CMV Inventory Development, Validation, and Application to Emerging Policy Analysis

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Chairman's Air Pollution Seminar Series
Monday, April 18, 2005 - Video Conference

Overview of Seminar (2 parts)

- Summary of recent ARB work to evaluate accuracy of current marine vessel emissions estimation methods
- Outline planned work to produce regional inventories of CMV emissions, including forecasts under various scenarios
  - Including possible SOx Emission Control Areas (SECAs)

Purpose: invite dialogue about strengths and limitations of regional CMV inventories, and value to scientific and policy analysis of mitigation strategies

Previous ARB Project Tasks

VERIFICATION OF SHIP EMISSION ESTIMATES WITH MONITORING MEASUREMENTS TO IMPROVE INVENTORY AND MODELING
Final Report

Submitted by

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and the California Environmental Protection Agency

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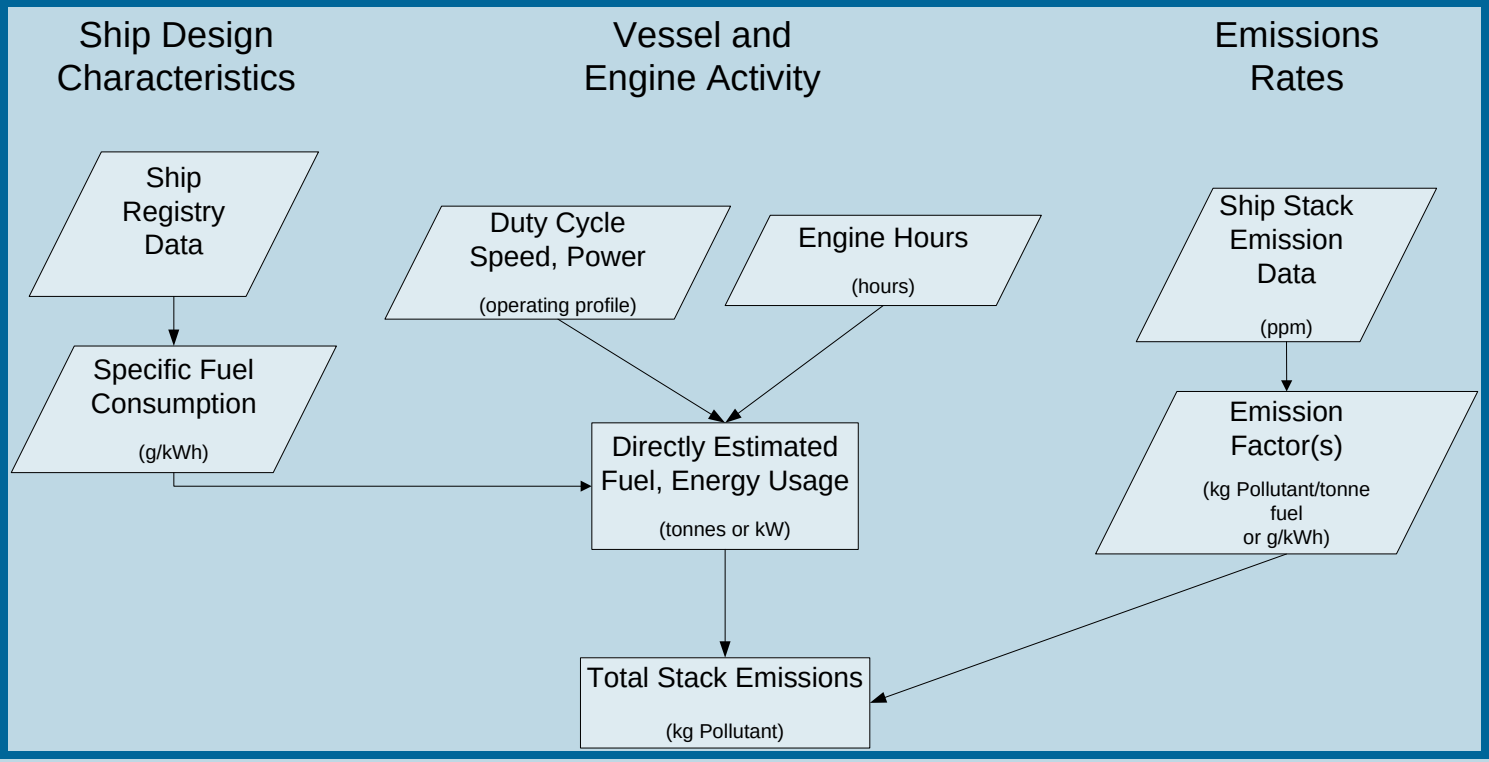
- Develop best-practices model
- Estimate emissions under actual operating conditions
- Compare emissions predictions with monitoring results and concurrent ship-stack plume observations for predetermined vessels
  - Sine Maersk stack test
  - New Spirit hip-stack plume observations by aircraft

Best practices for CMV, other nonroad

- Characterizing nonroad, CMV activity better
- Moving past indirect statistical relationships or fleet-average assumptions that ignore considerable variability among individual vehicles
  - < 100,000 commercial oceangoing vessels operate globally and < 800 oceangoing ships make < 3,000 ship calls annually on the Port of Los Angeles

    [*Corbett and Koehler*, 2003; *Starcrest Consulting Group LLC et al.*, 2004]
  - ~300 major ports in U.S.; 90,000 ship calls/year
  - Compare to ~200 million registered automobiles in U.S.
- Bottom-up methods become feasible, following several general steps

Best practices for CMV



$$\text{Fuel Consumption}_{\text{metric tonnes per year}} = \sum P_{\text{MW}} \cdot F_{\%\,\text{MCR}} \cdot t_{\text{hrs/yr}} \cdot SFOC_{\text{g/kWh}} \cdot \frac{1}{1000}$$

$$\text{Emissions}_{\text{metric tonnes per year}} = \sum P_{\text{MW}} \cdot F_{\%\,\text{MCR}} \cdot t_{\text{hrs/yr}} \cdot E_{\text{g/kWh}} \cdot \frac{1}{1000}$$

Best practices for CMV

- 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

Step 1: Identify vessels and engines in service

- General data sources include local vessel traffic services (VTS), port arrival data (USACE, USCG)
- Specific vessels chosen for this study:
  - Sine Maersk, 6600 TEU containership
  - New Spirit, 26,562 GT bulk carrier

Sine Maersk

- 6600 TEU containership built in 1998
  - Regularly visits to San Pedro Bay about four times per year
  - Arrived in port in March, June, and September of 2002, and in January 2003, according VSR Program model
  - A.P. Moller allowed onboard emissions measurement by MAN B&W on the main engine (Hitachi model 12K90MC) during transit from Los Angeles to Tacoma, 9-11 February 2004. Tests were funded by the Port of Los Angeles.

New Spirit

- 26,562 GT bulk carrier built in 2002
  - Made one visit to San Pedro Bay in 2002 and one in 2003
  - Arrived in port on 28 April 2002, and departed on 7 May 2002 for Vancouver, British Columbia, Canada. Voyage coincided with ITCT 2K2 ship plume experiment, conducted on 8 May 2002, about 100 km off the coast of California.
  - Vessel of opportunity. Flight photographs identified vessel enabling characterization. Port of Los Angeles provided fuel specifications from bunkering prior to this voyage.

From ICTC 2K2

From http://www.hcm.com.tw/newspirit.htm

Step 2: Estimate engine service hours

- VSR model provided weighted-average estimate of channel distances, vessel speeds
- Open ocean used “full-cruise” or observed speeds

Table 1. Summary of VSR model data regarding the speed and distances during vessel transits through the Air Quality Control Zone (AQCZ). The Air Quality Control Zone is the region in San Pedro Bay where the vessel speed reduction program applies.

Activity Date (Arrival or Departure)	Vessel Name	Weighted Avg. Actual Speed in AQCZ (knots)	Lloyd's Service Speed (knots)	Actual-to-Service Speed Ratio	Actual Distance in AQCZ (nmi)	Time in AQCZ (hours)
		A	B	C = A/B	D	E = D/A
28-Apr-02	New Spirit	12.34	14.5	0.85	21.75	1.76
7-May-02	New Spirit	14.19	14.5	0.98	21.5	1.51
21-Jun-02	Sine Maersk	12.22	25	0.49	21.75	1.78
24-Jun-02	Sine Maersk	11.95	25	0.48	21.5	1.80

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Step 3: Determine engine load profiles

- New Spirit observed at slower than “full-cruise” speed
  - 67% of rated speed, 30% of rated power
- Sine Maersk Speed-power profile confirmed

Table 2. Summary of energy and power estimates following the VSR model format.

Activity Date (Arrival or Departure)	Vessel Name	Actual-to-Service Speed Ratio	Load Factor	Lloyd's ME Power (KW)	Full-cruise ME Power (kW)	Composite ME Power (kWh)
		F (see Table 1)	$G = F^3$	H	I = 0.80*H	J = E*G*I
28-Apr-02	New Spirit	0.85	0.62	6,708	5,366	5,826
7-May-02	New Spirit	0.98	0.94	6,708	5,366	7,625
21-Jun-02	Sine Maersk	0.49	0.12	54,840	43,872	9,115
24-Jun-02	Sine Maersk	0.48	0.11	54,840	43,872	8,622

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Step 4: Apply specific emissions rates

Table 3. Emission factors for main engines used in model estimates, g/kW-hr.

Engine-fuel type	NOx	CO	CO_2	HC	PM_{10}	$PM_{2.5}$	SO_2
IVL emissions rates[1]	18.1	1.4	588	0.6	1.92	1.54	10.5
Sine Maersk emissions rates	20.6	0.19	578	0.1	1.70		8.79
Lloyd's emissions rates	17	1.6	660	0.5	1.5		4.2*%S
Original VSR model rates	Note 2						

1. The IVL emissions rates include a reanalysis of Lloyd's Marine Emissions Research Programme test data.
2. Rate varies with load according to statistical relationship; NOx (in g/kWh) = -1.8162 x % MCR at Actual Operating Conditions + 18.77; the average for these factors among the voyages modeled is 18.26 g NOx/kWh, with a minimum and a maximum of 17.07 g NOx/kWh and 18.58 g NOx/kWh, respectively.

Table 4. Emission factors for New Spirit derived from nearest plume observation.

Species	Fuel-based g/kg fuel	Power-based[1] g/kWh	Typical Range[2] g/kWh
NOx (as NO_2)	66 ± 26	13 ± 5	19 ± 8
SO_2[3]	30 ± 4	6 ± 0.8	8 ± 1
PM	4.6 ± 1.4	0.9 ± 0.3	7 ± 5 1.6 – 6.2[4]

1. Power-based emissions rates assume a SFOC rate of 195, per [*Cooper*, 2004].
2. Typical ranges from recent literature [*Cooper*, 2004; *European Commission and ENTEC UK Limited*, 2002].
3. These ranges represent the vessel plume observations containing both main engine emissions at 2.19% residual fuel-sulfur levels and auxiliary engine emissions at 0.86% distillate fuel-sulfur levels [*Patton*, 2004].
4. Ranges reported by other atmospheric science studies [*Hobbs et al.*, 2000; *Sinha et al.*, 2003].

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Step 5: Estimate emissions for voyage

- Multiply the composite power (in kWh) that represents the voyage or voyage segment by the emissions rate (in g/kWh)

Table 5. NOx emissions estimates in kilograms per transit, under different emission factor assumptions.

Activity Date (Arrival or Departure)	Vessel Name	Emissions (kg) per published literature	Emissions (kg) per Sine Maersk Engine Test 2004	Emissions (kg) per ITCT 2002 Plume Measurements	Emissions (kg) per VSR 2003
28-Apr-02	New Spirit	105		75	103
7-May-02	New Spirit	138		98	130
21-Jun-02	Sine Maersk	165	188		169
24-Jun-02	Sine Maersk	156	178		160

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Overall comparisons

- Small differences in emissions of CO_2, PM, NOx, SO_2
  - Similar to measurement uncertainty reported for Sine Maersk measurements at stack
  - Greater differences for in-plume-derived rates
- Much larger differences comparing measured emissions of CO and HC with modeled emissions
  - Uncertainties may be due to limited in-service test data

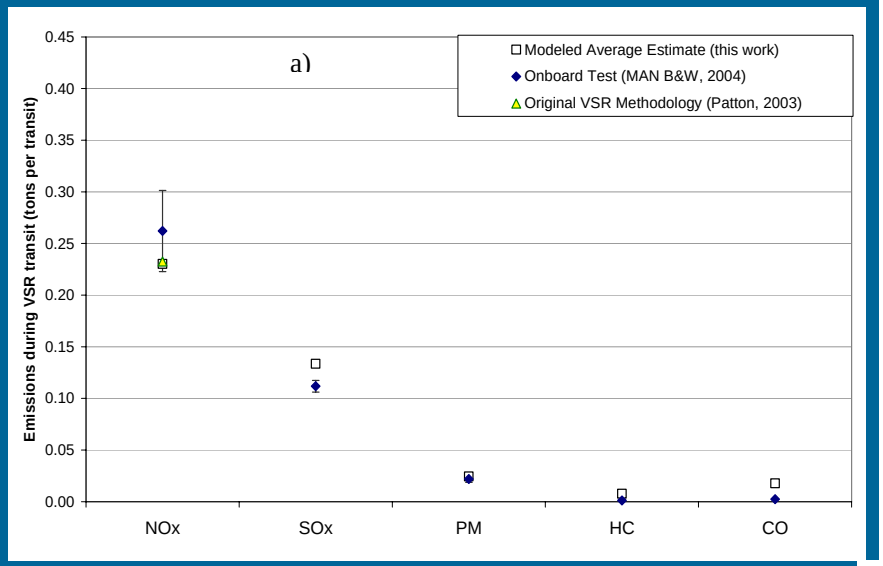
Overall comparisons, conclusions

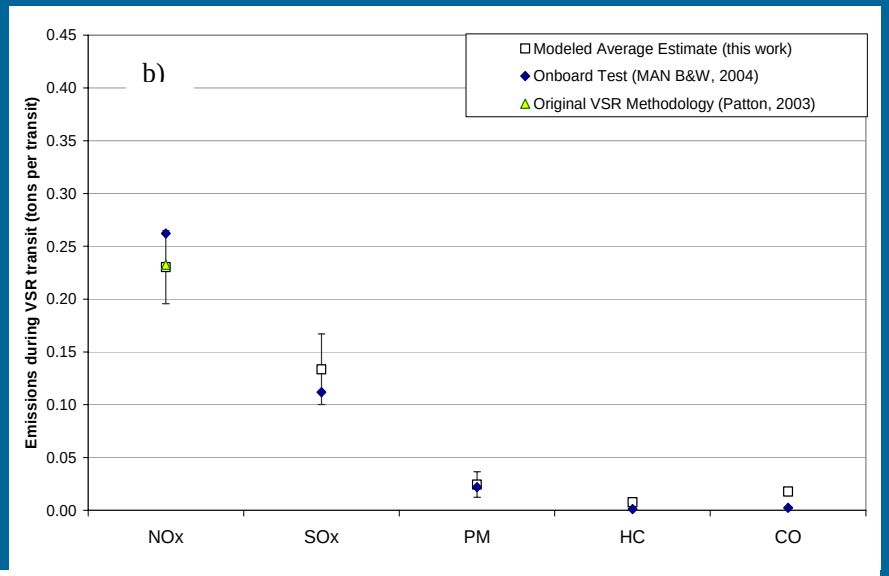
Table 11. Estimated main engine emissions in tons per day using published emissions rates and empirical emissions rates for a) Sine Maersk[1] estimated full-cruise conditions of 80% rated power; and b) New Spirit[2] observed at-sea conditions (corresponding to ~62% of full-cruise speed).

	CO_2	NOx	SO_2	PM	HC	CO
Sine Maersk using published rates	619	19	11	2.0	0.6	1.5
Sine Maersk using stack monitoring rates	608	22	9	1.8	0.1	0.2
Percent difference	2%	-12%	19%	11%	508%	640%
New Spirit using published rates		0.7	0.4	0.07		
New Spirit using in-plume observed rates		0.5	0.3	0.03		
Percent difference		41%	23% (33%)	114%		

1. For the Sine Maersk, the MAN B&W report included data for engine speed but not vessel speed, so "full-cruise" conditions are assumed to represent 80% rated power (see Table 2, column I).
2. For the New Spirit, the at-sea conditions during the plume study corresponded to about 30% power; one possible reason for this may be that the vessel was in an economy cruising mode (typical of bulk carriers). Corresponding "full-cruise" conditions for the New Spirit would increase activity assumptions and, therefore, the emissions reported here, but would not modify the comparative differences reported for New Spirit. The difference between estimates using published and in-plume-derived rates adjusting for main engine fuel sulfur content is 23%; if this adjustment was not made, the difference would be about 33%.

Model uncertainty versus variability





Uncertain emission rates affect overall estimates less than variability in vessel operation

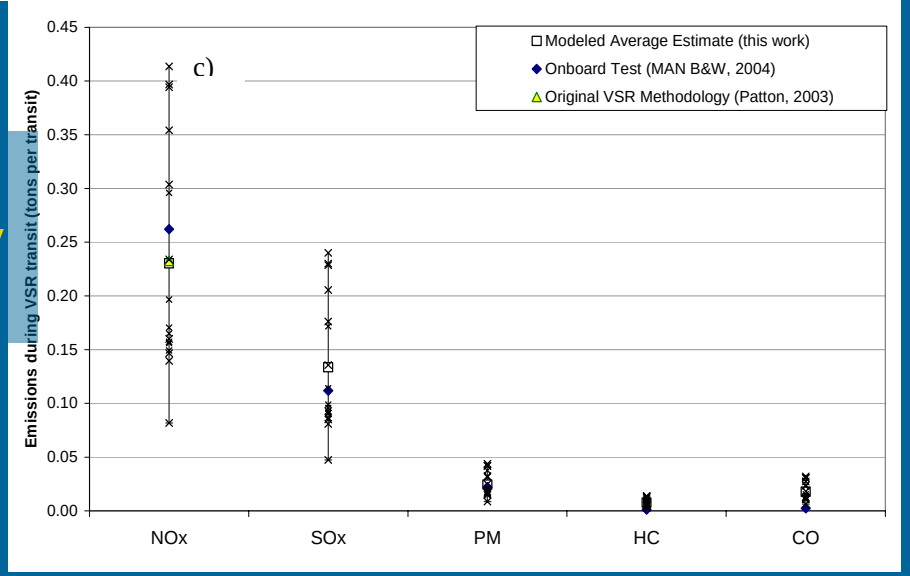


Figure1. Comparison of transit emissions estimates with modeled and measured average emissions factors a) Applying measurement uncertainty reported for emission factors [*MAN B&W Diesel A/S*, 2004]; b) Applying uncertainty estimates from emission factor summaries [*Cooper*, 2004]; and c) Demonstrating variability among transit estimates at different speeds. All transit estimates represent the Sine Maersk.

Conclusions, recommendations

- Stack gas comparison: improved emission inventories are consistent with monitoring
  - Important for baseline & ECT reduction modeling
  - Agreement varies; where greater disagreement, emissions factors tend to overestimate emissions
- Plume analysis comparison: significant disagreement across all pollutants studied
  - Likely due to chemical processing within plumes
  - Reduction in gaseous SO_2 emissions may be associated with the increase in PM emissions
- Better characterization of vessel activity, engine service, time-in-mode improves inventory estimates
  - Plume effects also merit further study

Part I Acknowledgements (partial)

- ICTC 2K2 science research team, support in part by NOAA OGP – 17 NA06GP0410
- Dr. Gao Chen, NASA Langley Research Center
- Mr. Chris Patton, Port of Los Angeles
- A.P. Moller and MAN B&W
- Funding by ARB, Toyota Motor Corporation, University of Delaware
- Guidance from Dongmin Luo and Eileen McCauley

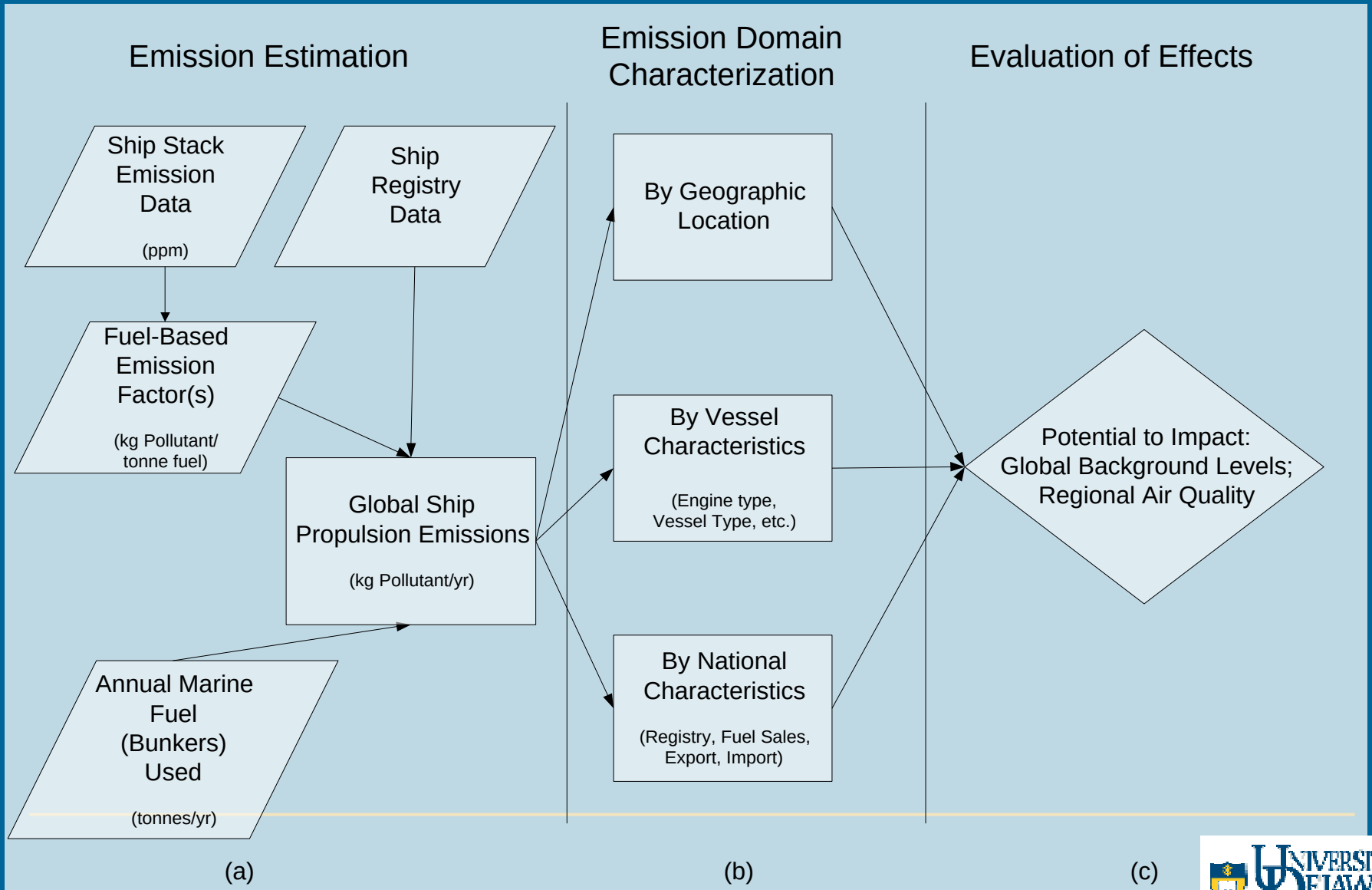
Transition to current work effort

- Applying bottom-up CMV inventory methodologies
- Spatially resolving CMV activity regionally
  - Shipping lanes identified empirically, validated
  - Allocation of CMV traffic intensity patterns
  - Ongoing effort to validate, calibrate regional activity
- Produce spatially resolved regional inventories
  - Assignment of environmental characteristics
  - Baseline, forecasts with and without policy scenarios
  - Enables direct contributions to policy analyses (early look)

ARB proposal fits within this body of work

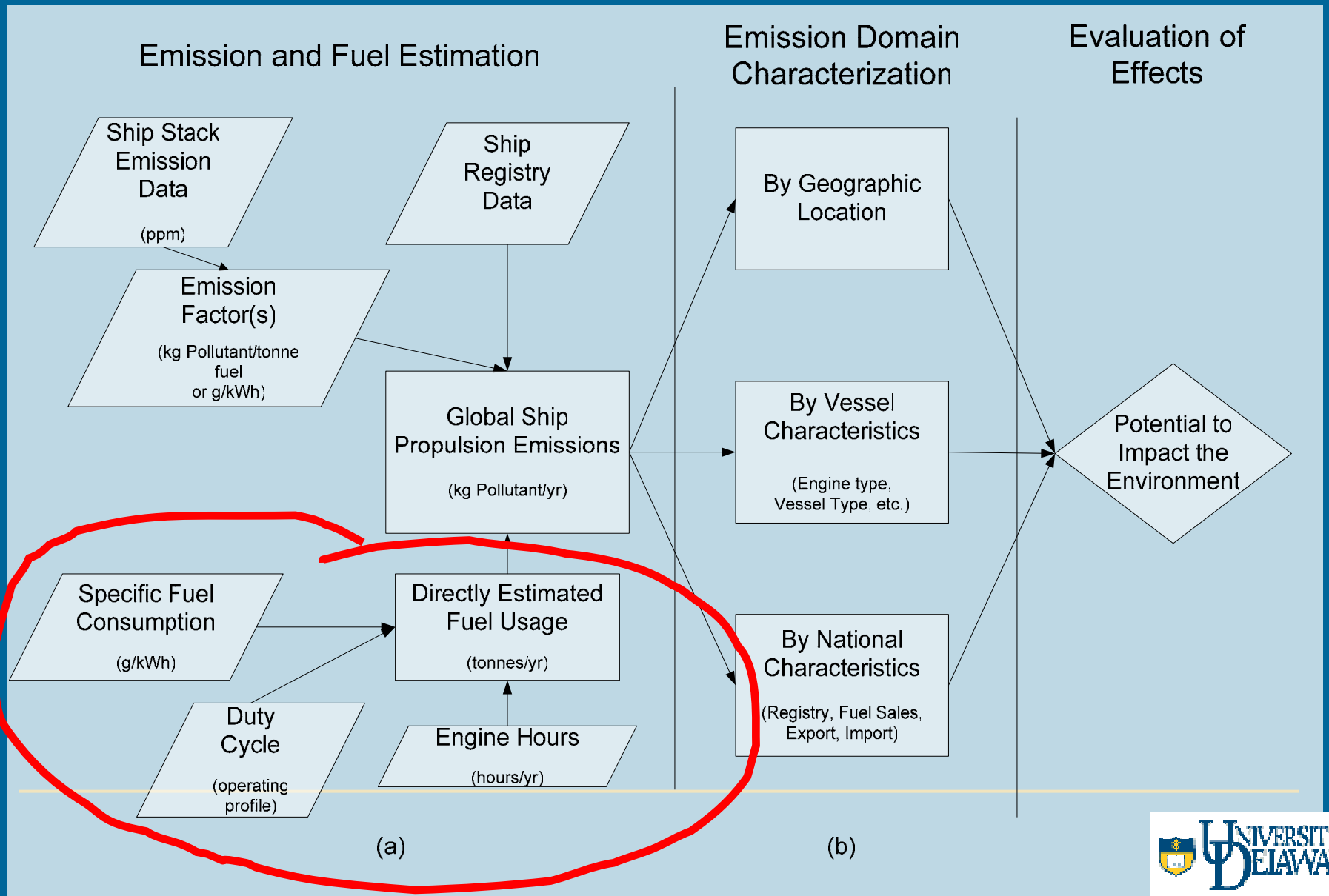
Old General Estimation Methodology

Corbett and Fischbeck, JGR, 1999



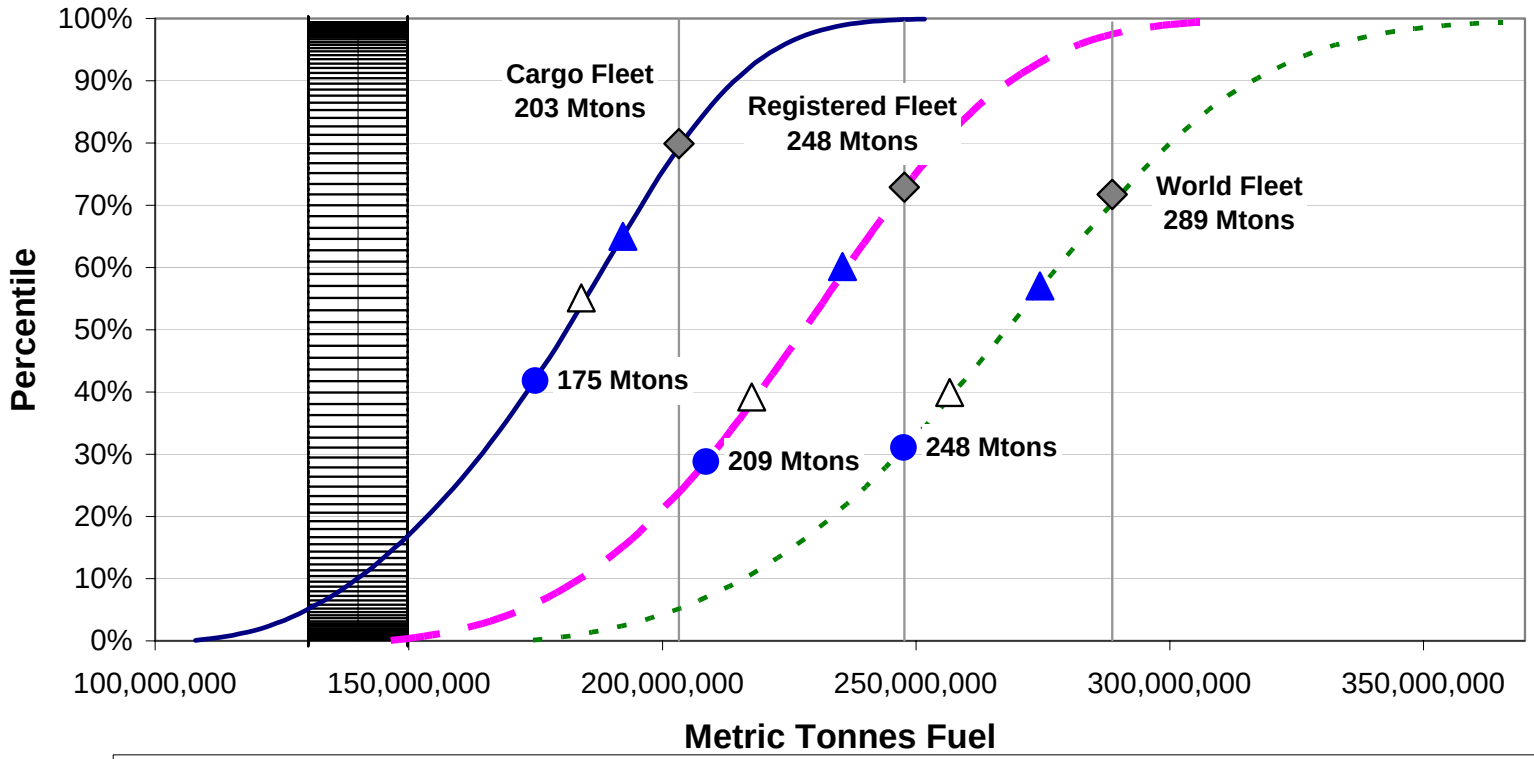
Updated Estimation Methodology

Corbett and Koehler, JGR, 2003



Uncertainty remains, but bounding is improving

Corbett and Koehler, JGR, 2004



- International Bunker Statistics (with statistical error bars)
- Estimated Cumulative Distribution of Cargo Fleet Fuel Consumption
- Estimated Cumulative Distribution of Registered Fleet (Cargo + Non-Cargo Ships) Fuel Consumption
- Estimated Cumulative Distribution World Fleet (Cargo + Non-Cargo + Military Ships) Fuel Consumption
- Best estimates (Corbett and Koehler, JGR, 2003)
- Lower specific fuel consumption rates
- Fewer at-sea and in-port days, assuming only 1% of vessels are laid up, lower specific fuel consumption
- Fewer at-sea and in-port days, more days laid up, lower specific fuel consumption

University of Delaware

Current ARB Proposal Objectives

TECHNICAL PROPOSAL

Estimation, Validation, and Forecasts of Regional Commercial Marine Vessel Inventories

Principal Investigator:
James J. Corbett

Official Authorized to Bind this Proposal:

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Signature _____

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- Provide spatially resolved baseline CMV inventory of emissions at regional scale
- Evaluate port-based inventories for potential agreement, validation
- Spatially forecast future CMV emissions
- Forecast future-year ship emissions under potential SECA designation

ARB focus on U.S. coastlines

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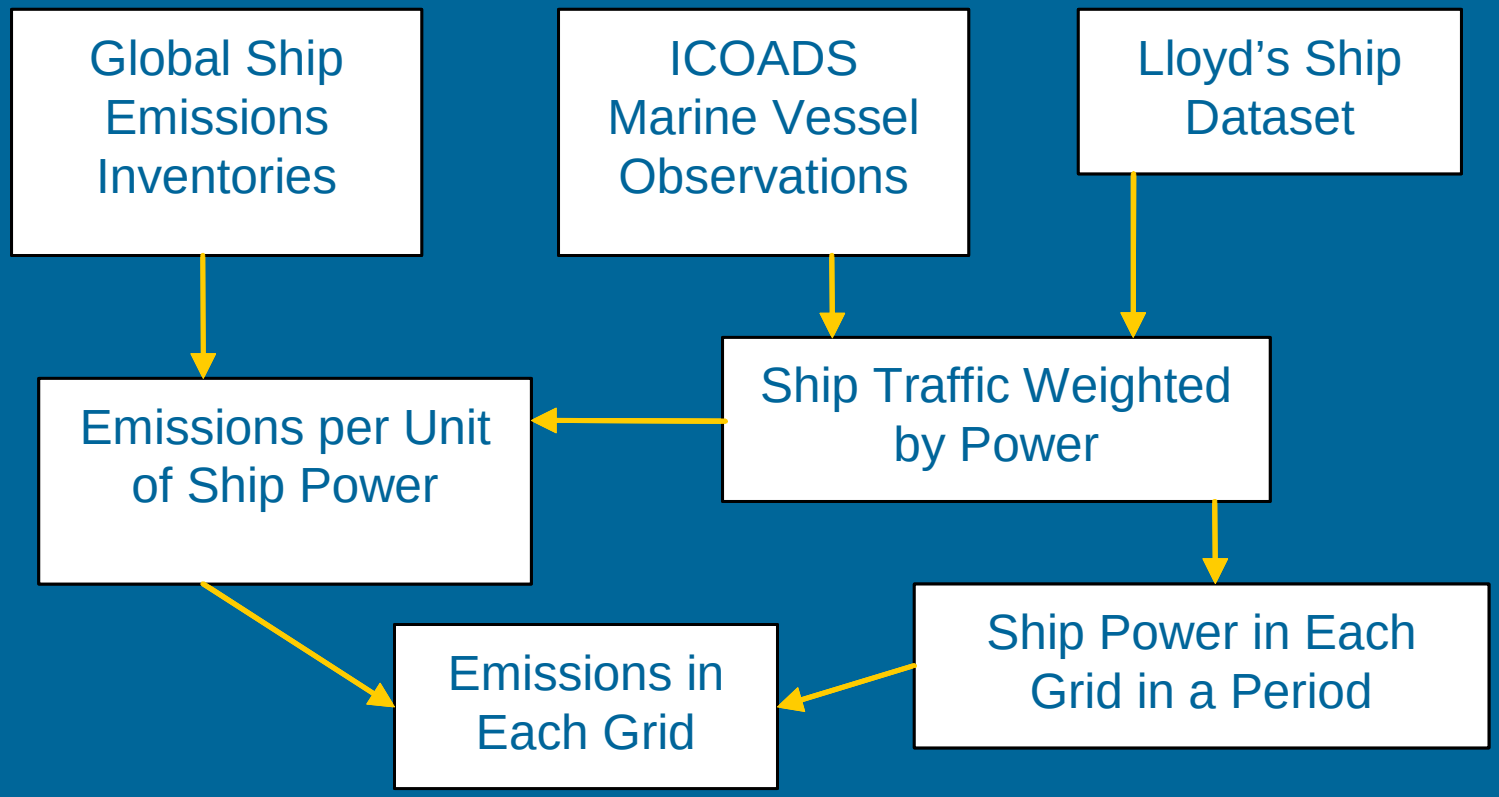
Model synthesizing non-spatial inventories with spatial activity indicators for CMVs



Current Step: Use global estimates to bound regional inventories

Based on the work related to Corbett and Koehler, JGR 2003; Endresen et al, JGR, 2004; and Corbett and Koehler, JGR , 2004

	Global Ship Emissions Inventory (Tg)			
	Lower-Lower Bound	Lower Bound	Base Case	Upper Bound
Fuel	130	175	203	222
NOx (N)	4.17	4.68	5	6.79
SOx (S)	4.21	4.52	4.72	6.54
CO2 (C)	164	171	176	249
HC (CH4)	0.459	0.53	0.574	0.778
PM (PM10)	0.755	1.02	1.19	1.97
CO	0.911	1.01	1.08	1.5

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Where are the ships? How might we know?

- Where trade moves (cargo tonnage)
- Where charts say ships are (maps, logs)
- Where volunteer ships say they are (empirical)
- Where port statistics say ships are going (modeled)
- Where AIS transponders say they are (not public)

- Data sources
  - Local VTS data for ports and regions
  - National statistics, not well resolved spatially
  - Analyses of cargo O/D
  - Large samples of self-reporting vessels (ICOADS, AMVER)
  - Other?

Where in the World?
Historical Shipping Activity

Courtesy: National Maritime Museum, Britain

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Description of ICOADS, AMVER

Some overlap between the COADS and AMVER datasets;
about 33% of the AMVER vessels are weather observation vessels
But different data sets lead to highly different regional perturbations of air pollutants

- ICOADS
  - World's largest dataset for global marine surface observations
  - Sponsored by NOAA/NCAR
  - Collected primarily from ships and buoys
  - 2,564 unique ships in 2002
  - Publicly available
- AMVER
  - Global ship reporting system for search/rescue assistance to persons in distress at sea
  - Sponsored by the USCG
  - Open to all merchant ships, but mainly ships over 1000 GT, on voyages $\geqslant$ 24 hr
  - ~2,700-3,000 unique vessels
  - Not publicly available

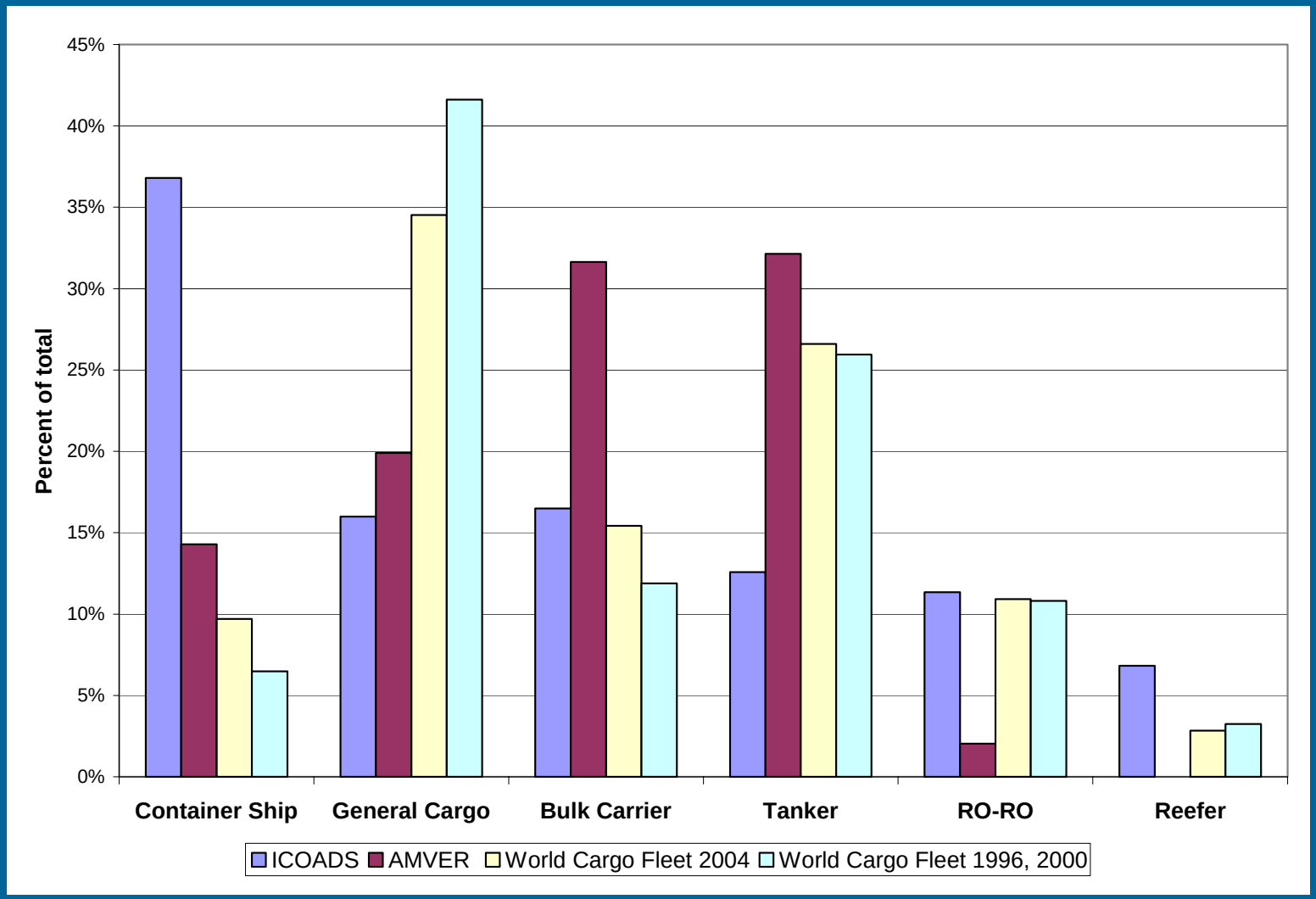
ICOADS detail for our current work

Summary of ICOADS

Year	Total Obs.	Identified ships[1]	Obs. by identified ships	Cargo Ships[2]	Obs. by cargo ships	Cargo Ships after trimming[3]	Obs. by cargo ships after trimming
2002	966,194	2,564	651,698	2,177	509,843	2,172	474,929
2001	1,029,132	2,127	631,211	1,803	497,657	1,798	460,329
2000	1,096,795	1,972	572,037	1,655	449,948	1,650	417,299
Sum	**3,092,121**	**N/A**	**1,854,946**	**N/A**	**1,457,448**	**N/A**	**1,352,557**

1. Using 15,048 unique ship identifiers with valid ship power from Lloyds Registry.
2. We identified properties for 2,453 unique cargo ships from 2000 to 2002.
3. Five over-reporting ships are trimmed

Compare ICOADS, AMVER & World Fleet



Data Strengths and Limitations

Strengths

1. Can identify specific vessels for individual observations and associate them with actual power, tonnage, etc., for direct spatial consideration of factors necessary to evaluate environmental impacts.
2. Spatial representation of shipping lanes is excellent, especially major trade routes.
3. Seasonal variation in shipping lanes is consistent over time, and predictable. Weather routing behavior is clearly identified.
4. Very little inter-annual variability in shipping lanes. Twenty years of monthly ICOADS data shows from year to year, and season to season, same shipping lanes used by different sets of vessels. (AMVER data not cumulative or long-term.)
5. Number of observations and sample of world fleet vessels by type is large enough to support statistical analysis and correction for known bias.

Limitations

1. Voluntary reporting conditions create sample bias that is globally non-random. This can be quantified and corrected at a global level.
2. Variability in reporting by vessel type ***may*** demonstrate different non-random behavior locally than implied by the global sample bias, above.
3. Variability of reporting frequency among vessels of same type is large and non-random. Can be quantified and corrected at a global level.
4. Variability in reporting frequency by geographic region ***is apparent*** and non-random. For example almost all observations made by five vessels with highest reporting frequencies in the three years (2000-2002) are located in the North Atlantic.
5. Items 2 and 4 require more advanced adjustment and/or validation with independent data samples or comprehensive traffic analysis.

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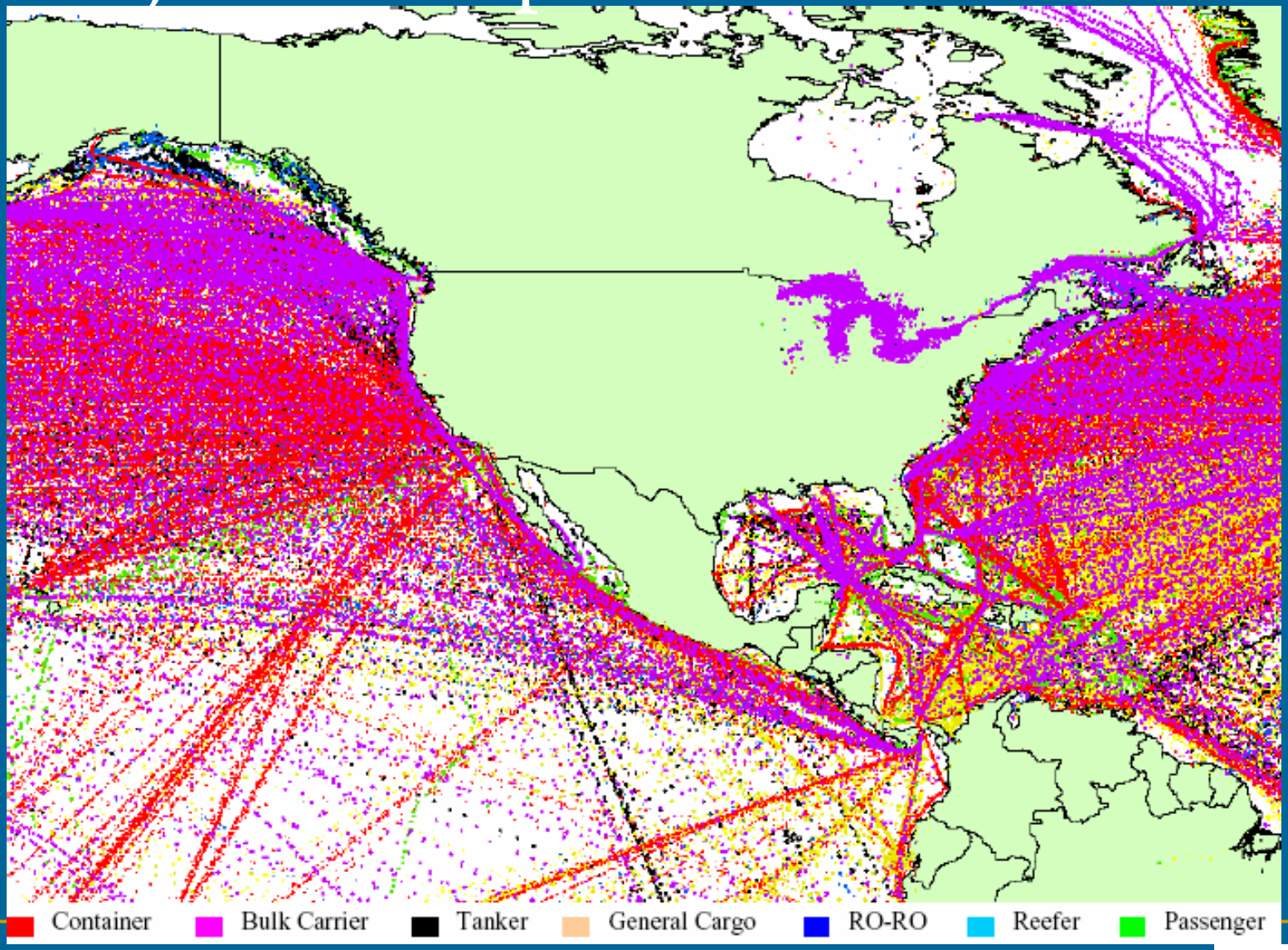
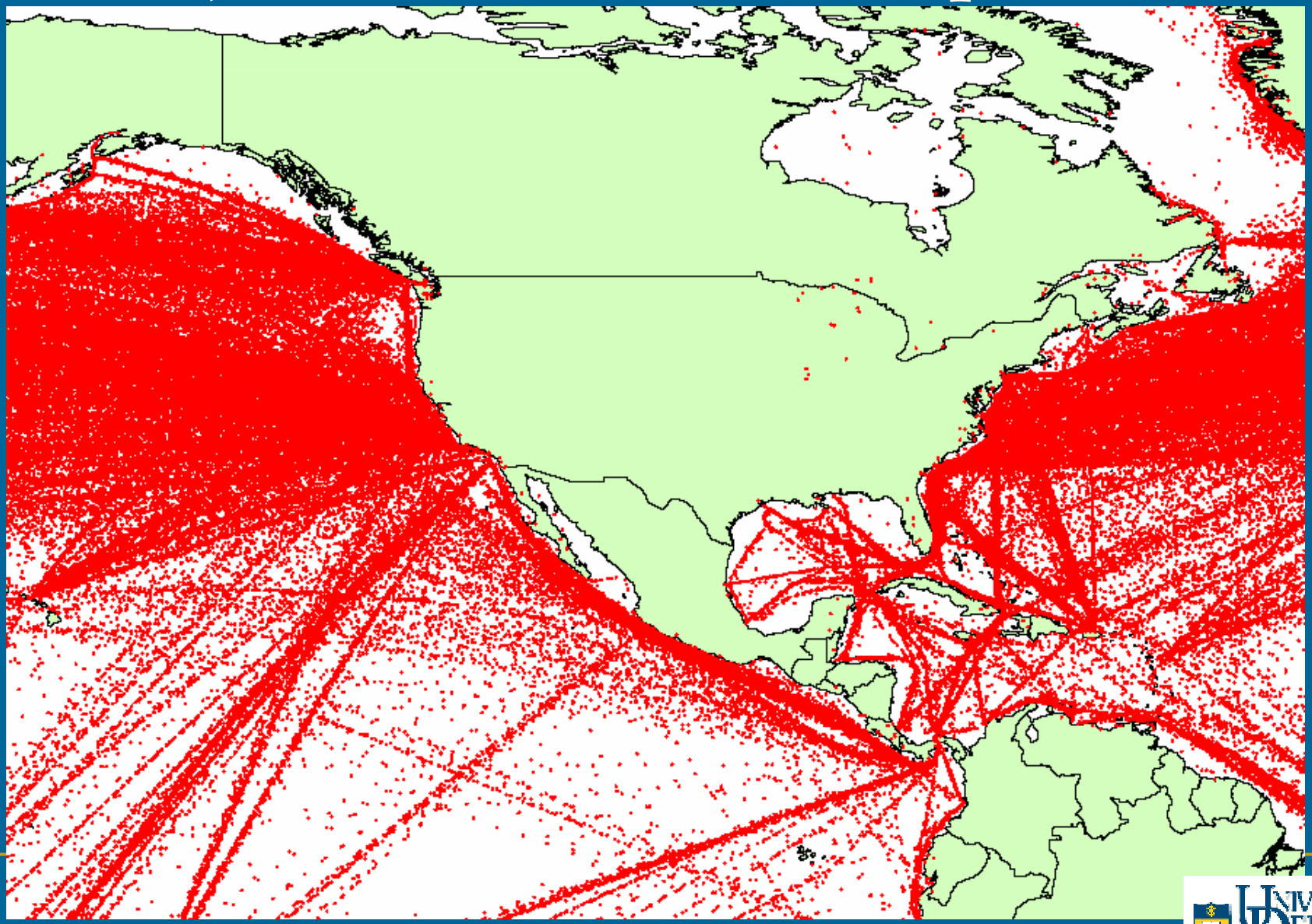
Unadjusted Ship traffic



Unadjusted Container Ship traffic



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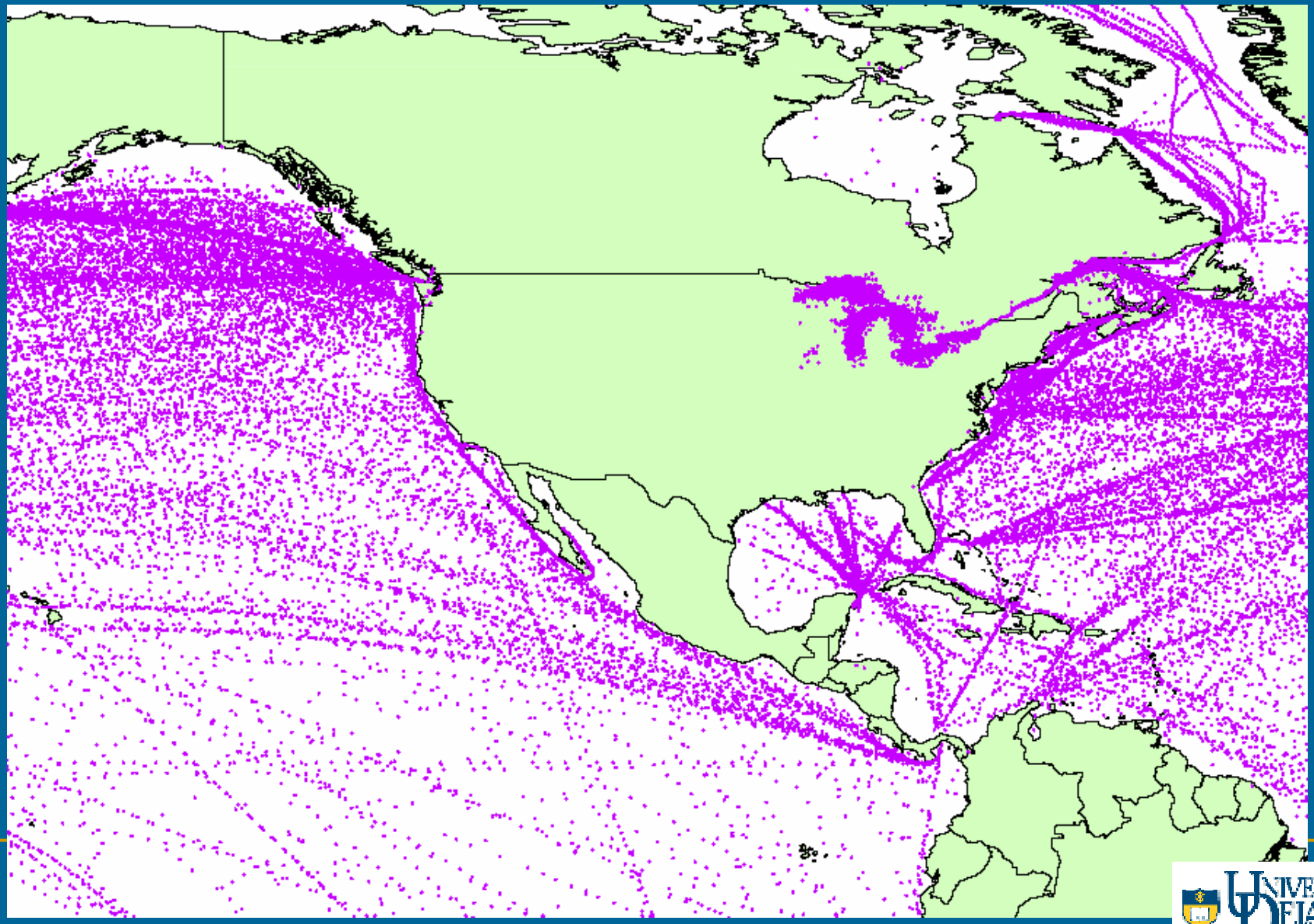
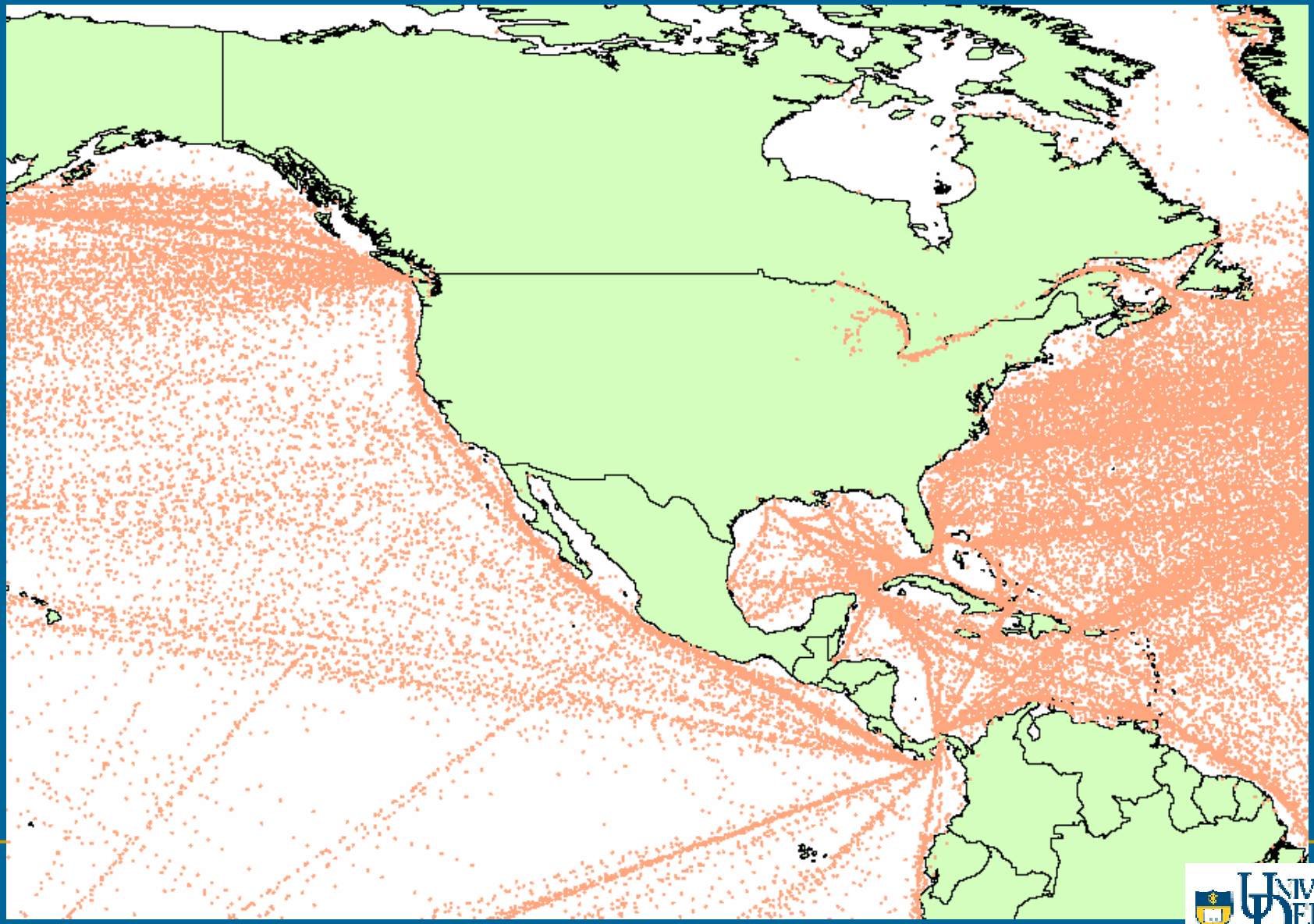
Unadjusted Bulk Carrier traffic



Unadjusted General Cargo traffic



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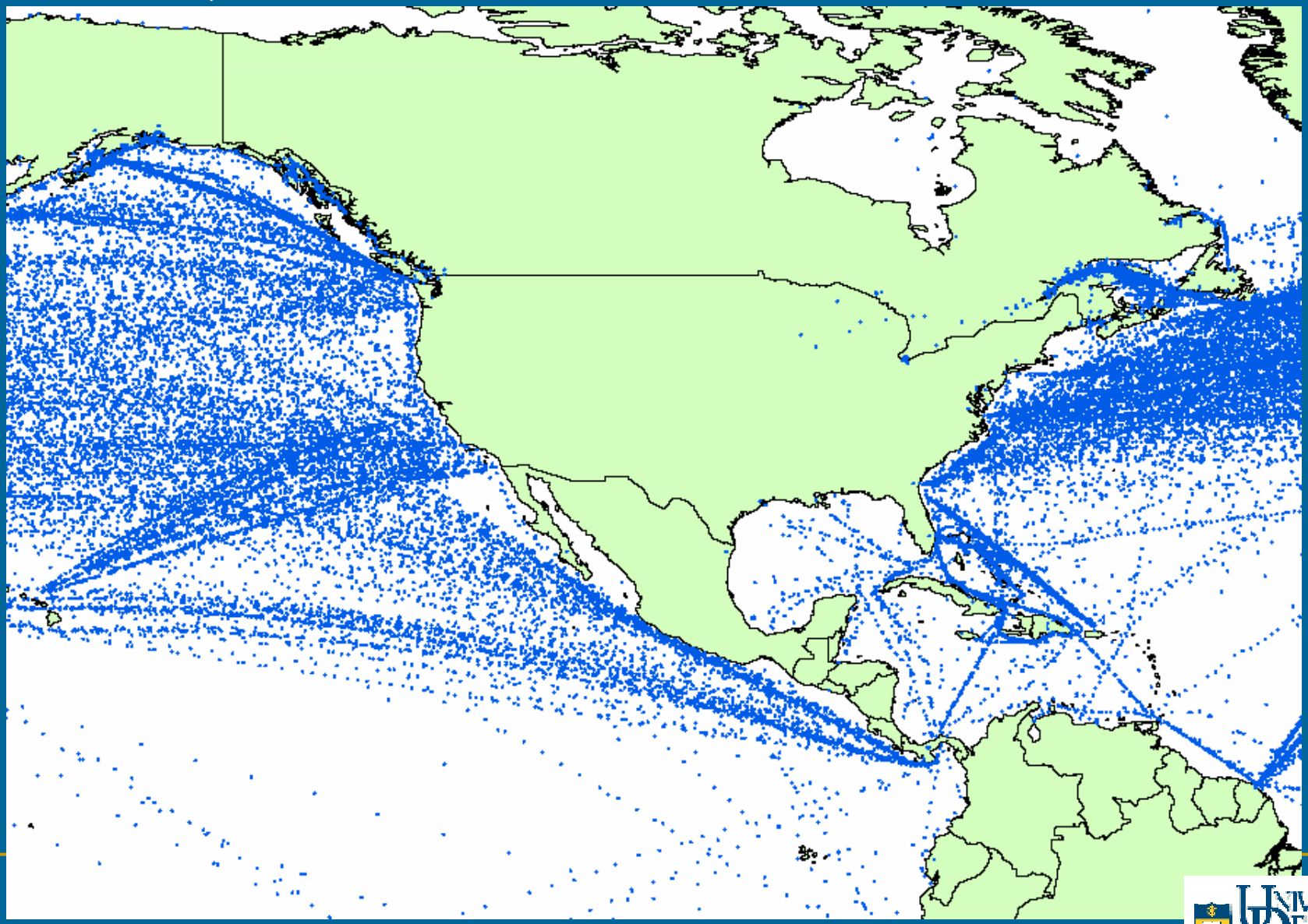
Unadjusted RO-RO traffic



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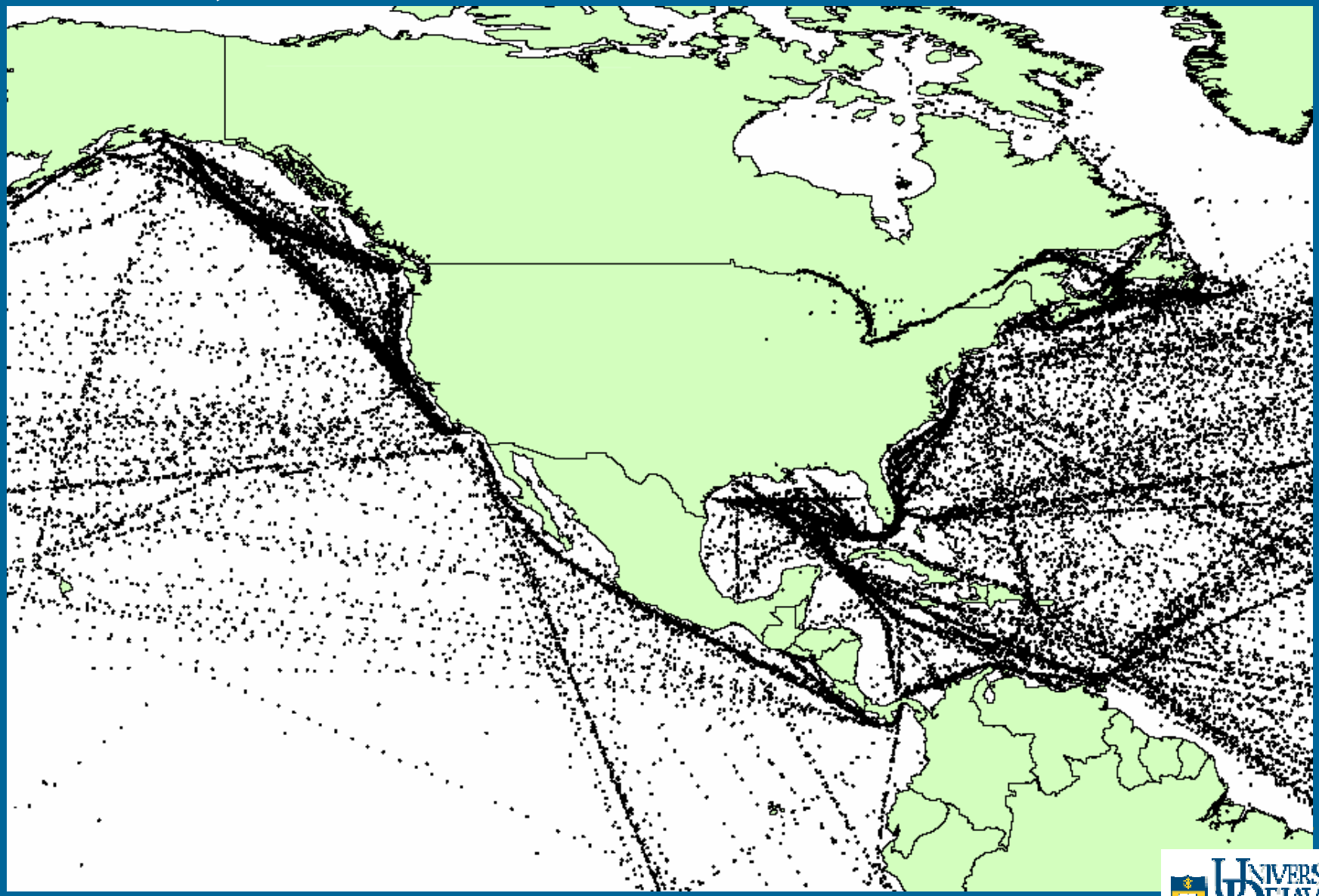
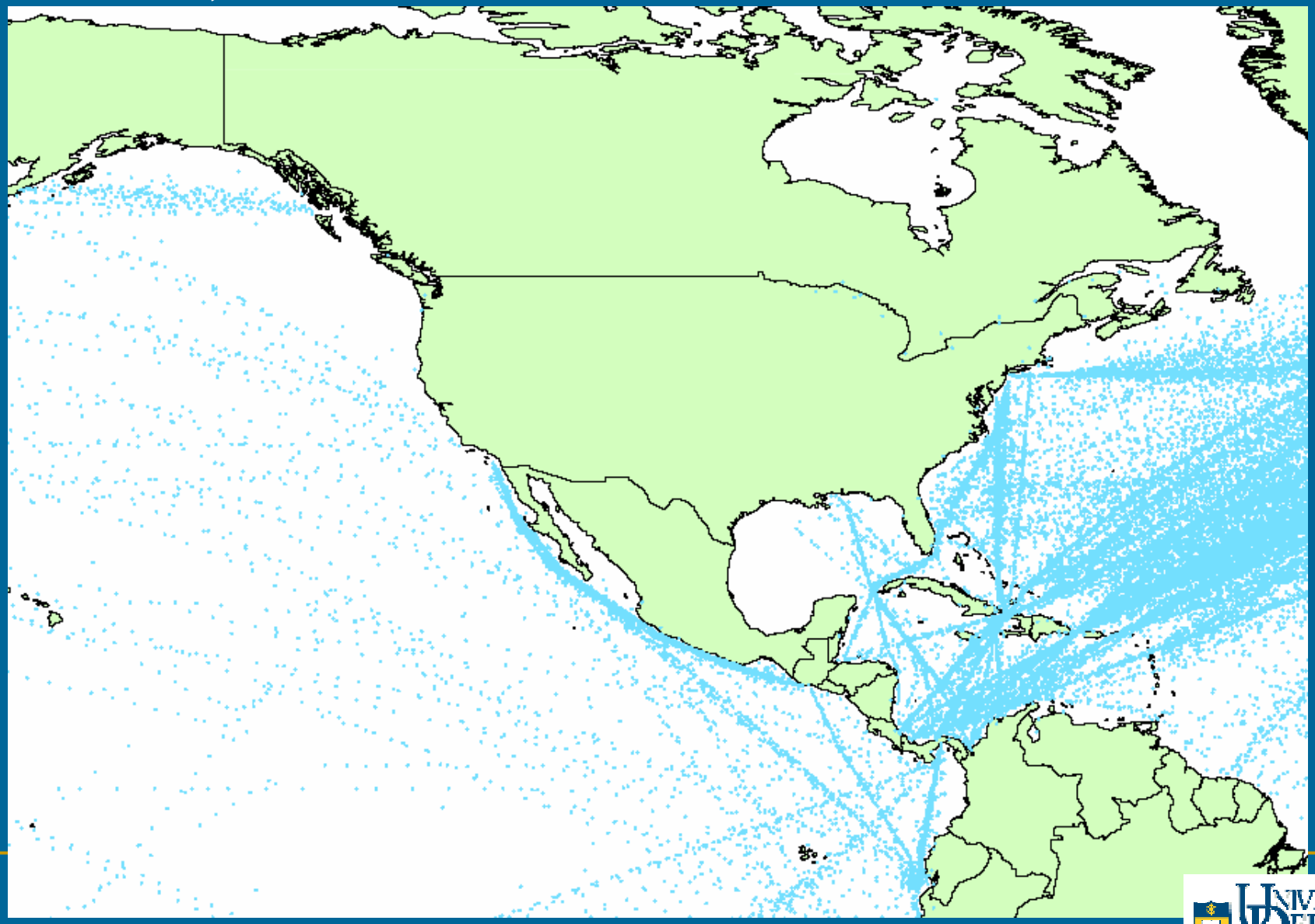
Unadjusted Tanker traffic



Unadjusted Reefer traffic



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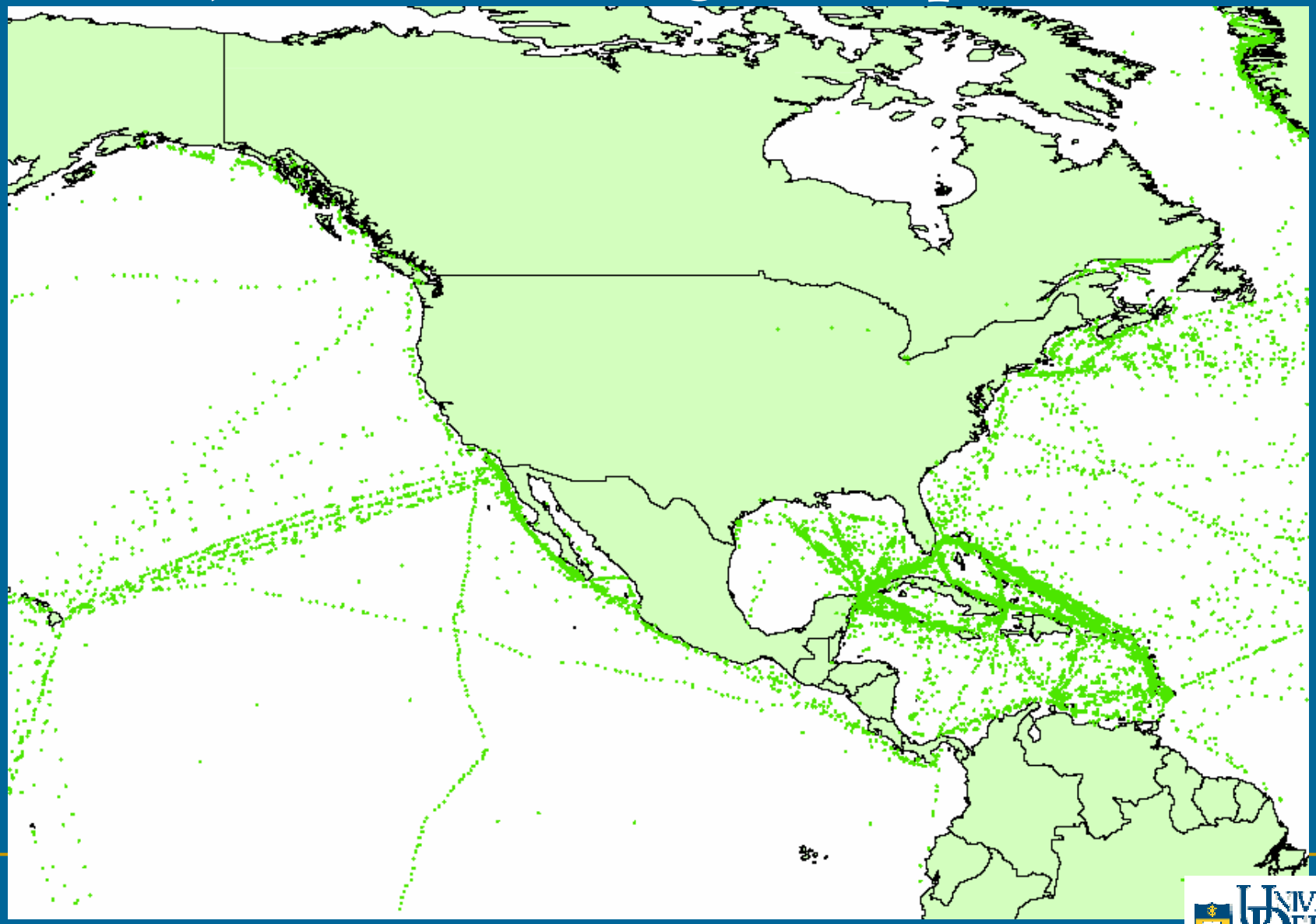
Unadjusted Passenger Ship traffic



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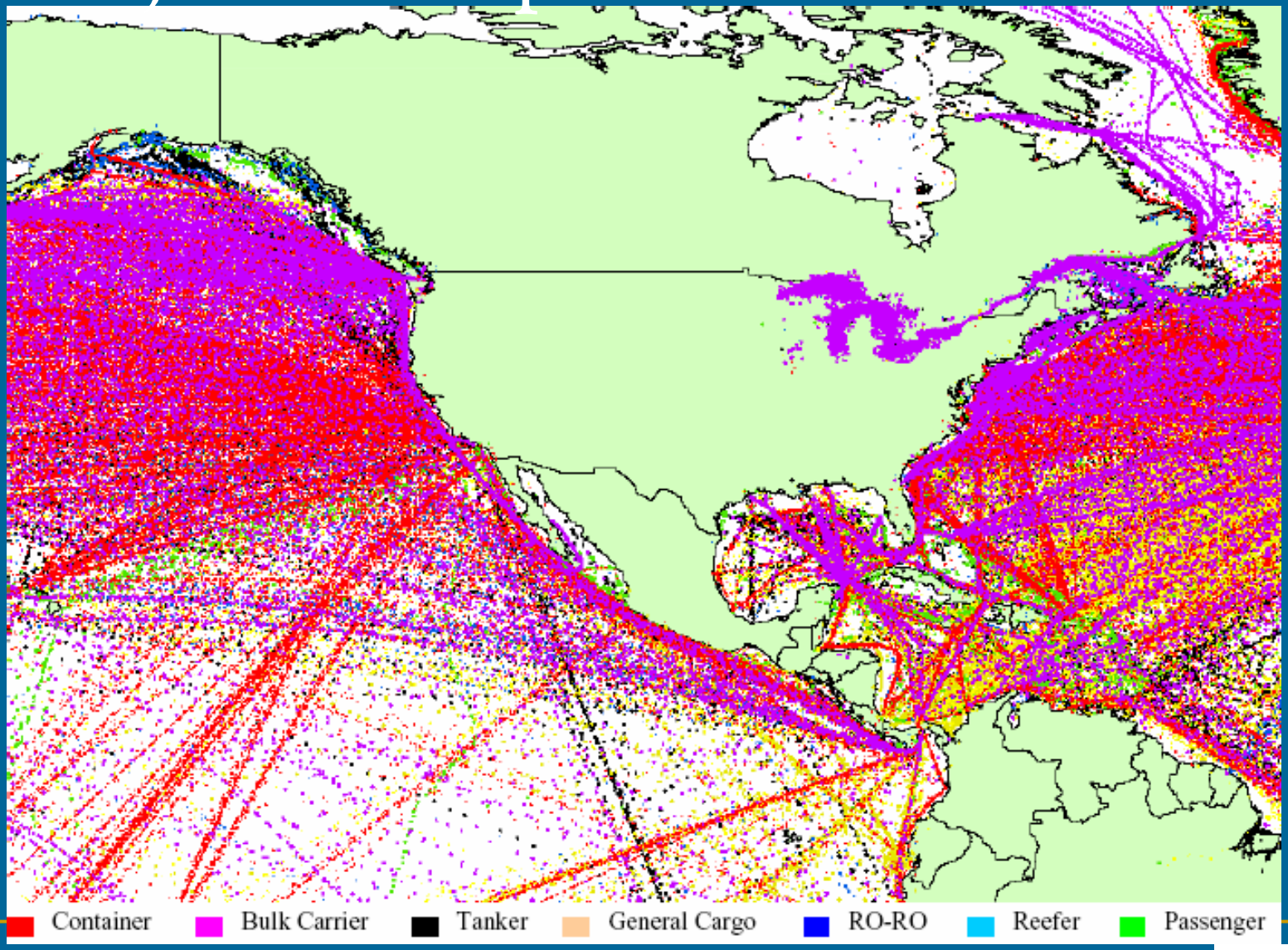
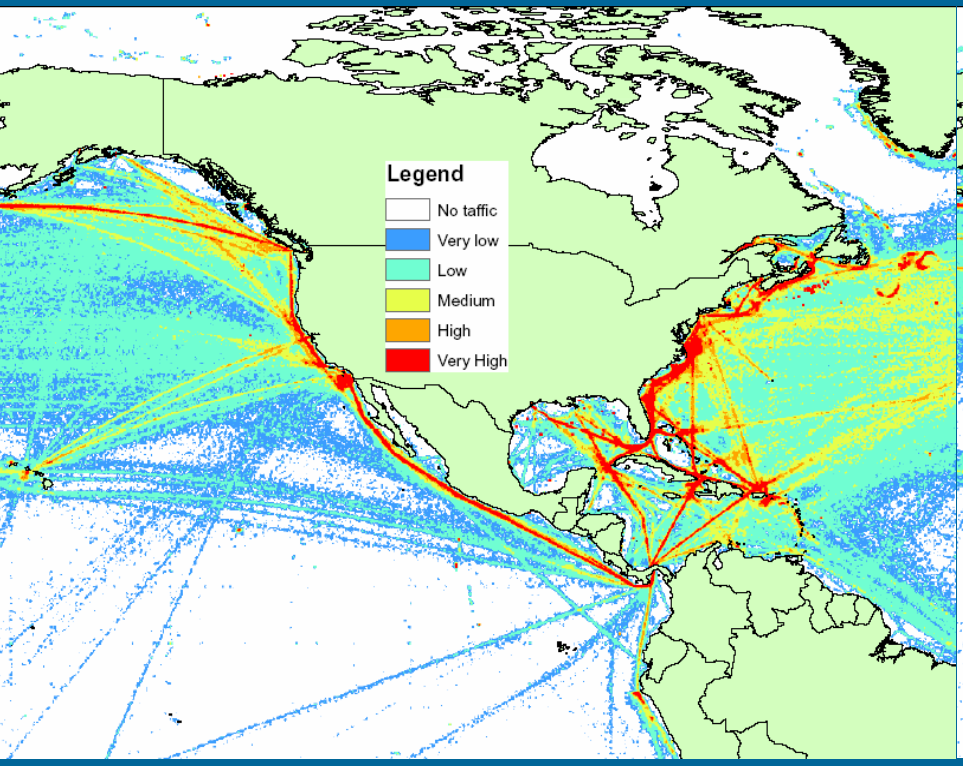
Unadjusted Ship traffic

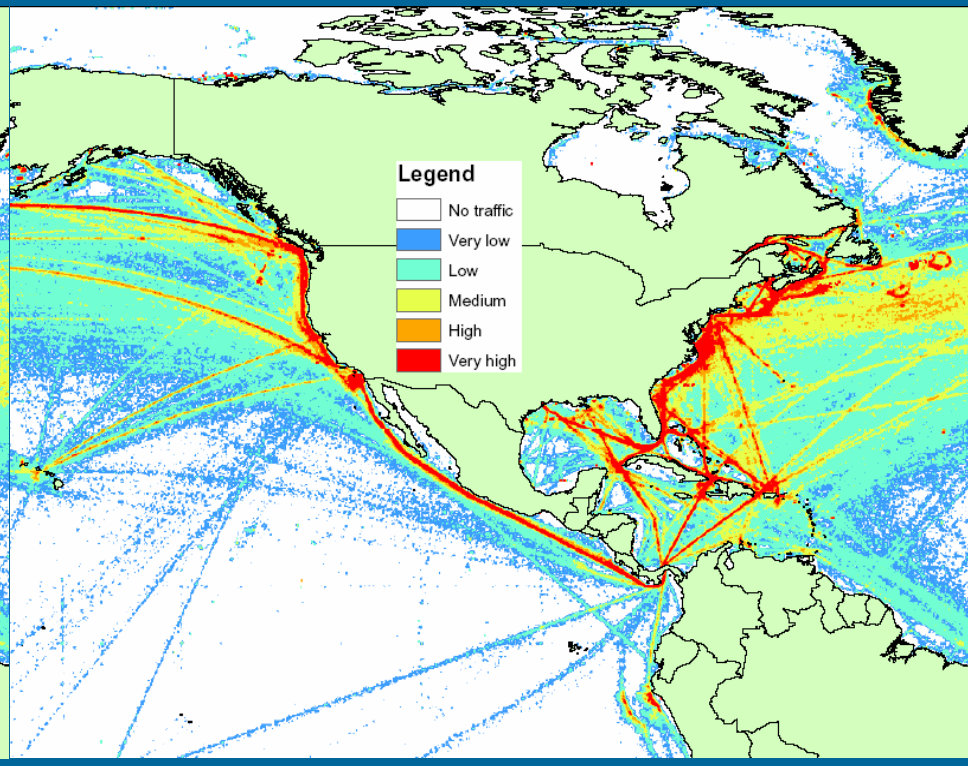


Seasonality of Ship Traffic (unadjusted)

Using 20 years of ICOADS data to evaluate shipping lanes



Winter Traffic



Summer Traffic

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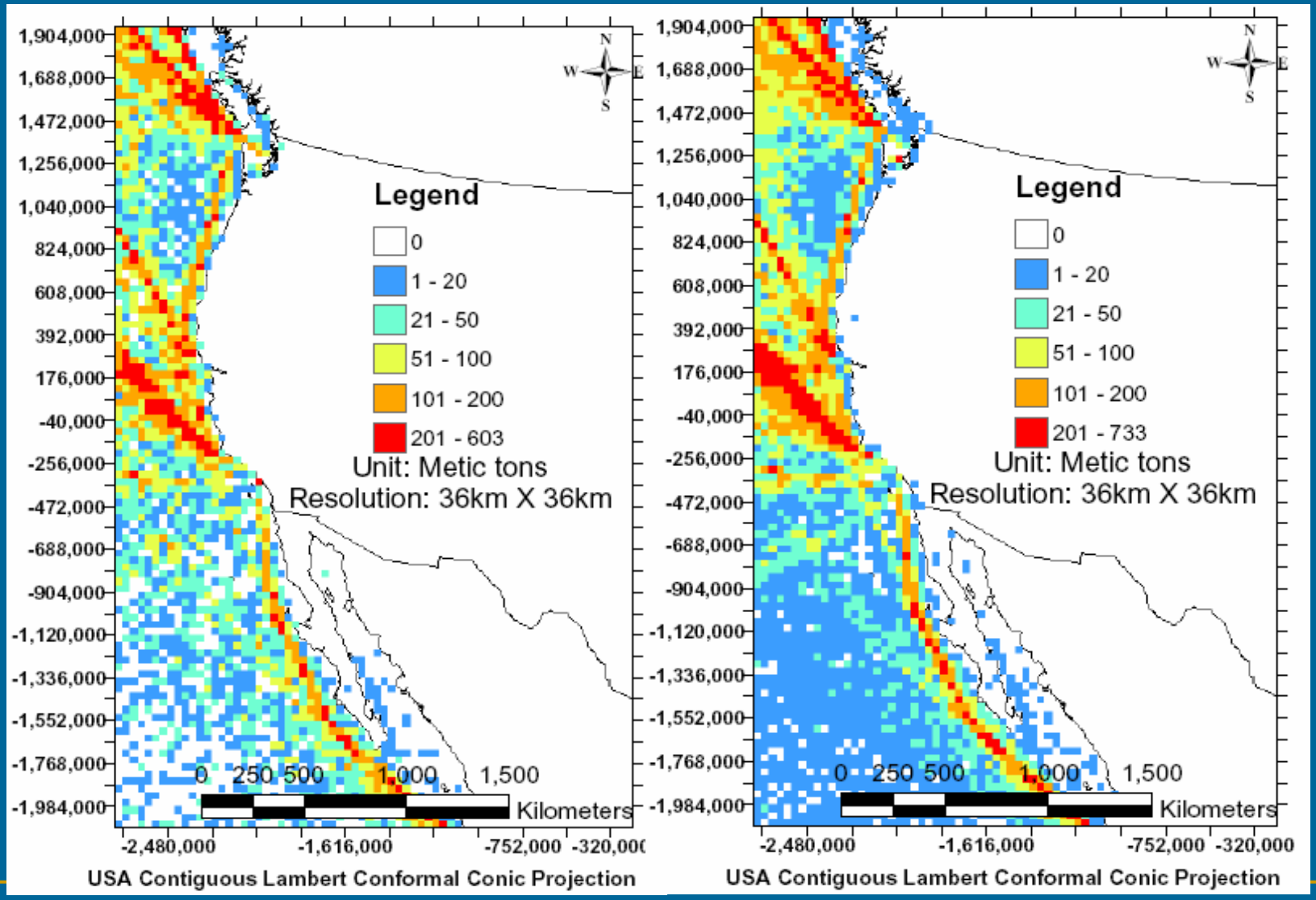
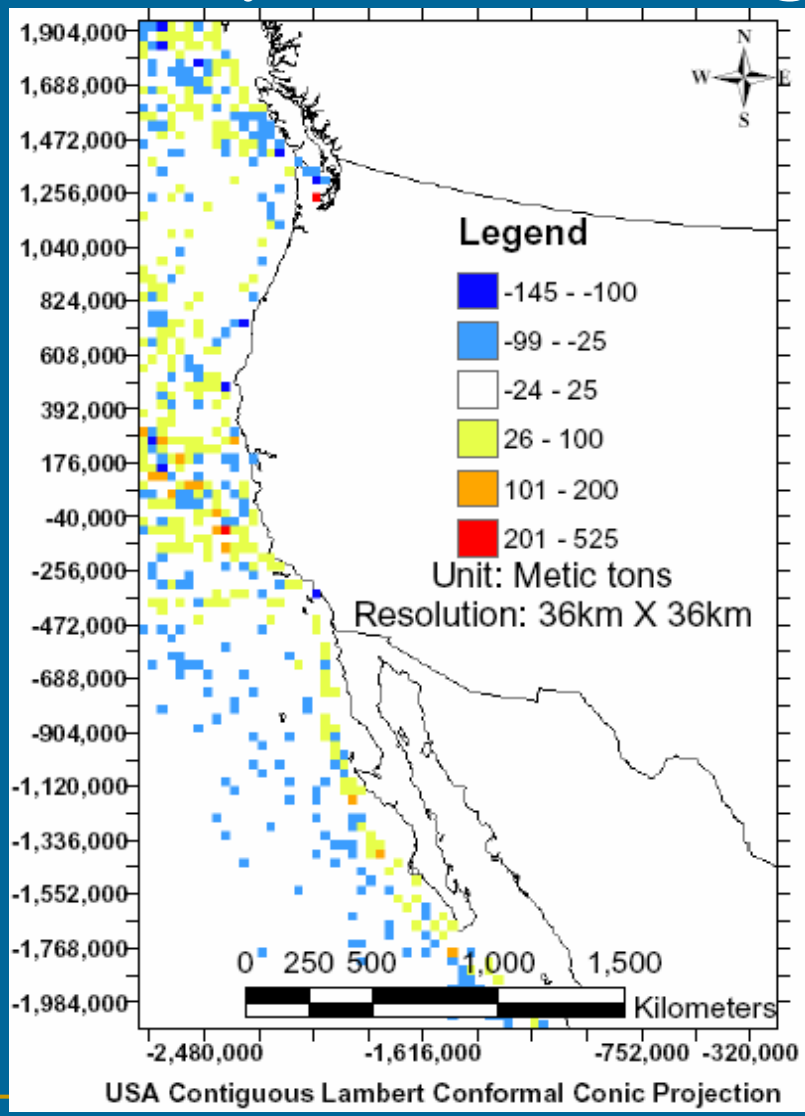
Adjusting and validating the data

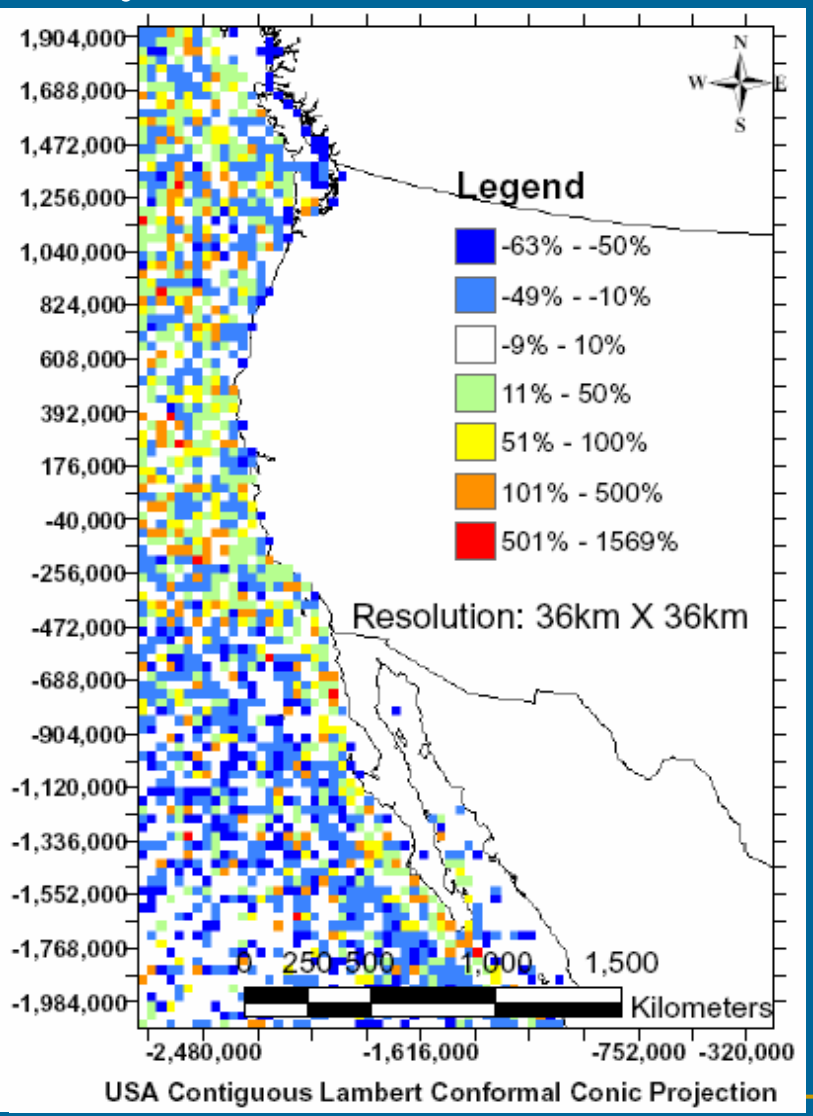
- Use multiple years to improve sample size
- Trim five exceptionally over-reporting vessels
- Use various GIS techniques to present and analyze the data and traffic modeling results
- Evaluate according to vessel characteristics
- Validate with port arrival data

Multi-year vs. Single-year Data

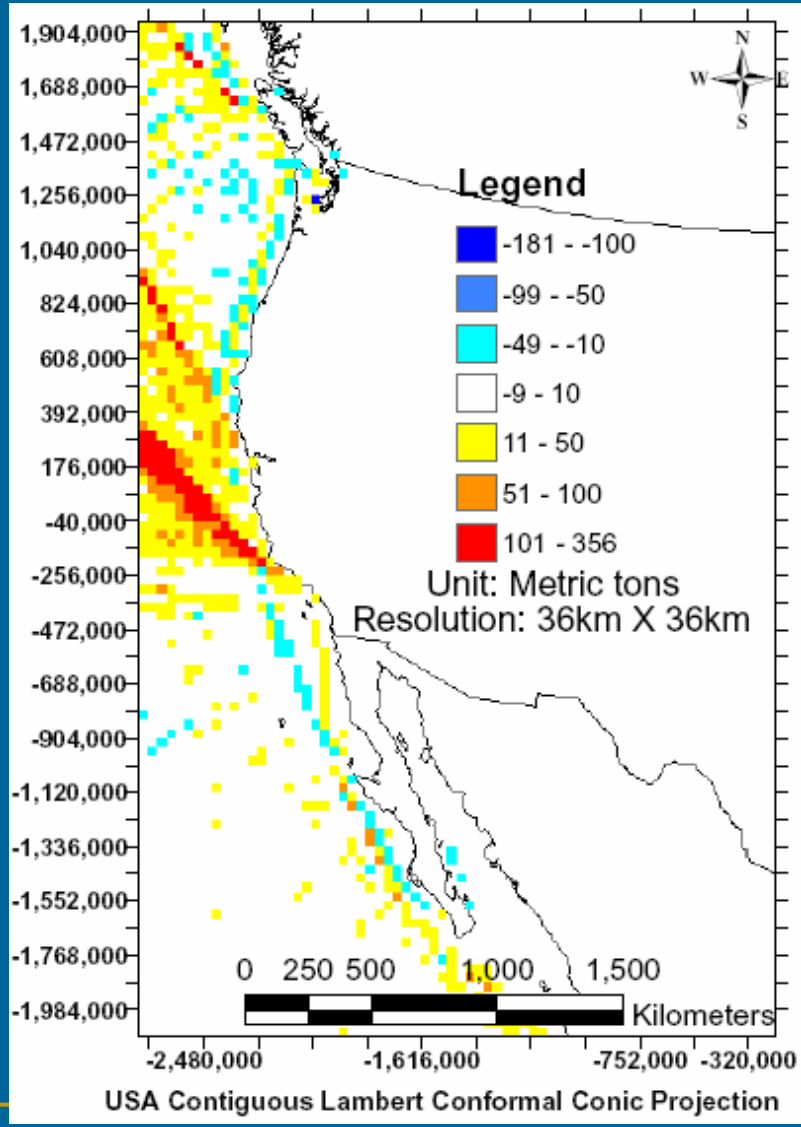


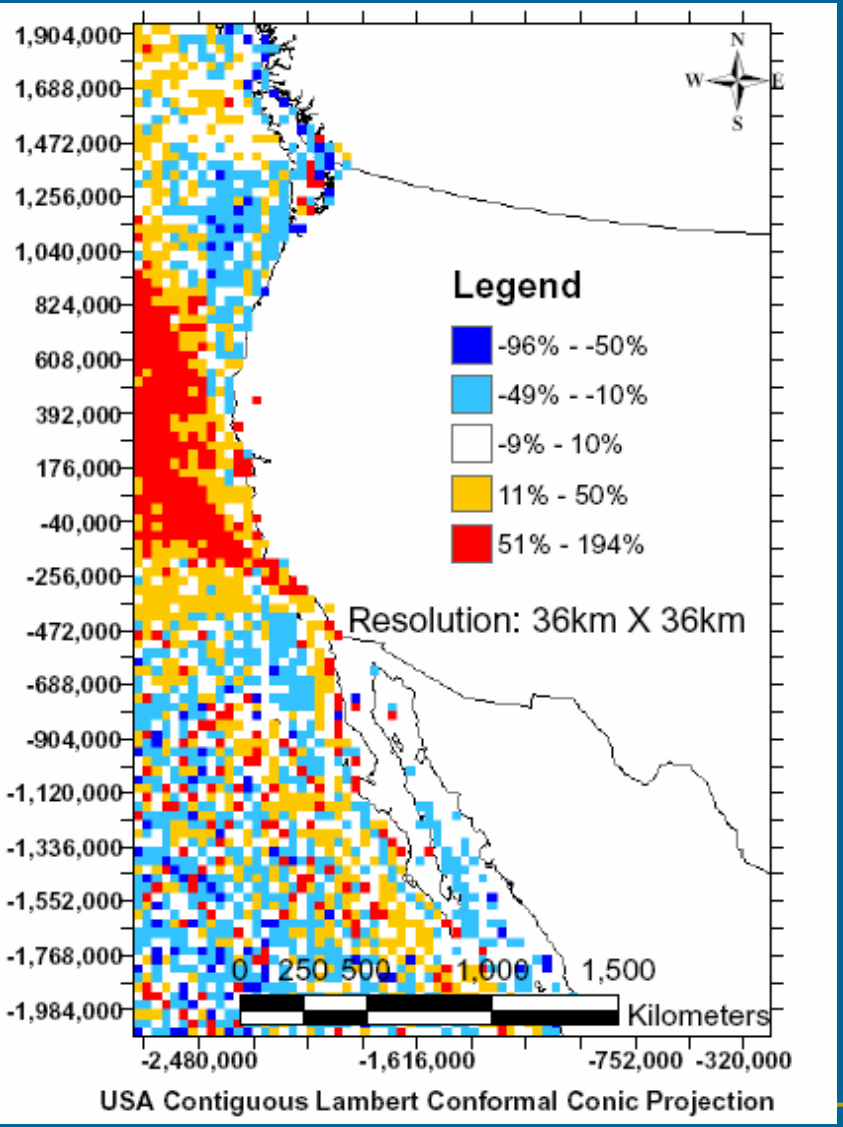
Multi-year vs. Single-year Data





Power-weighed vs. Non-weighted Data





Policy analysis supported by this work

Control Policy Scenarios

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Spatial Distribution of Emissions

↓

Emissions Transport Model

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Impacts & Policy Analysis

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Chose “Best set” of policies

Next improvement: Use regional bottom-up data to develop regional inventories

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Summary with regard to SECA analysis

- Large scale inventories directly support
  - Emissions estimate with and without SECA
  - Fuel usage estimate with and without SECA
  - Enables estimation of direct costs of fuel-switch
  - Enables analysis of other compliance strategies
- Modeling using these inventories supports
  - Estimate of CMV pollutant concentrations
  - Supports analyses of environmental, health effects
- Can evaluate broader economic, policy impacts
  - Helps visualize potential shifts in traffic volume

A modern fleet of ships does not so much make use of the sea as exploit a highway.

-- Joseph Conrad

The Mirror of the Sea, Ch. 22, 1906

Discussion welcome

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