18, 19)*, modified through discussion with U.S. EPA contractors and review of port-based best practices *(20)*.

Task 2: Evaluate change in ship inventories patterns for 2010 and 2020

This task will produce forecast emissions for 2010 and 2020 using these vessel-type inventories and applying corresponding growth rates. Three critical questions for understanding freight activity and environmental impacts defined two phases of the project:

1. **Baseline Conditions:** What are freight energy and activity patterns?
2. **Rates of Change:** What is forecast trend in energy needed?
3. **Patterns of Change:** Where is future freight activity located?

The previous project made a simplifying assumption with regard to the future patterns of shipping activity by applying a common North American growth rate to all routes. In this task, we will identify prominent routes that are shared by many ship types and differentiate routes that serve dominantly one or another type of vessel (and cargo group). Applying heterogeneous forecast trends separately for different vessel types and trade routes is an enabling analysis that helps address at least three recommended improvements to earlier STEEM results. First, these forecasts will produce spatial results revealing asymmetry among future trends for liner trades and bulk trades that will help understand which coastal regions and air basins may be most affected. Second, the information may assist in understanding how implementation of planned or proposed actions to modify shipboard technology and operations would differ among ship types; this could be useful in evaluating the economic efficiency of alternate strategies in terms of ship operating costs and in terms of the transport costs for different commodity groups (e.g., liquid petroleum versus grain versus refrigerated foods or containerized goods). Third, vessel-type forecasts could also inform efforts to understand drivers affecting change in ship performance.

We will represent these forecasts geographically by scaling up vessel traffic characteristics. Products of this task will be ***36 gridded monthly emission inventories for pollutants (named above) for 2010*** and ***36 gridded monthly inventories for 2020*** using the same extent and resolution as used previously. A ***technical memorandum*** will describe data produced.

Resources: This task will apply results of the vessel-specific forecasts derived from work previously funded by the California Air Resources Board under ARB Contract Number 04-346 *(9)*. We are familiar with the economic principles of maritime trade and with models that estimate supply and demand for shipping *(21)*. However, all of these forecasting resources include uncertainty and often under- or over-estimate actual performance *(22)*. We will conduct a review of several available sources for past and forecast shipping growth estimates, and apply annual average growth rates developed from these sources *(22-27)*.

Task 3: Progress Reports and Final Summary Report

Progress reports will be provided after completion of Task 1 and Task 2, or as needed to support University invoicing. Each progress report will summarize work activity and milestone progress to date in a brief written document.

As described above in Tasks 1-3, each task deliverable includes a technical memorandum. These memoranda will be submitted in a format that addresses the task scope, presents results of analyses related to the task, and other documentation in support of the objectives. Documentation will include a complete description of the estimation methodologies, and other tools used to develop the inventory so that ARB can produce inventory updates in the future. As working documents, these memoranda may be revised upon timely review and comment by ARB technical staff (e.g., comment provided within two weeks and prior to subsequent task memoranda or draft final report), but would not be submitted as draft and final versions.

The final report integrates important parts of prior technical memoranda into one document with an executive summary and overall conclusions, into a stand alone summary of the project. This document will be subject to the standard review and comment terms described in ARB proposal guidance.

Work Plan

	Month:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Personnel (Name and Classification)																				Total by Task
J. Corbett	Task 1	2	2	2	2	2	2													12
PI	Task 2							2	2	2	2	2	2							12
	Task 3													3	3	3	3	2	2	16
Subtotal																				40
TBD	Task 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Res. Assistant	Task 2	45	45	45	45	45	45													270
	Task 3							45	45	45	45	45	45							270
Subtotal														30	30	30	30	30	30	180
TBD	Task 1	22	22	22	22	22	22													133
Res. Assistant	Task 2							22	22	22	22	22	22							133
	Task 3													15	15	15	15	15	15	88
Subtotal																				354
TOTAL		69	69	69	69	69	69	69	69	69	69	69	69	48	48	48	48	48	48	1114

Project Schedule

Task 1: Produce ship emissions inventories by vessel type
Task 2: Evaluate change in ship inventories patterns for 2010 and 2020
Task 3: Progress Reports and Final Summary Report

	MONTH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
TASK																			
1		■	■	■	■	■	■												
2								■	■	■	■	■	■						
3														■	■	■	■	■	■
							t						t			d		f	

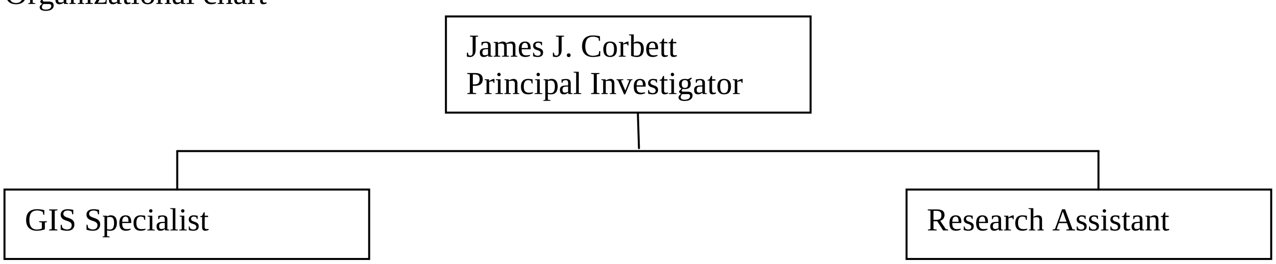
t = Deliver technical memorandum
d = Deliver draft final report
f = Deliver final report

Project Management Plan

Key Personnel

James Corbett: Principal Investigator Corbett is an Associate Professor in the Marine Policy Program in the Graduate College of Marine Studies with a joint appointment as Associate Professor in Civil and Environmental Engineering. He holds a Ph.D. degree (1999) in Engineering and Public Policy (EPP) from Carnegie Mellon University, where he also earned M.S. degrees in the Department of EPP (1997) and the Department of Mechanical Engineering (1998). His undergraduate work was in Marine Engineering Technology from the California Maritime Academy, and he holds a California Professional Engineering License (Mechanical). Dr. Corbett's experience includes work as a licensed engineer in the U.S. Merchant Marine, industrial operations, and engineering and environmental consulting supporting industry and government. Professor Corbett's research has focused on transportation and environment, specifically air emissions from maritime transport and an engineering assessment of technological control strategies. The work includes both theoretical and empirical research areas, which are crucial to important decisions in environmental, maritime, and technology policy. Results of this research have become central in the international efforts to develop a more sustainable marine transportation system (MTS), and are motivating new lines of funded research from a variety of sources in both industry and government. He has published more than twenty-six peer-reviewed papers and five book chapters on air pollution from marine vessels and multimodal transportation, including technology policy and legal analyses.

Organizational chart



Assigned responsibilities

This project is small enough to be managed by the Principal Investigator through his direct involvement in each task. There will be regular meetings of the project team to coordinate and delegate work elements for each task.

Curricula vitae of James J. Corbett, P.E., Ph.D. is attached.

Related Work

The principal investigator has been actively researching the environmental impacts of emissions from marine transporation and waterborne goods movement since 1995. His prior research has focused on transportation and environment, specifically air emissions from maritime transport and an engineering assessment of technological control strategies. The work has included both theoretical and empirical research areas, which are crucial to important decisions in environmental, maritime, and technology policy. Results of this work have become central in international efforts to develop a more sustainable marine transportation system (MTS), and are motivating new lines of funded research from a variety of sources in both industry and government.

Previous work for ARB: Dr. Corbett's research group has been researching technology policy aspects related to designation of SOx Emission Control Areas (SECA), and focusing on U.S. coasts in particular, since 2003. He supervised Dr. Chengfeng Wang's Ph.D. research and dissertation, *A Study Of Geographical Characterization Of Ship Traffic And Emissions And Cost-Effectiveness Of Reducing Sulfur Emissions From Foreign Waterborne Commerce For The U.S. West Coast*, completed in January 2006, with the U.S. west coast as a case study. This work produced the Ship Traffic, Energy and Environment Model (STEEM). Development and demonstration of ship routing model assigning port calls to empirical routing network for global ocean commerce. This work is being used to produce a set of baseline and forecast energy and emissions inventories for North America (U.S., Canada, and Mexico), and as a basis for evaluating ship traffic characteristics under alternative technology-policy strategies to mitigate ship air pollution, whale-strikes and aquatic invasives. Collaborators: Chengfeng Wang, California Air Resources Board; Jeremy Firestone, UD CMES; James J. Winebrake, RIT

A study completed in 2004 by the Principal Investigator considered estimation methodologies by comparing estimates with direct stack measurement with environmental observations of ship plumes to show that current port-based inventory methodologies provide good agreement with stack tests and reasonable agreement with plume observations *(18)*. This work was related to a ship plume experiment conducted about 100 km off the California coast during the NOAA ITCT 2K2 airborne field campaign *(30)*.

Related ongoing work:

Improving spatial representation and forecasting of shipping activity and emissions: We are developing methods to improve global-proxy representativeness in ship data used to infer activity and emissions in global gridded inventories. This work enables atmospheric modelers to perform in-depth uncertainty analysis of ship air emissions impacts. Gridded inventories using our best estimates are avialable, and a set of underlying global proxy data is derived from independent sources (ICOADS and AMVER and their combination) to model alternative inventory estimates.Collaborators: Chengfeng Wang, California Air Resources Board; Jeremy Firestone, UD CMES

Environmental and energy performance measures in intermodal/multimodal transportation: Analysis of freight transport comparing land-side and water-side short-sea routes. This work develops a GIS -based model and optimization framework to evaluate emissions and energy use from alternate routing constraints using ocean-based foreign commerce, domestic freight, and intermodal networks. Collaborators: James J. Winebrake, RIT; Alex Farrell, UC Berkeley

Total fuel cycle emissions for marine transportation: Total Energy & Emissions Analysis for Marine Systems (TEAMS) model. This model adapts the GREET algorithm for onroad vehicles to evaluate energy use and emissions for alternative fuels in maritime transportation. Collaborators: James J. Winebrake, RIT

Ship-Whale Encounters: Assessment of Commercial Vessel Traffic Characteristics and Ship Strike Probabilities of North Atlantic right whales (Eubalaena glacialis) along the North Atlantic Coast of the U.S. and Canada. Through the production of spatially and temporally resolved probabilities of a whale strike for different types of commercial vessels, we aim to assist government management strategies that seek to reduce the risk of human factors that contribute to vessel collisions with right whales. Collaborators: Jeremy Firestone, UD CMES; Christopher Taggart, Dalhousie

Invasive Species: Consideration, assessment and modeling of risks posed by the introduction non-native stocks and species. The primary focus is on developing a ballast water discharge compliance and policy support model using linear programming to assist policy makers, ship operators and port managers in the implementation of the Ballast Water Convention and to consider alternative policy objectives. Collaborators:Jeremy Firestone, UD CMES; James J. Winebrake, RIT; David Wright, UMD

Previous related work:

IMO Study of Greenhouse Gases from Ships *(31)*. Corbett's early research to evaluate ship emissions produced the first geographically resolved inventory of air pollution from international shipping *(2, 32)*. This research has had significant impact on policy making at the International Maritime Organization in London, where it has been directly cited in the U.S. position statements for greenhouse gases from ships *(33, 34)*. It helped frame the scope of the IMO-funded study of greenhouse gases from ships, for which Corbett was a principal investigator and author. This study was called for in the Kyoto Protocol *(35)*, and will be used by the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC) in forming global climate policy for international aircraft and marine fuels.

The IMO study of greenhouse gases from ships provided a comparative summary of ship inventory research. This summary included Corbett's inventory methodology, producing a geographically resolved inventory in close agreement with prior research *(32)*, which explicitly considered uncertainty in inventory inputs. Corbett was the principal author of the chapter that evaluated potential impacts from NOx emissions and tropospheric ozone and discussed the need for further research to improve scientific understanding. Corbett co-authored a peer-reviewed article based in part on this analysis that included modeling emissions, chemical transport and atmospheric processes *(36)*. The IMO study also summarized technological and operational means to reduce stack emissions (for greenhouse gases and other pollutants), and evaluated the effects of reduction measures within an intermodal freight transportation context. This chapter included methodology and results from Corbett's research *(37-39)*. Corbett and Fischbeck developed a modeling framework to compare emissions between freight transportation modes that was used to evaluate the effects of implementing reduction measures. This research has led to a ship environmental assessment calculator (SEACalc®) currently under development *(40)*. The IMO report also included an assessment of market-based policy alternatives for reducing greenhouse gas and pollutant emissions from shipping.

National Inventory of Emissions from Waterborne Commerce *(41, 42)*. This research was partly funded by the U.S. Environmental Protection Agency (EPA) and produced the first nationwide geographically resolved inventory of emissions from shipping on the U.S. navigable waterways including inland rivers, Great Lakes and coastal waterways. This work showed that nearly all vessel air emissions in U.S. waters occur in shipping channels outside of port regions, either on rivers or within 200 miles of shore. Previous nationwide emissions inventories from shipping ignored shipping channels outside of port regions. NOx emissions from commercial marine engines considered in this study account for about half of the U.S. EPA baseline inventory of ~1000 tons per year for all marine vessels *(43)*. NOx emissions from river commerce in the top twenty states with waterborne trade accounted for 65% of total waterborne commerce emissions in those twenty states. In contrast, 72% of SOx emissions in these states occurs along coastal (ocean or Great Lake) areas, where high-sulfur fuels are more commonly used. These results have been included in broader research efforts to produce more accurate inventories of off-road emissions *(44)*.

Regional Emissions Inventory for Modeling Purposes *(45)*. This research builds on the national emissions inventory research to produce a commercial marine vessel (CMV) emissions inventory for Washington and Oregon using detailed statistics regarding fuel consumption, vessel movements, and cargo volumes for the Columbia and Snake river systems. The inventory estimates emissions for oxides of nitrogen (NOx), particulate matter (PM), and oxides of sulfur (SOx). This analysis estimates that annual NOx emissions from marine transportation in the Columbia and Snake River systems in Washington and Oregon equal 6,900 tonnes NOx per year; statewide CMV NOx emissions are estimated to be 9,800 tonnes NOx per year. This base-case estimate is 2.6 times greater than previous NOx inventories for this region. By relying on fuel consumption estimates modeled in a "bottom-up" calculation that includes vessel characteristics and transit information, the river system inventory is considered to be more accurate than previous estimates for this region. This inventory was prepared for inclusion in regional haze and pollution models with the explicit objective to provide modelers with bounded parametric inputs for sensitivity analysis in pollution modeling. The ability to parametrically model the uncertainty in commercial marine vessel inventories also will help policy makers determine whether better policy decisions can be enabled through further vessel testing and improved inventory resolution.

Publication List

Relevant Publications and Articles by the Principal Investigator

Wang, C., **J.J. Corbett**, and J. Firestone, Modeling Energy Use and Emissions from North American Shipping: Application of Ship Traffic, Energy and Environment Model, *Environmental Science & Technology*, *Web Release Date: 4 April*, 2007.

Winebrake, J.J., **J.J. Corbett**, and P.E. Meyer, Energy Use and Emissions from Marine Vessels: A Total Fuel Cycle Approach, *Journal of Air and Waste Management*, **57**(January), 102-110, 2007.

Corbett, J.J., and D.S. Chapman, An Environmental Decision Framework Applied to Marine Engine Control Technologies, *Journal of Air and Waste Management*, **56**(June), 841-851, 2006.

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