PM$_{2.5}$ Impacts From Ship Emissions in the Pacific Northwest

Robert Kotchenruther Ph.D.
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Why look at ship emissions?

Human Health & Ecosystem Concerns

- Health studies have shown that there is no known lower-bound or "safe" exposure threshold for PM.

- Ship emissions not only affect urban areas (near ports), but also rural & remote areas that are predominantly thought of as 'clean'.

- Ship emissions are predicted to cause 8,100-21,000 cases of premature mortality annually in US and Canada, 8.9 Million annual cases of acute repertory symptoms.

- Many ocean going ships burn residual fuel oil -- emissions are very dirty: rich in sulfur, metals, and toxics.
  - Sulfur emissions are linked to acid deposition, climate effects, and possible ecosystem impacts.
  - Marine diesel engines are enriched in smaller particles over other engine PM emissions. Thus, can be longer lived and have greater health impact.

Why look at ship emissions?
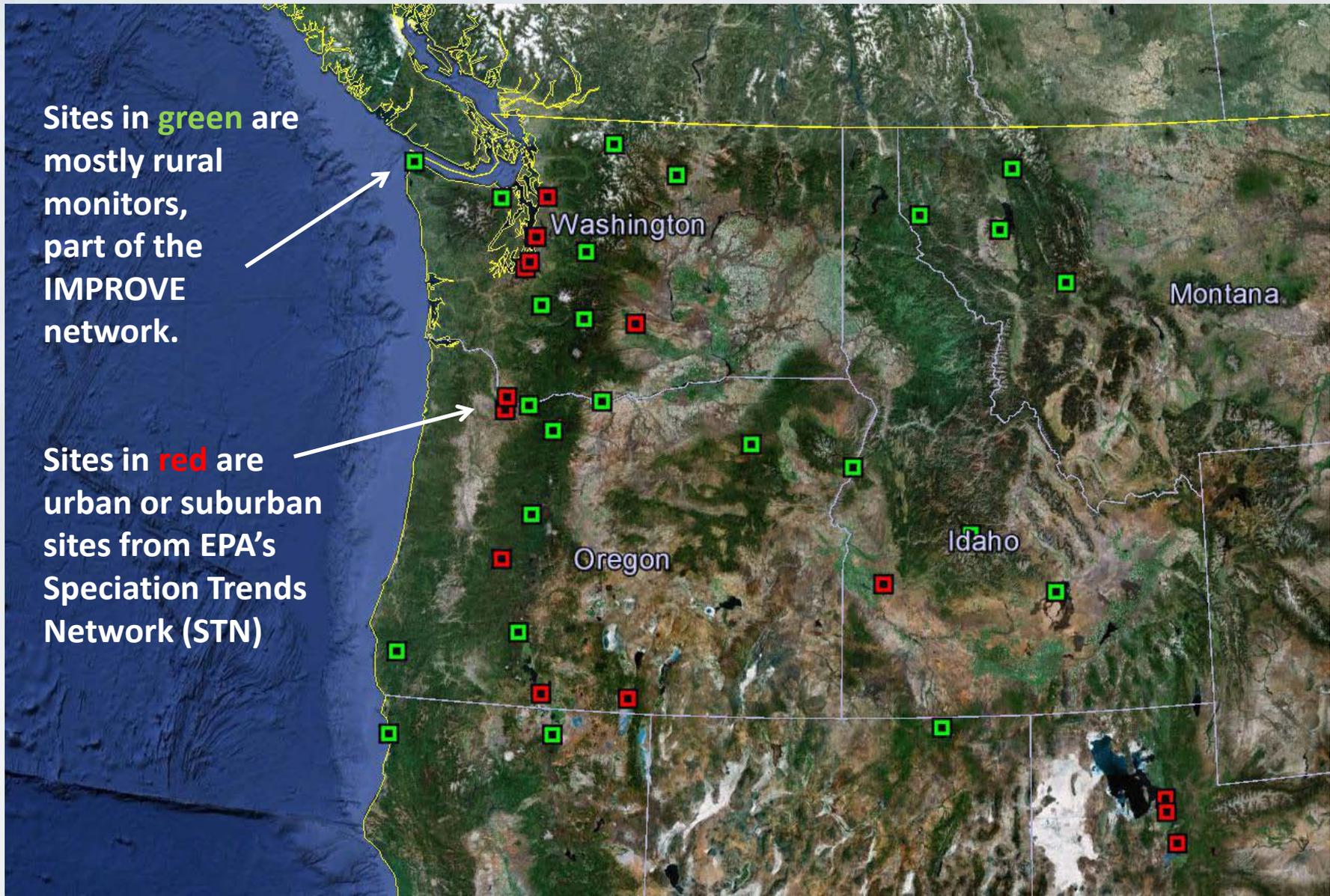

Tracking emissions reductions

In 2008 the International Maritime Organization (IMO) agreed to include North America into an Emissions Control Area (ECA)

- **Becomes effective August 2012 (currently voluntary)**

- **Emissions must be controlled within 200 nautical miles of coast.**
    - ➢ **2012 - 2015 fuel sulfur content no higher than 10,000 ppm (1%)**
        - **- outside ECA limit is 35,000 ppm (3.5%) fuel sulfur content**
    - ➢ **2015 & onwards fuel sulfur content no higher than 1000 ppm (0.1%)**
        - **- estimated to reduce SOx and PM2.5 emissions by 86% & 74%, respectively**
    - ➢ **2016 & onwards NOx controls**

A current real-world impact analysis can help set a baseline to track the effects of upcoming ship emissions reductions.

Monitoring sites analyzed for shipping impacts.

Data from 39 urban and rural PM2.5 monitoring sites was analyzed.

Sites in green are mostly rural monitors, part of the IMPROVE network.

Sites in red are urban or suburban sites from EPA's Speciation Trends Network (STN)

Washington
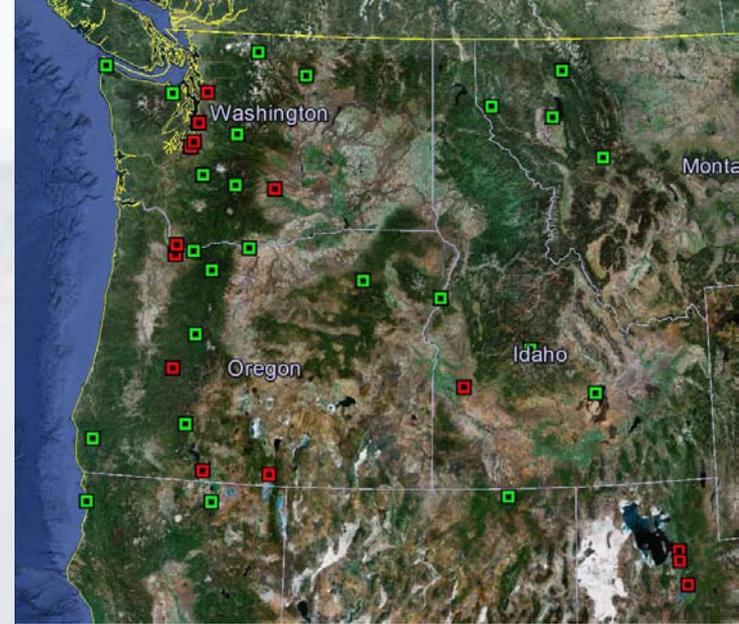
Montana

Oregon

Idaho

Kinds of data that were used

These sites were chosen because they chemically speciate the PM2.5.

These sites monitored for total PM2.5 and then chemically speciated the PM2.5 into 31 components including:

  sulfate & nitrate organic carbon
  elemental carbon Na, Cl
  soil components (Al, Ca, Fe, Ti, Si)
  & trace metals (Ni, V, K, Mg, etc.)

More details:

-> all measurements were 24-hour average PM2.5.

**-> time period was Jan 2007 – Sept 2011,
(or subset depending on data availability and monitor activity)**

-> number of samples ranged from ~90 to ~550, depending on the site.

How was Marine Shipping Identified?

Most ocean going vessels burn residual fuel oil (bunker fuel).
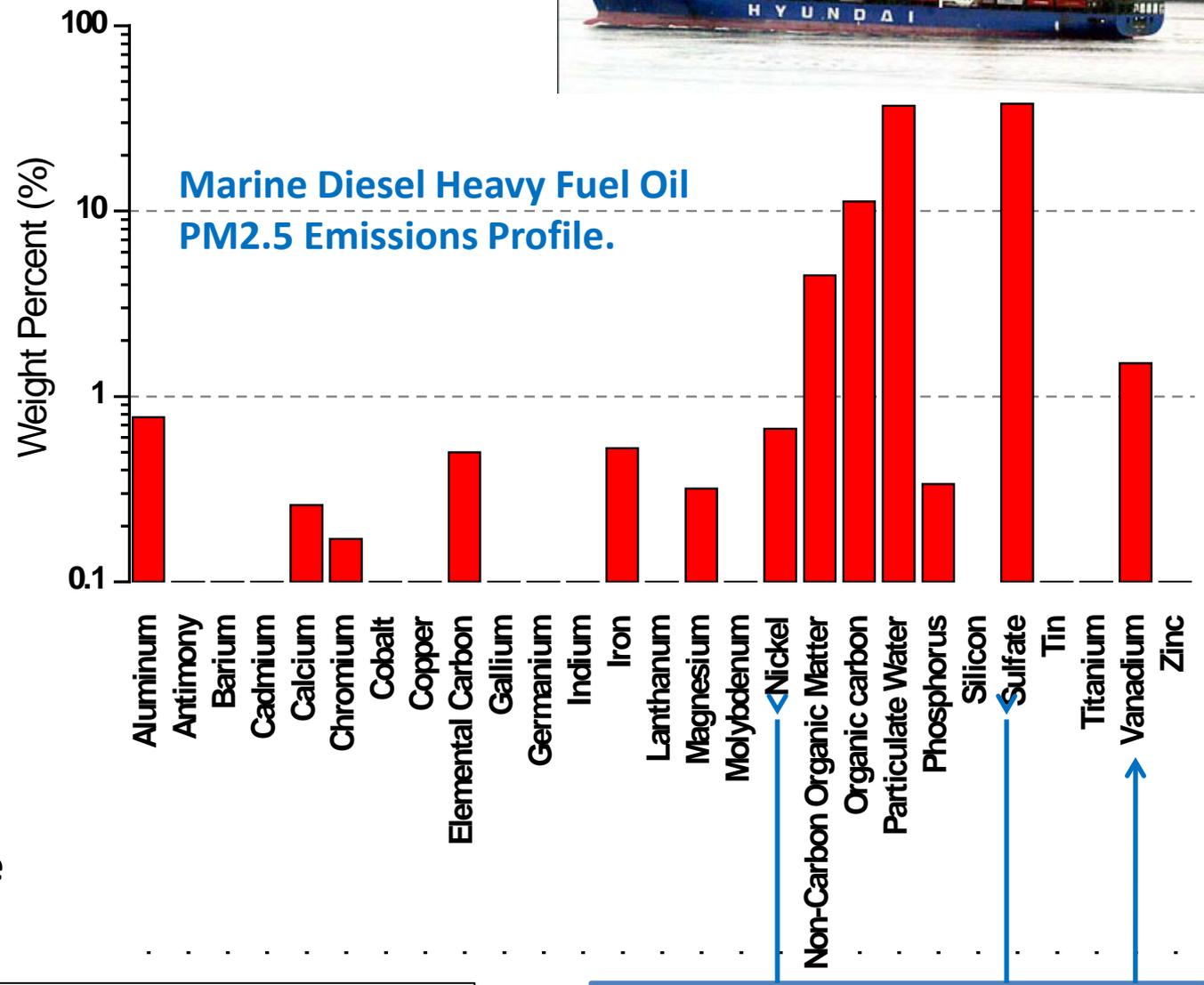
Key features:

Particle Emissions
- **High sulfate (~40%)**
- **High V + Ni (~2%)**
- **V:Ni ~3:1 ratio**

Gas Emissions
- **SO2 & NOx**

Downwind:
Expect V:Ni ratio to be maintained.

Marine Diesel Heavy Fuel Oil PM2.5 Emissions Profile.

Weight Percent (%) vs elements: Aluminum, Antimony, Barium, Cadmium, Calcium, Chromium, Cobalt, Copper, Elemental Carbon, Gallium, Germanium, Indium, Iron, Lanthanum, Magnesium, Molybdenum, Nickel, Non-Carbon Organic Matter, Organic carbon, Particulate Water, Phosphorus, Silicon, Sulfate, Tin, Titanium, Vanadium, Zinc

Source: EPA Speciate v4.3

Key Species: Sulfate & V:Ni ~3:1

How was shipping emissions isolated from other pollution sources?

Traditionally, 'Receptor' models (aka 'source apportionment' models) have been used to estimate source contributions.

The Receptor Model used here was the Positive Matrix Factorization (PMF) model.

PMF uses a mathematical/statistical approach and is a form of 'Factor Analysis' (also related to Principal Component Analysis [PCA]).

Each of the 39 monitoring sites was modeled independently.

How the model works:

The model looks for systematic patterns in the day-to-day chemical variations and quantifies a smaller set of 'factors' that can explain the overall data variability.

These model 'factors' can often be linked to aerosol sources or source categories by comparing the model factors to known source chemical emissions profiles.

How was shipping emissions isolated from other pollution sources?

Model Inputs:

For each 24-hour data sample, what was input was
- Total PM2.5 mass
- Masses for each of 31 different chemical species
  (sulfate, nitrate, OC, EC, Na, Cl, trace metals ..)

What the model outputs:

A time series PM2.5 mass from each factor. (Each factors contribution to PM2.5 on each sample day)

The chemical composition of each factor. (The percent contribution of the input chemical species to each factor's overall makeup)

14 of the 39 monitoring sites had a factor that matched residual fuel oil combustion based on V:Ni ratio and high sulfate concentration.

Modeling Results – Spatial distribution of sites indicating residual fuel oil combustion Impacts

- **14 (red dots) of the 39 sites indicated a factor linked to residual fuel oil combustion**

- **Essentially, most monitors west of the Cascade Mountain range.**

Identified from:
- **high sulfur content**

- **Vanadium (V) and Nickel (Ni) trace metal signatures**

- **V:Ni ratio, roughly 3:1**

Is this spatial extent reasonable?
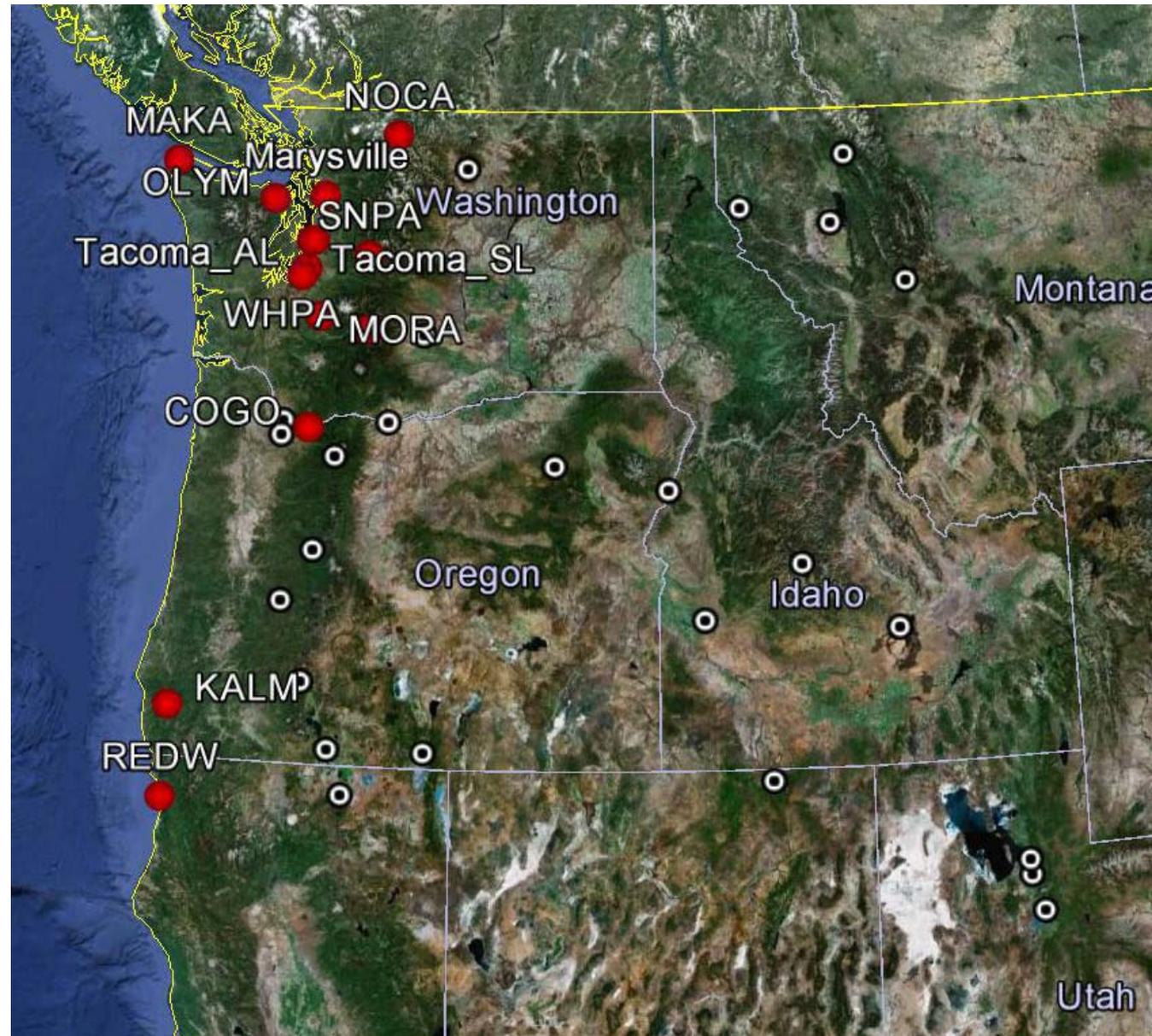
The spatial extent of Fuel Oil Combustion is similar to that of other marine aerosol: Sea Salt & Aged Sea Salt.

Sites indicating Fuel Oil Combustion (SO4, V, Ni)
(Marine Related Primary + Secondary PM)

Sites indicating Sea Salt (Na, Cl, Mg, Ca)
(Marine Related Primary PM)

Sites indicating Aged Sea Salt (Na, NO3, Mg, Ca)
(Marine Related Secondary PM)

Amount of Impact - Residual Fuel Oil Combustion PM2.5 Monthly Average Mass Impacts

Wintertime impacts likely from primarily primary PM (low rural, higher urban)

Summertime maximums likely from primary PM + secondary PM (SO2 -> SO4)

Largest impacts in urban areas (close to ports or waterways) in both winter and summer.
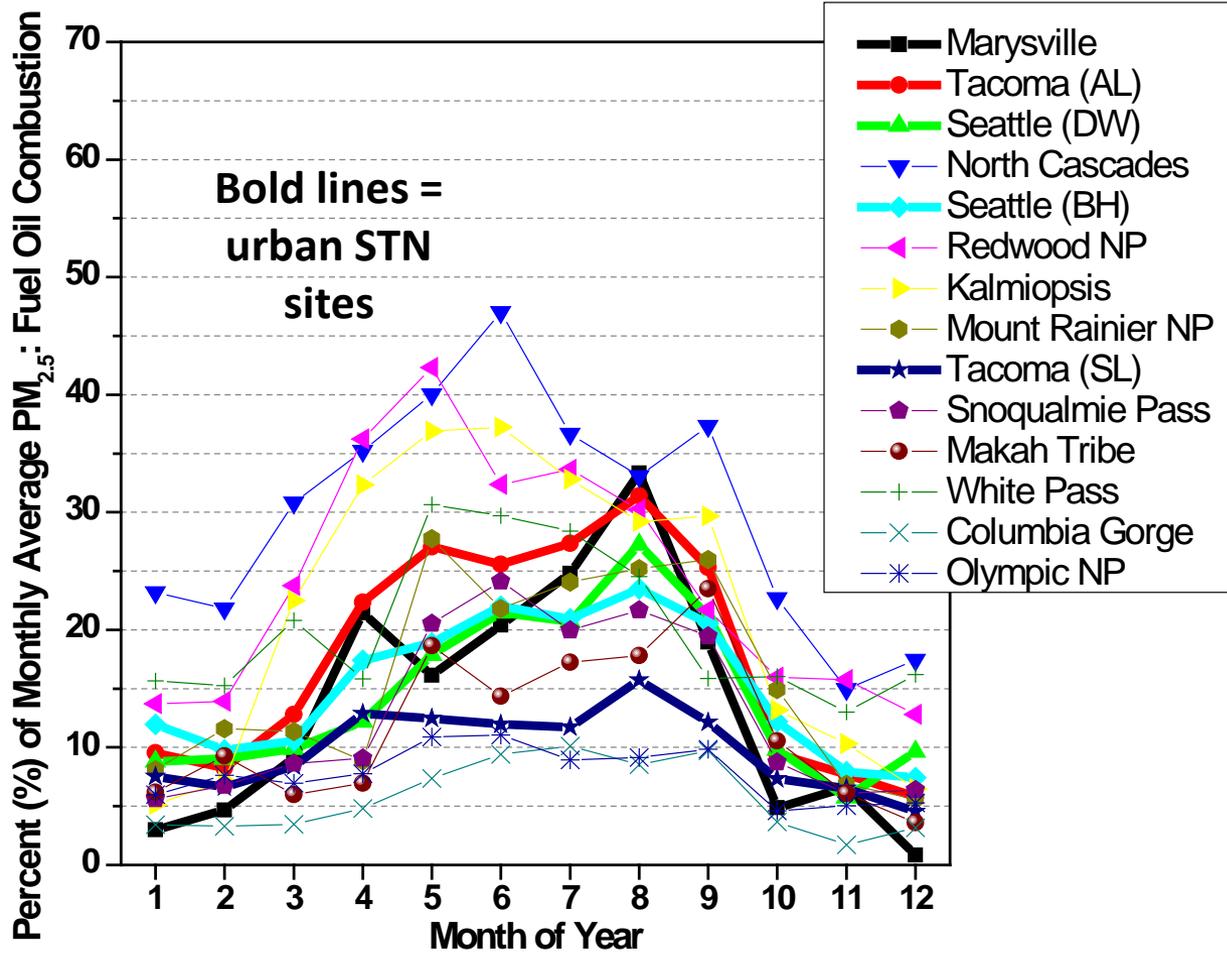
Bold lines = urban STN sites
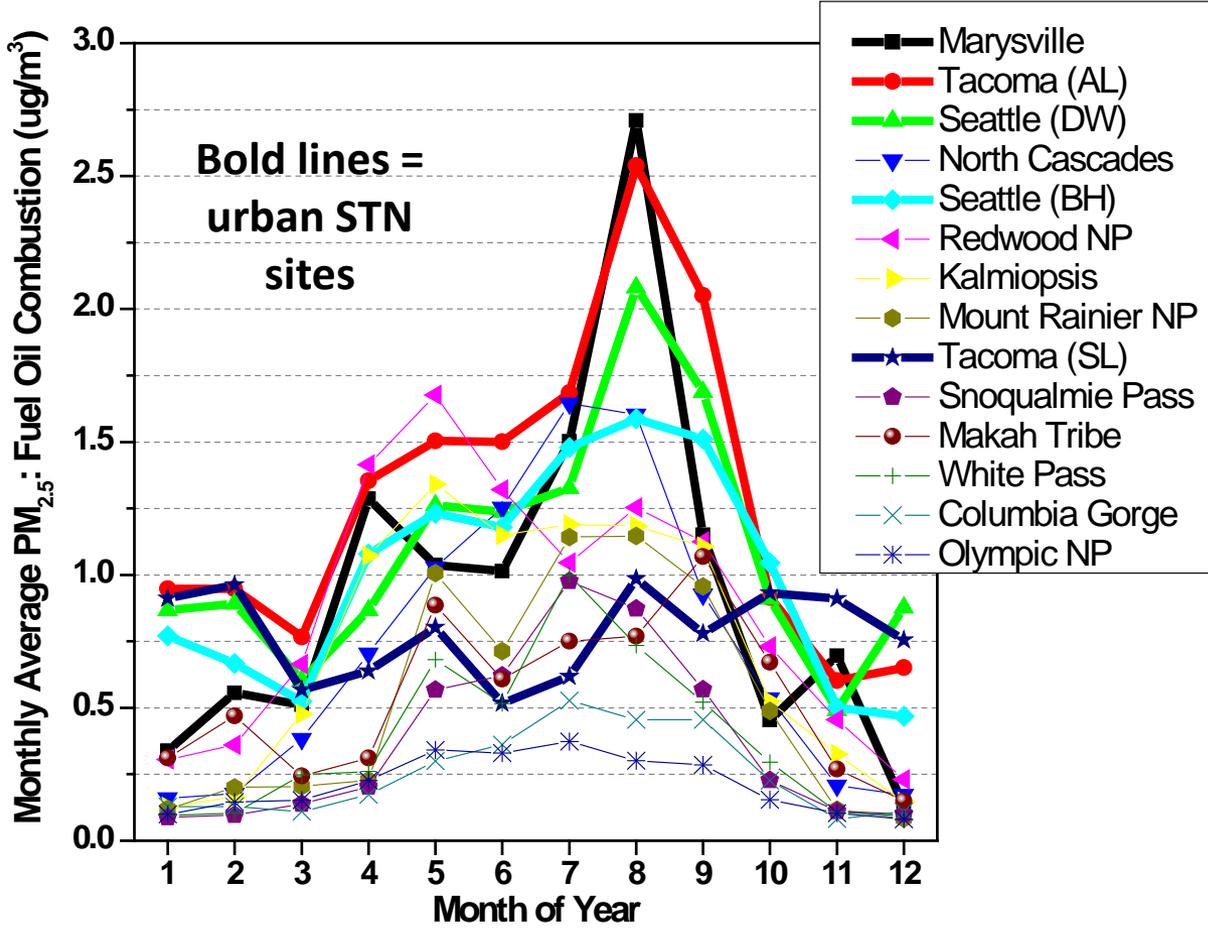
Amount of Impact - Residual Fuel Oil Combustion Impacts as a percent of monthly average PM2.5

Wintertime impacts range from 0 – 20% of average monthly PM2.5.

Summertime impacts range from 10 – 45%.

Biggest % contribution in rural sites for both winter and summer.

Summary & Conclusions:

➢ **Marine vessels burning residual fuel oil (bunker fuel) impact most PM2.5 monitoring sites west of the cascade mountains in the Pacific Northwest.**

➢ **Monthly average PM2.5 impacts range from**
    0 – 1 ug/m3 in winter and
    0.5 – 2.5 ug/m3 in summer.

➢ **Marine vessels can contribute up to**
    30% to monthly average PM2.5 in urban locations and
    up to 50% to monthly average PM2.5 in rural/remote areas.

➢ **These impacts are expected to decrease with the implementation of the North American Emissions Control Area in 2012 & 2015.**

➢ **Actual 'on the ground' PM2.5 improvements from these emissions controls can be tracked into the future through ongoing monitoring and source apportionment analyses.**

Thank you for your attention!

Questions?

Supplementary Slides

Diesel BC matters to health and to climate

- Diesels do not produce the greatest mass of BC; they may produce high numbers of small size BC particles per mass of BC emitted; ships diesels operate at HTHPs making them the "best emitters of BC numbers & small size per mass"

- People exposed to small particles have health impacts
  - We have been addressing this with a series required technologies

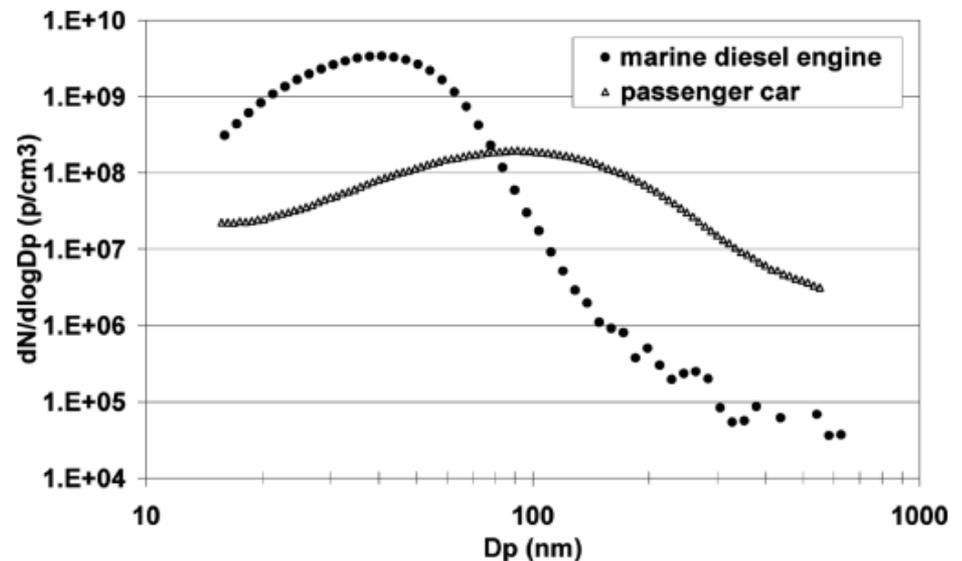- Small particles that are light-absorbing affect climate

FIG. 10. Typical number size distributions for this marine diesel engine (circles) at 100% load and a diesel passenger car (triangles) at 100% load.

Kasper, A., S. Aufdenblatten, et al. (2007). "Particulate Emissions from a Low-Speed Marine Diesel Engine." Aerosol Science and Technology **41(1): 24-32.**