Measurements of Marine Vessel Emissions

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- MVE: Description and Significance
- Measurements of Different Vessels
- Emission Factors: Data vs. References
- Particulate emissions

The New England Air Quality Study

NEAQS is a multi-laboratory effort focused on understanding the factors that affect air quality in this region.

NEAQS 2002 used a network of ground-based observing sites, the DOE G1 aircraft, and the NOAA research ship Ronald H. Brown (above). The ship was equipped to measure a wide variety of gas-phase and aerosol species, meteorological parameters, and vertical profiles of ozone, aerosols, wind, and temperature.

In the summer of 2004 NEAQS will be part of a larger study, called ICARTT, that will examine the transport and transformations of pollutants from North America across the Atlantic Ocean to Europe.

Inventory Development for Marine Vessel Emissions

Classification: mobile, non-road

Emissions inventory development:

1) emissions factors (fuel-based; load-based)
2) activity factors (fuel use; time in mode)
3) location information (ports, waterways; seaways)

Earlier EPA inventory work:

Fuel-based emission factors (AP-42; ca. 1985)

Allocate all emissions to port where fueling occurred

Current EPA inventory:

Fuel-based factors (AP-42)

Emissions allocated by fuel use

Distillate: 75% in port; Residual: 25% in port

Inventory uncertainties: Emission factors are significant!!

Evaluate under operating conditions

Marine Vessel Propulsion Characteristics

Slow-speed diesel: (SSD)	55% of total fleet: ~58,000 vessels (>95% commer.) low-grade residual fuel ("bunkers"; high S; cheap!) power: < 10 MW up to ~100 MW directly coupled to propeller shaft (~130 rpm)
Medium-speed diesel: (MSD)	40% of total fleet: ~42,000 vessels (40% military) uses residual or distillate fuels; power: ~1 - 20 MW diesel-electric - motor powers propeller shaft coupled via gears to propeller (130-2000 rpm)
Steam-turbine engines:	<5% of total fleet: ~5,000 vessels (70% military) uses distillate or residal fuels or blend steam generation drives turbine; powers prop.

[Ref.: Corbett and Fishbeck, Science, 278, 31 October 1997; and refs therein]

Marine Vessel Emission Characteristics

N emissions: mostly from combustion (temperature dependent)

S emissions: from fuel S-content (typically <1% to 5% by weight)

C emissions: virtually complete combustion!! ($CO/CO_2 << 1\%$)

Particulate: soot; organic (unburned fuel; lube oils); some S

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Global N-emissions: 3.08 TgN/yr (~14% of total fossil fuel source)
(~100% of U.S. mobile sources)
U.S. N-emissions: 0.25 TgN/yr (~7% of U.S. mobile source)

Global S-emissions: 4.24 TgS/yr (~5% of total fossil fuel source)
(~20% of global DMS source)

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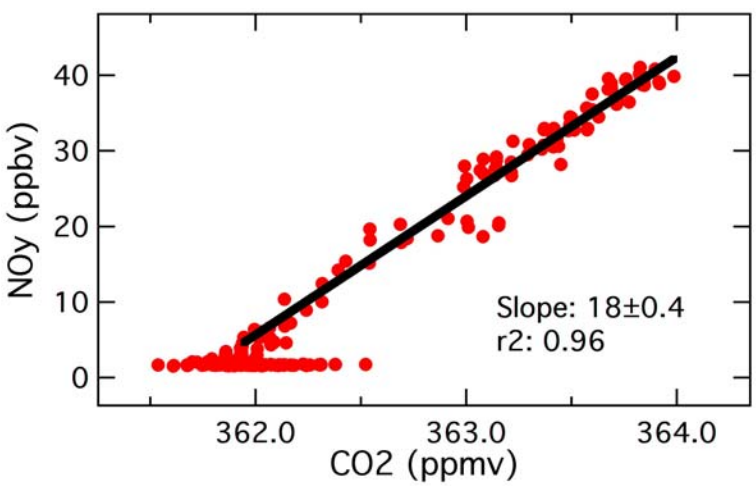
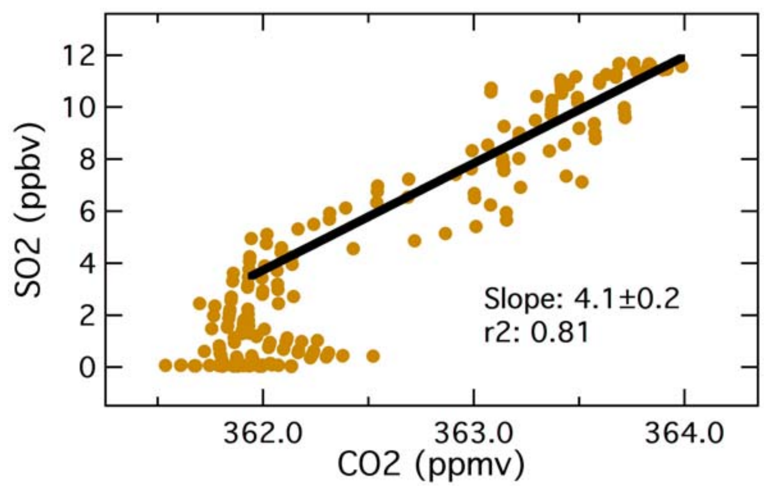
BUT, shipping patterns and activities matter a lot:
- MVE are heavily skewed toward the Northern Hemisphere
- Meteorology has strong influence on fate of emissions
- Port activities are crucial (Port of LA: Alt. Marine Power)



40
30
20
10
0
NOy (ppbv)
362.0
363.0
364.0
CO2 (ppmv)
Slope: 18±0.4
r2: 0.96



12
10
8
6
4
2
0
SO2 (ppbv)
362.0
363.0
364.0
CO2 (ppmv)
Slope: 4.1±0.2
r2: 0.81

Emission Factor Calculations

Assume: Average fuel C content: 86±0.5% C or 13.9±0.1 g fuel/mole C

[Average fuel N content: 0.3±0.2%]

[Average fuel S content: 1.5±1.2%]

[Source: Lloyd's Register, 1995]

$$\text{E.F.}_{(NO_x)} = \frac{\text{ppmv } NO_y * 46\text{e-3 kg } NO_x/\text{mole } NO_y * 1000 \text{ kg}}{\text{ppmv } CO_2 * 13.9\text{e-3 kg fuel/mole } CO_2 * \text{tonne fuel}} = \text{Slope} * 3.31(\pm 0.02)$$

$$\text{E.F.}_{(SO_2)} = \frac{\text{ppmv } SO_2 * 64\text{e-3 kg SO2/mole } SO_2 * 1000 \text{ kg}}{\text{ppmv } CO_2 * 13.9\text{e-3 kg fuel/mole } CO_2 * \text{tonne fuel}} = \text{Slope} * 4.60(\pm 0.03)$$

Marine Vessels: Emission Factor Data

Date	Time	(per 1000kg [tonne] fuel) kg NO_x	kg SO_2	Vessel type
18 Jul	1035	49(±2)*	~5	Cruise ship
19 Jul	1055	83(±4)	0.7(±0.09)	Fishing vessel
30 Jul	2230	75(±2)	0.7(±0.04)	Casino boat
6 Aug	1155	60(±1)*	19(±1)	Tanker
8 Aug	2230	95(±4)**	22(±1)	Container & Freighter
8 Aug	2320	39(±4)*	6(±0.5)	Deep-water tanker
8 Aug	2335	67(±7)*	11(±2)	Container
9 Aug	0015	41(±5)*	5(±0.7)	Container
9 Aug	0115	81(±7)*	17(±3)	Freighter
Average		56±16* {62±21}**	11±6* {12±7}**	

Marine Vessels: Emission Factor Data

Source	(per 1000kg [tonne] fuel) kg NO_x	kg SO_2
Lloyd's Register of Shipping, 1995	87 (SSD)	20 X % S
Marine Exhaust Emission Research Program	57 (MSD)	
Booz-Allen & Hamilton, Inc., 1991	78	22 X % S
Inventory of Air Pollutant		
Emissions from Marine Vessels		
Environment Canada	39 - 179	{4.7 - 64}
Port of Vancouver Marine Vessel		{calc'd}
Emissions Test Program		
THIS WORK: AVERAGE	**56**	**11**
(RANGE	**39 - 95**	**5 - 22)**

Significance of Emission Factor Measurements

Emission factors are key element in inventory development and can be significant source of uncertainty

Measured factors for N are reasonably consistent with literature data:

1) if these data are representative, existing factors may be high
2) measured factors appropriate to "underway" conditions: med.-high load
3) N emissions drop significantly for idle conditions: need data here

Measured S emission factors seem low, but need fuel S content information

Particulate emission factors?

Particulate Sulfate Emissions

Plume transit time of 20-30 minutes implies conversion rate >10% per hour, but "typical" heterogeneous conversion rates for SO_2 are 0.5 - 2% per hour.

Possible fast sulfate production: 1) excess O_2 in exhaust and SO_3 chemistry
2) catalyzed SO_2 conversion on particles

Plans for NEAQS 2004

- **Improvements to instruments:**
  - New fast-response CO instrument
  - Improved SO_2 instrument response

- **Ship-plume studies:**
  - Successive downwind intercepts to evaluate chemistry: aging; dispersion
  - Targets of opportunity: emission factors
  - Smaller vessels: high CO, NO_x; no SO_2

Conclusions

- **Ship-based measurements are an effective means of evaluating emissions of marine vessels under operating conditions**
- **Characteristics of individual vessels readily apparent**
- **"Under-way" emission factor measurements are reasonably consistent with literature data**
- **More data needed at different load conditions (in 2004!): slow speed; idle ("hotelling")**
- **Fast sulfate production/emissions in some ship plumes**