

# Using PM<sub>2.5</sub> Monitoring Data to Track Pollution From Marine Vessels

## How Effective have Fuel Sulfur Regulations Been at Reducing PM<sub>2.5</sub> from Ships?

(an update to my 2015 NW-AIRQUEST talk)

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# Why regulate marine vessel fuel sulfur?



Controlling fuel sulfur is an effective means of reducing  $PM_{2.5}$  and  $SO_2$  emissions from marine vessels

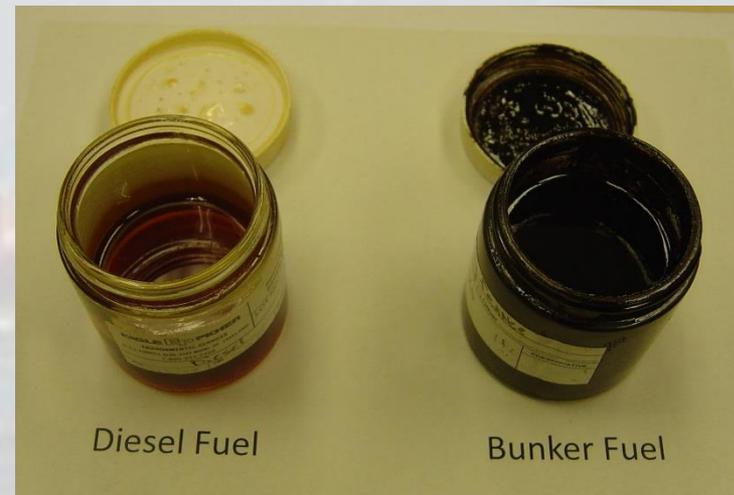
Many ocean going ships use an inexpensive, very dirty, high sulfur fuel - **residual fuel oil (bunker fuel, fuel oil No. 6)**

## Residual fuel oil

**Waste product of crude oil distillation**

**World Average ~ 2.7% sulfur  
(27,000 ppm sulfur)**

**Combustion emissions also are very rich in metals and other toxics.**



# In the U.S., there have been 2 fuel sulfur regulations effecting ocean-going ships.

★ **California Ocean-Going Vessel  
Clean Fuel Regulation:**  
24 mile coastal zone, California only



24 NM zone

## Important differences:

- Regulated off-shore distance  
**California = 24 NM**  
**NA-ECA = 200 NM**
- California mandates the use of distillates  
**NA-ECA, fuel S achieved by any means**
- Implementation timelines

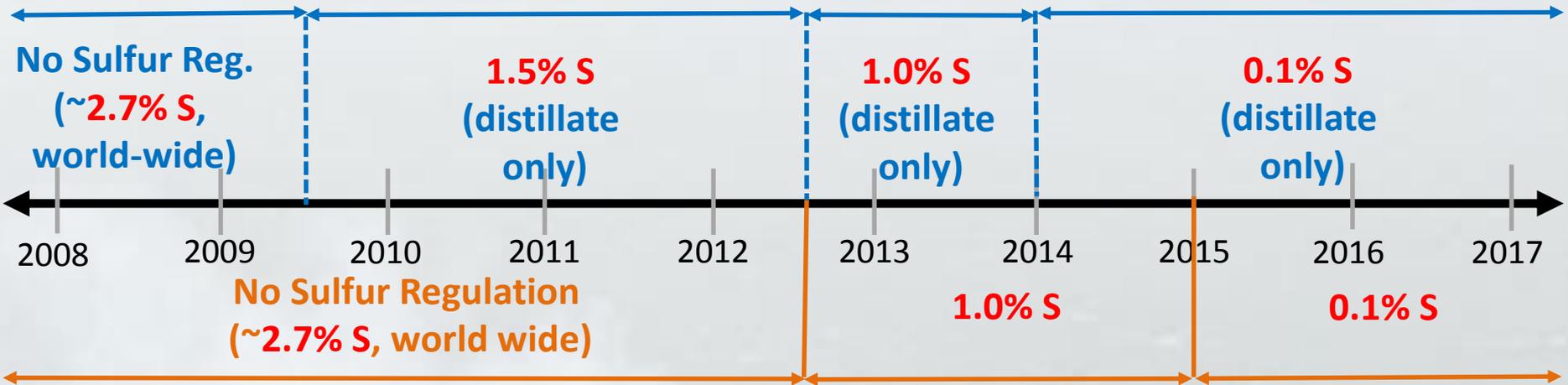
★ **North American Emissions  
Control Area (NA-ECA):**  
200 mile coastal zone, U.S. & Canada



200 NM zone

# Implementation timelines

## California Ocean-Going Vessel Clean Fuel Regulation: 24 mile coastal zone, California only

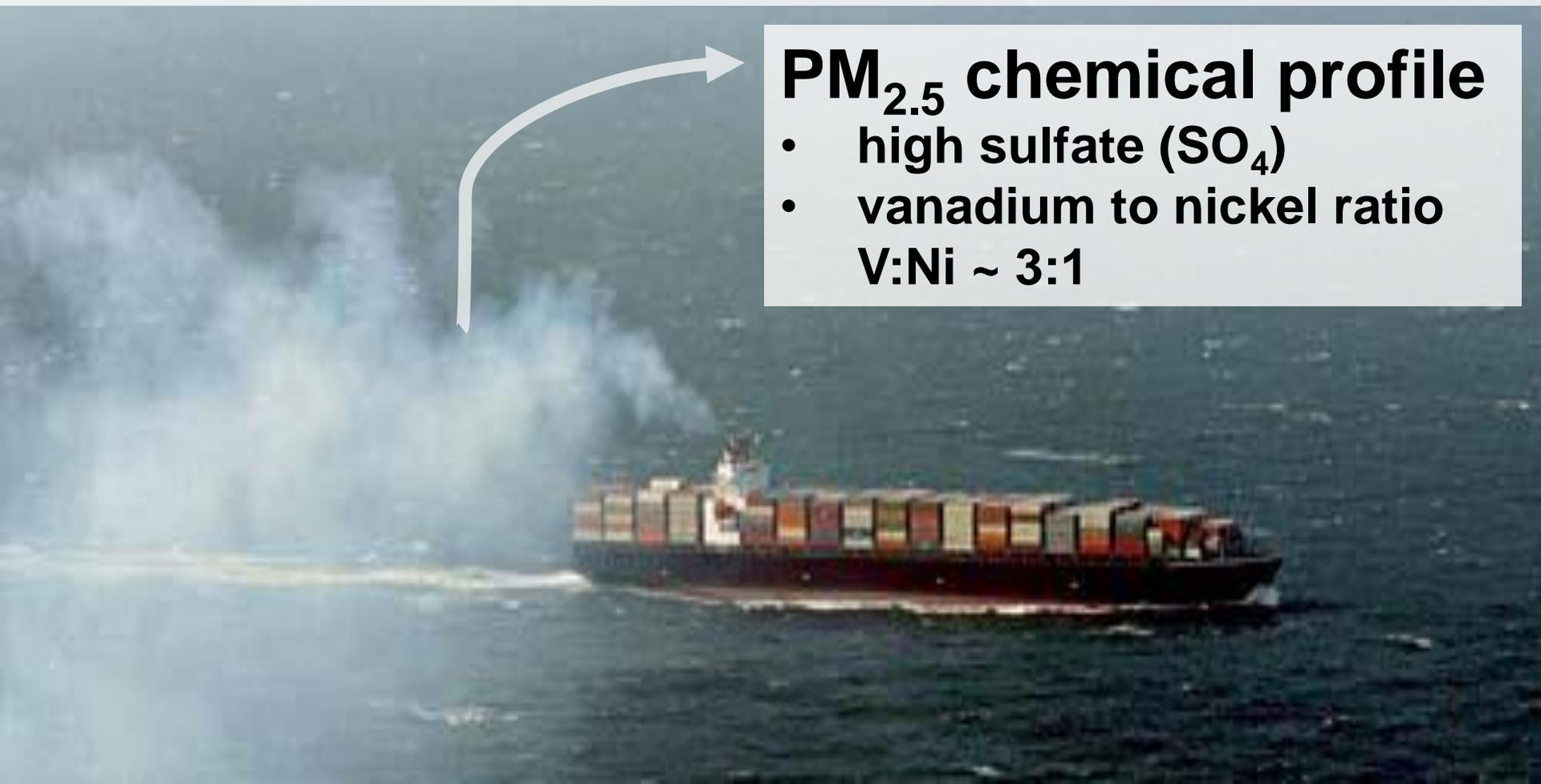


## North American Emissions Control Area (NA-ECA): 200 mile coastal zone, U.S. & Canada

Switching to lower sulfur fuels in regulation zones means that we expect there to be a reduction or elimination of residual fuel oil use in these zones.

**Can we track the amount of residual fuel oil combustion that is occurring? Yes!**

**Residual fuel oil combustion emissions have a unique chemical signature.**



**PM<sub>2.5</sub> chemical profile**

- high sulfate (SO<sub>4</sub>)
- vanadium to nickel ratio  
V:Ni ~ 3:1

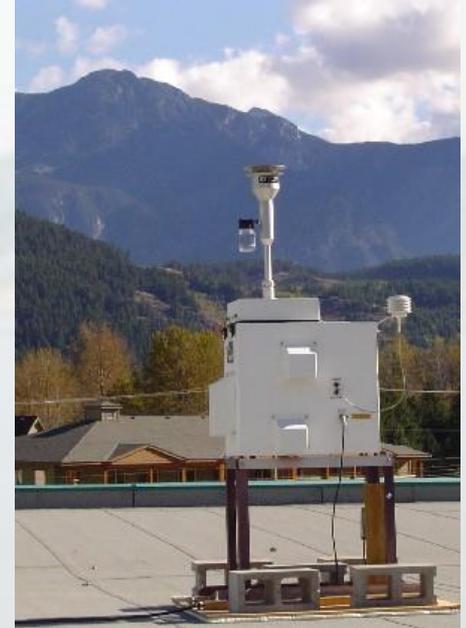
**This unique chemical signature can then be identified in ambient monitoring data.**

**We can use this to track residual fuel oil combustion impacts over time.**



# What U.S. PM<sub>2.5</sub> monitoring data are available for this analysis?

Two U.S. monitoring networks conduct the routine chemical speciation needed for this analysis.



## EPA Chemical Speciation Network

- urban - air quality tracking
- can track V and Ni, but not down to background levels (because of instrumental design and analysis methods)

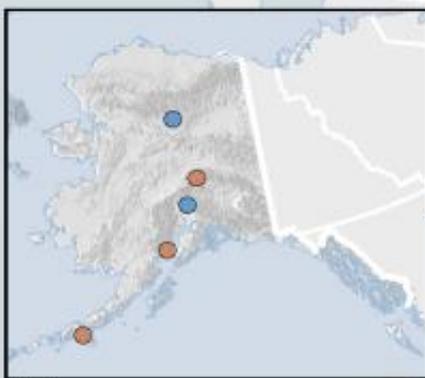
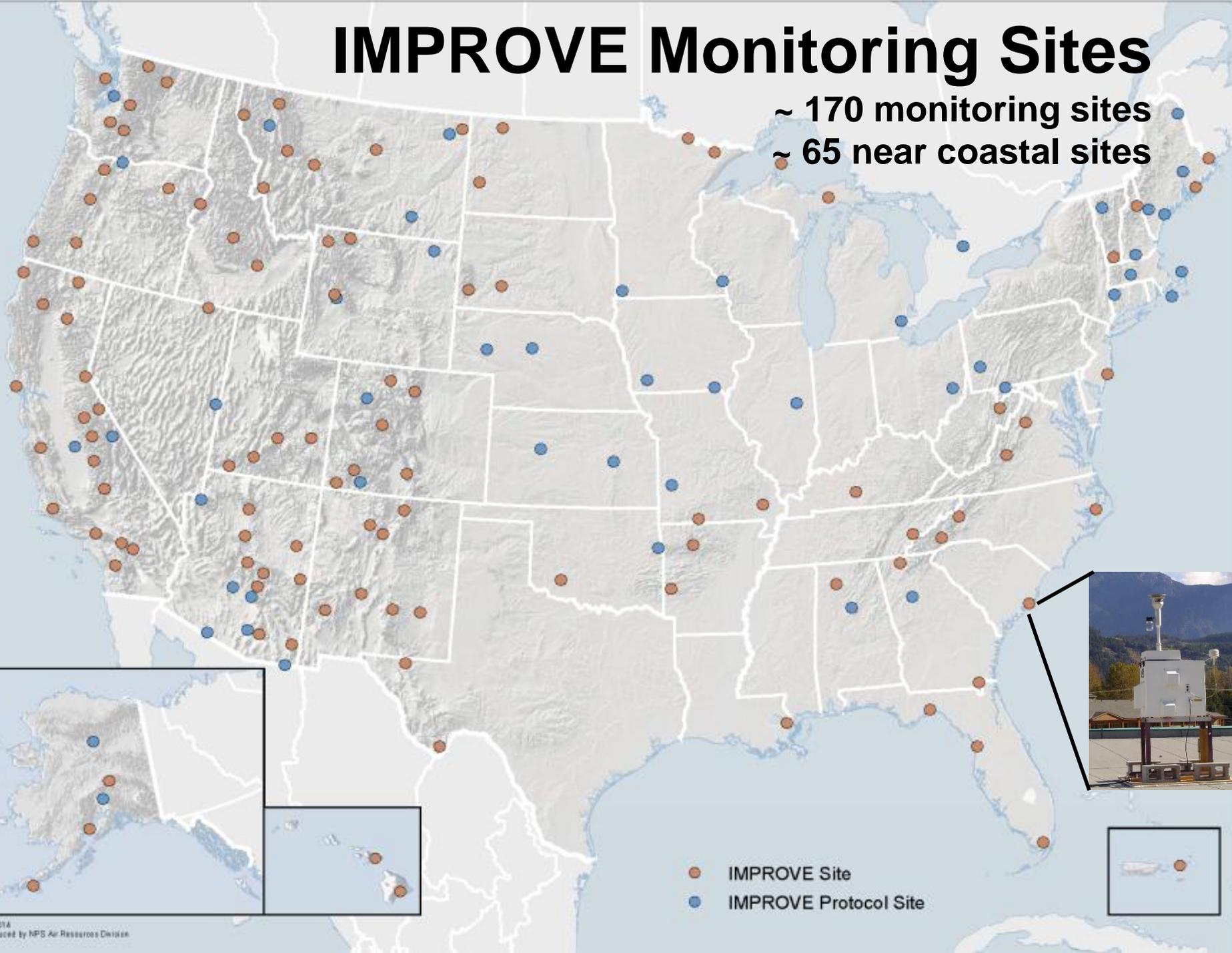
## IMPROVE Network

- Rural/remote - visibility tracking in national parks
- can track V and Ni down to natural background levels
- **best dataset for tracking residual fuel oil combustion**

# IMPROVE Monitoring Sites

~ 170 monitoring sites

~ 65 near coastal sites



Once we have the  $PM_{2.5}$  data, how can residual fuel oil use be isolated from other pollution sources?

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

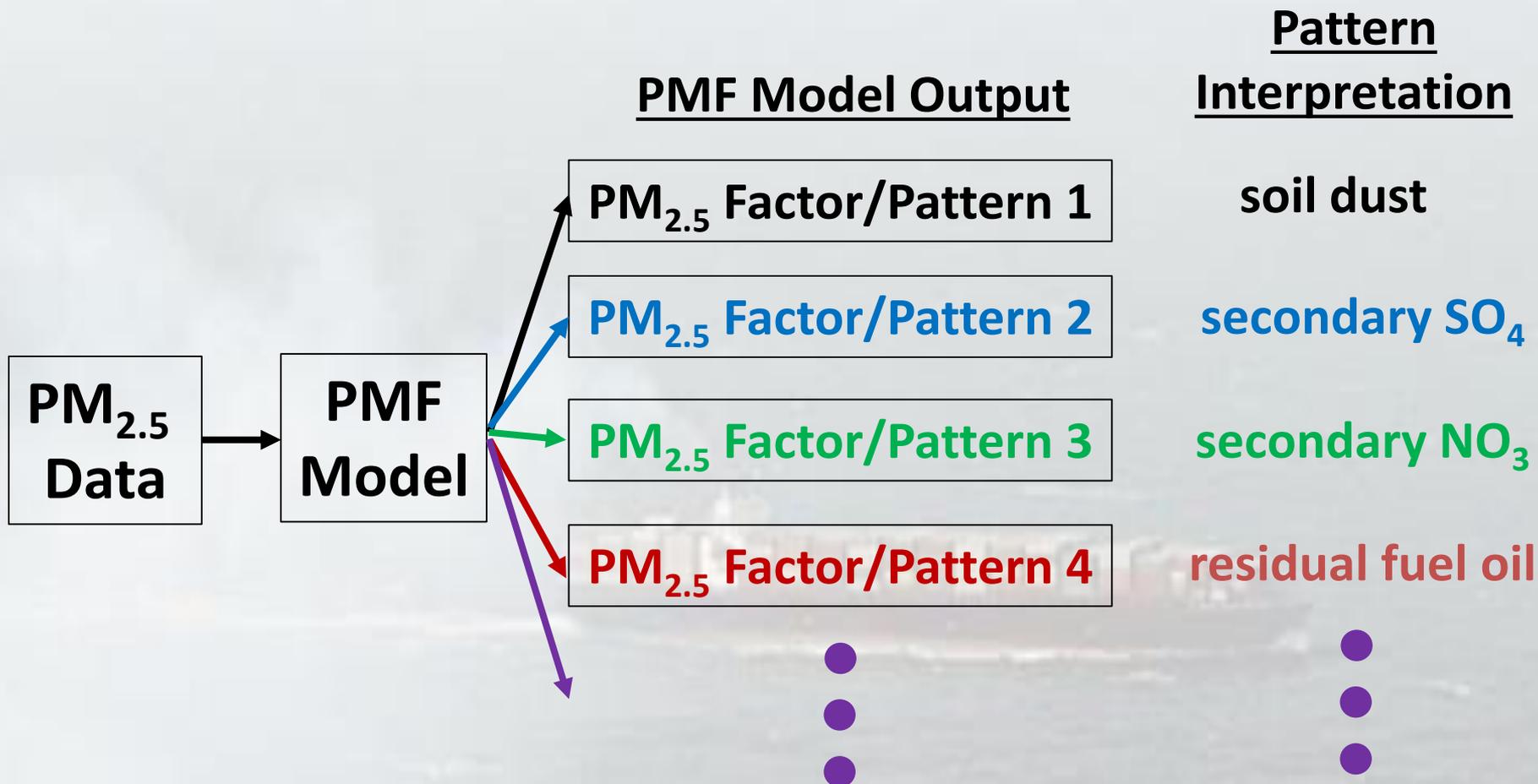
These mathematical/statistical models known by many names:

- pattern recognition models
- factor analysis
- principal component analysis
- multivariate analyses

The model used to isolate residual fuel oil combustion was the EPA Positive Matrix Factorization (PMF) model.

# How does the PMF source apportionment model work?

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.



# To select sites for PMF analysis

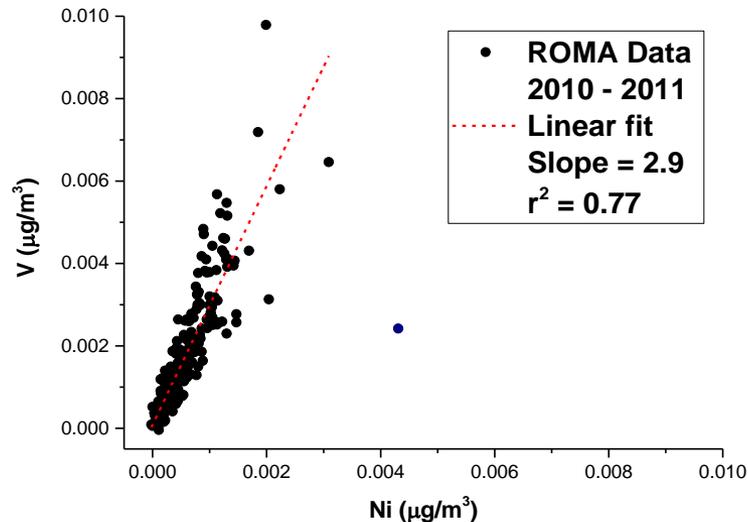
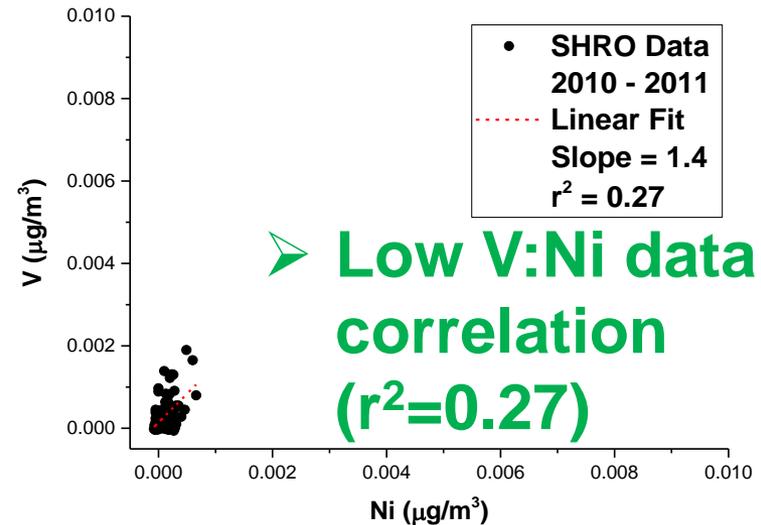
- 65 coastal IMPROVE sites were initially screened
- looked at V and Ni data from 2010 – 2011 (pre-ECA)



# Sites that had high V & Ni correlation were chosen

## Example comparing V:Ni data between two sites

- High V:Ni data correlation ( $r^2=0.77$ )
- V:Ni Slope (2.9) similar to V:Ni ratio in residual fuel oil combustion



The results was that **22 sites** were identified having a high V:Ni linear correlations (**blue diamonds in map,  $r^2 > 0.65$** ). These sites were chosen for PMF source apportionment.



## PMF source apportionment isn't perfect.

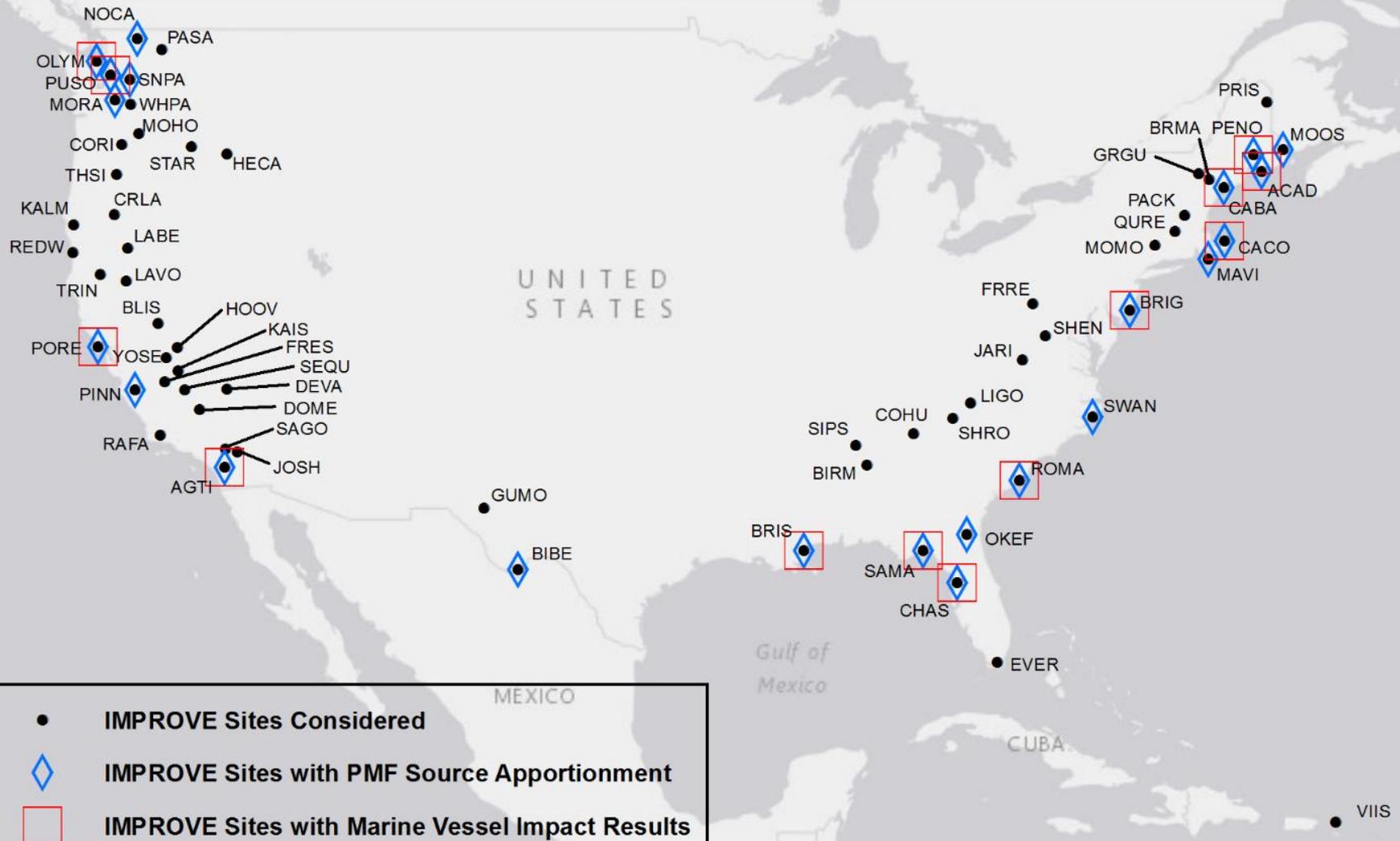
### PMF Factors/Patterns can represent

- a single source or source category  
Example: residual fuel oil combustion  
biomass combustion
- a chemical composition  
Example: secondary ammonium nitrate ( $\text{NH}_4\text{NO}_3$ )  
sea salt ( $\text{NaCl}$ )
- a mixture of sources and compositions

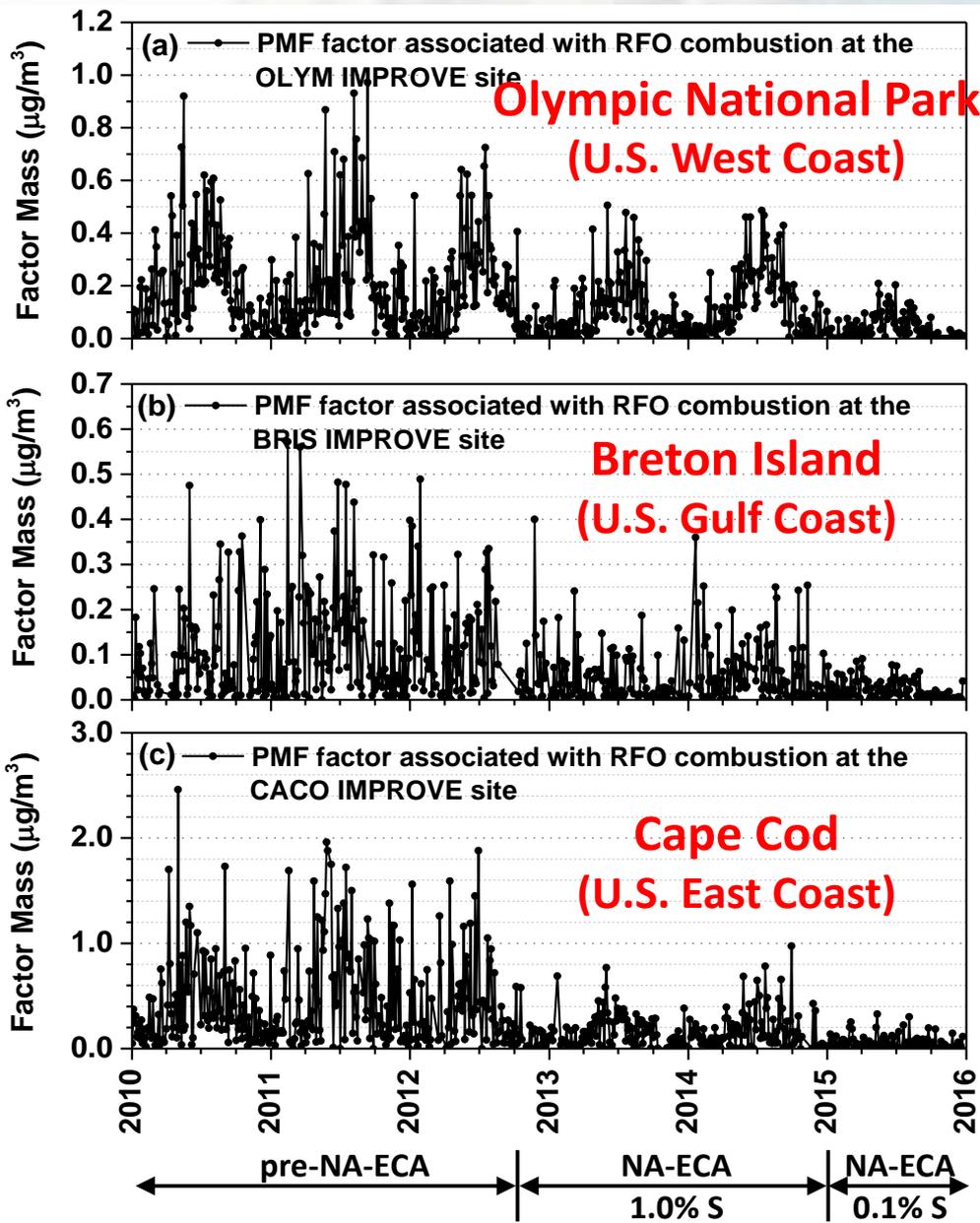
For this analysis, all 22 sites had a factor containing residual fuel oil (RFO) combustion.

But ...            9 sites had Factors with RFO mixed with other sources  
13 sites had Factors that were just RFO

At the **13 sites** identified with **red boxes**, PMF analysis isolated the  $PM_{2.5}$  from residual fuel oil combustion, from other sources. **4 west coast, 3 gulf coast, 6 east coast sites.**



# Examples: PM<sub>2.5</sub> from residual fuel oil combustion at 3 sites



Annual average PM<sub>2.5</sub> from residual fuel oil combustion (μg/m<sup>3</sup>)

**0.205**      **0.119**      **0.039**

**0.108**      **0.051**      **0.021**

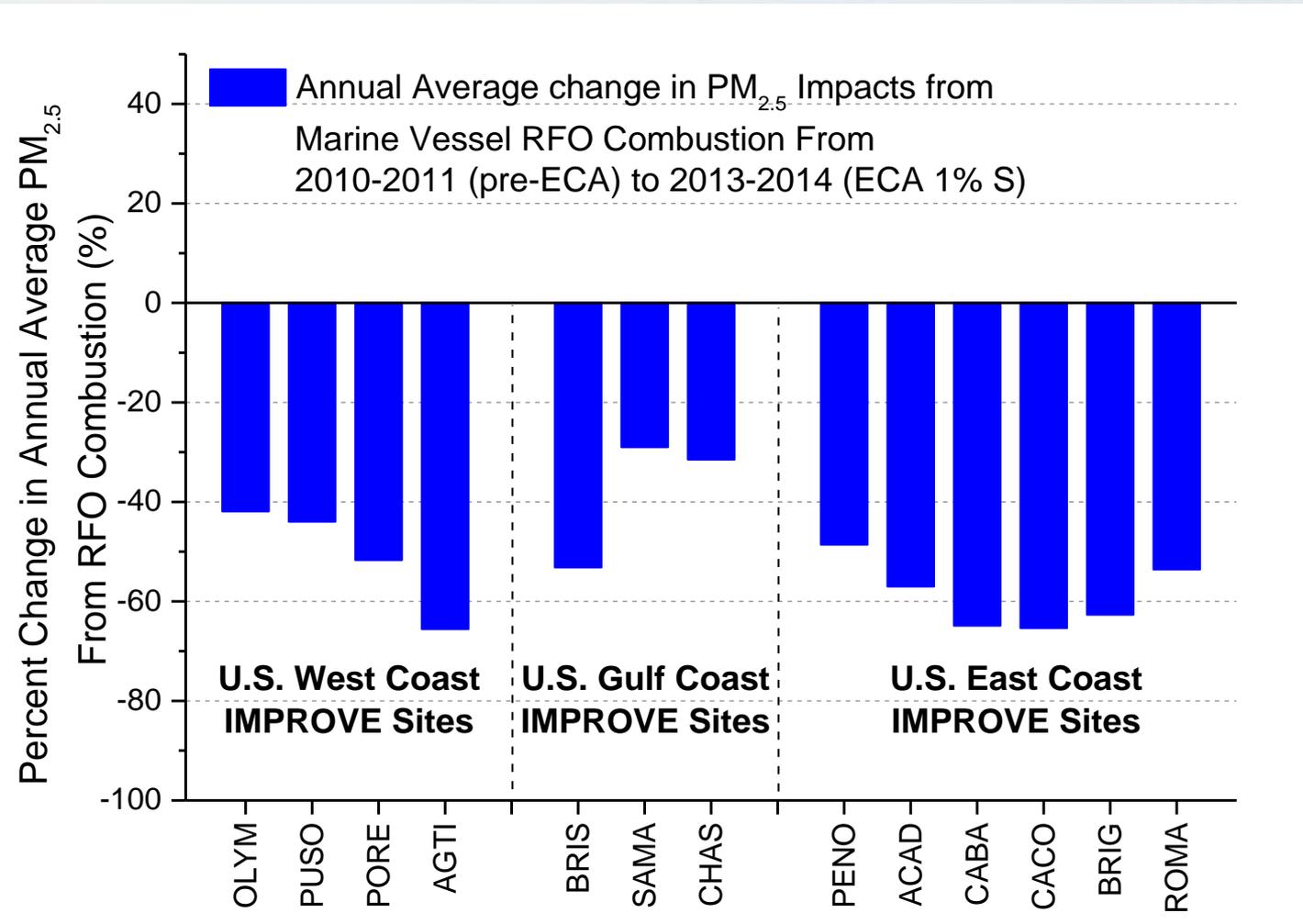
**0.459**      **0.159**      **0.053**

**pre-ECA**      **ECA 1.0% S**      **ECA 0.1% S**  
**2011-2012**      **2013-2014**      **2015**

# Results for all 13 sites

## Percent change in PM<sub>2.5</sub> impacts from residual fuel oil combustion: **pre-ECA to 1.0% S periods**

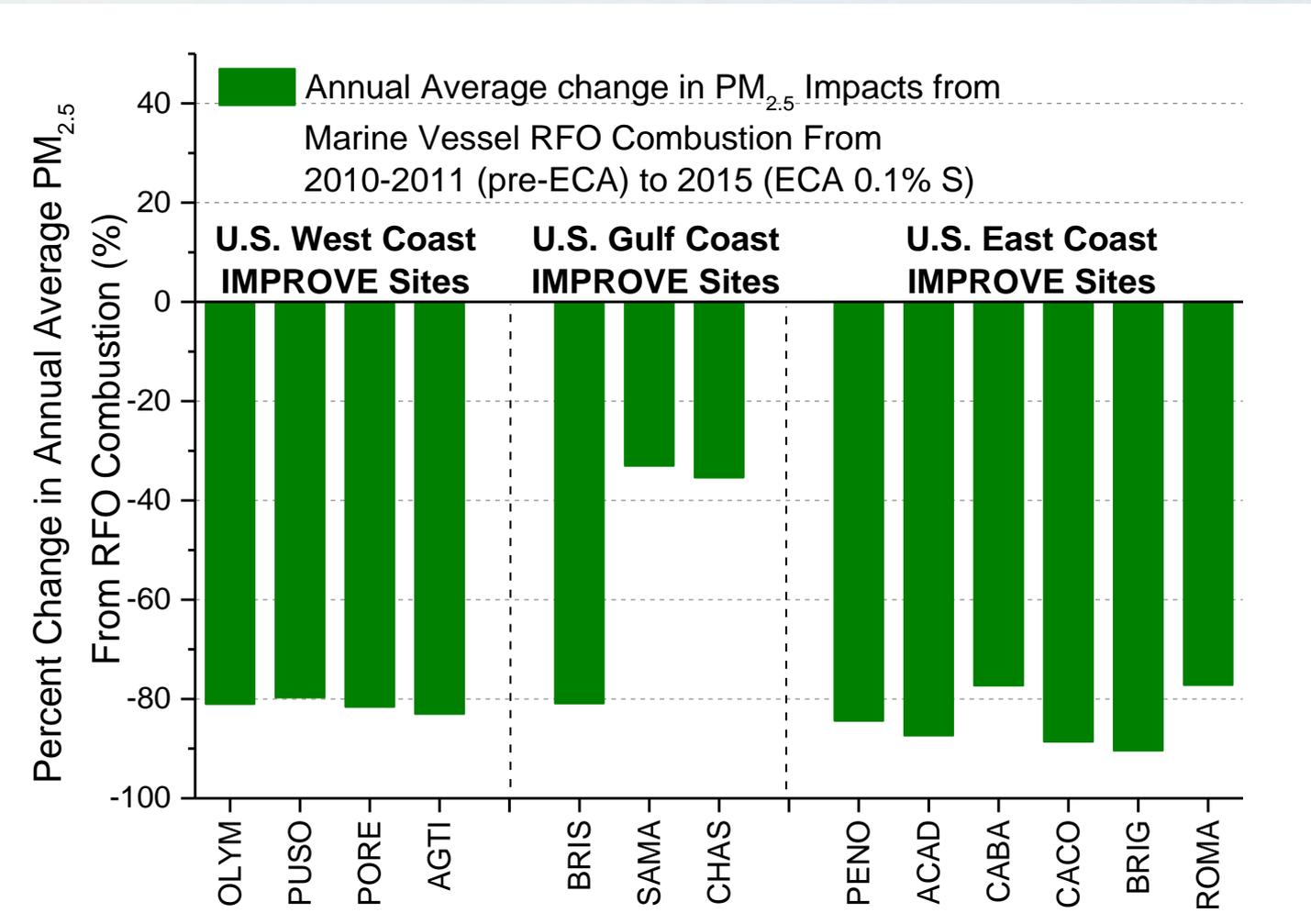
Average PM<sub>2.5</sub> reductions from RFO combustion were 51.5% overall (50.2% excluding CA sites)



# Results for all 13 sites

## Percent change in PM<sub>2.5</sub> impacts from residual fuel oil combustion: **pre-ECA to 0.1% S periods**

Average PM<sub>2.5</sub> reductions from RFO combustion were 75.4% overall (74.1% excluding CA sites)



## **Limitations:**

- **PM<sub>2.5</sub> reductions shown in this analysis may be mostly associated with primary emissions reductions.**
- **Combusting lower sulfur fuel also leads to reduced SO<sub>2</sub> emissions, and lower PM<sub>2.5</sub> from secondary sulfate.**
- **This analysis may not account fully for reductions in secondary PM<sub>2.5</sub> associated with the fuel sulfur regulations.**

## Conclusions and findings:

- Marine vessel  $PM_{2.5}$  from residual fuel oil combustion can be tracked using chemically speciated  $PM_{2.5}$  monitoring data coupled with source apportionment analysis.
- Implementation of the first ECA period, uncontrolled to 1.0% fuel sulfur, resulted in a average decrease in  $PM_{2.5}$  impacts from residual fuel oil combustion of 50.2%.
- Implementation of the second ECA period, uncontrolled to 0.1% fuel sulfur, resulted in a average decrease in  $PM_{2.5}$  impacts from residual fuel oil combustion of 74.1%.

## What's next?

- The International Maritime Organization has set a world-wide fuel sulfur limit of 0.5% S starting in 2020.

## **This work:**

- **Kotchenruther, R.A., *The effects of marine vessel fuel sulfur regulations on ambient PM<sub>2.5</sub> at coastal and near coastal monitoring sites in the U.S.*, Atmospheric Environment 151, 52-61, 2017.**

## **Related publications:**

- **Kotchenruther, R.A., *A regional assessment of marine vessel PM<sub>2.5</sub> impacts in the U.S. Pacific Northwest using a receptor-based source apportionment method*, Atmospheric Environment 68, 103-111, 2013**
- **Kotchenruther, R.A., *The effects of marine vessel fuel sulfur regulations on ambient PM<sub>2.5</sub> along the west coast of the U.S.*, Atmospheric Environment 103, 121-128, 2015**



**Thank you for your attention!  
Questions?**

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# Supplemental Slides



**Possible reasons why gulf coast SAMA & CHAS sites are not seeing the same level of reduction in RFO combustion PM2.5 with implementation of ECA regulations.**

- 1. Lax compliance in that specific region? Perhaps there is a gulf region operator who is not fully on-board with ECA compliance?**
- 2. Narrowing of the ECA zone in waters SE of Florida? Perhaps unregulated emissions from these areas are impacting the Gulf sites?**
- 3. Refinery operation in the Gulf? Perhaps PM2.5 with similar V:Ni ratios as marine vessel RFO combustion are mixing with marine vessel emissions and impacting those specific Gulf sites.**

# Back-trajectory endpoint analysis.

Now the 48-hour back-trajectories are layered into the plot for 20% of days most impacted by RFO combustion.

20% highest RFO 2010 – 2011

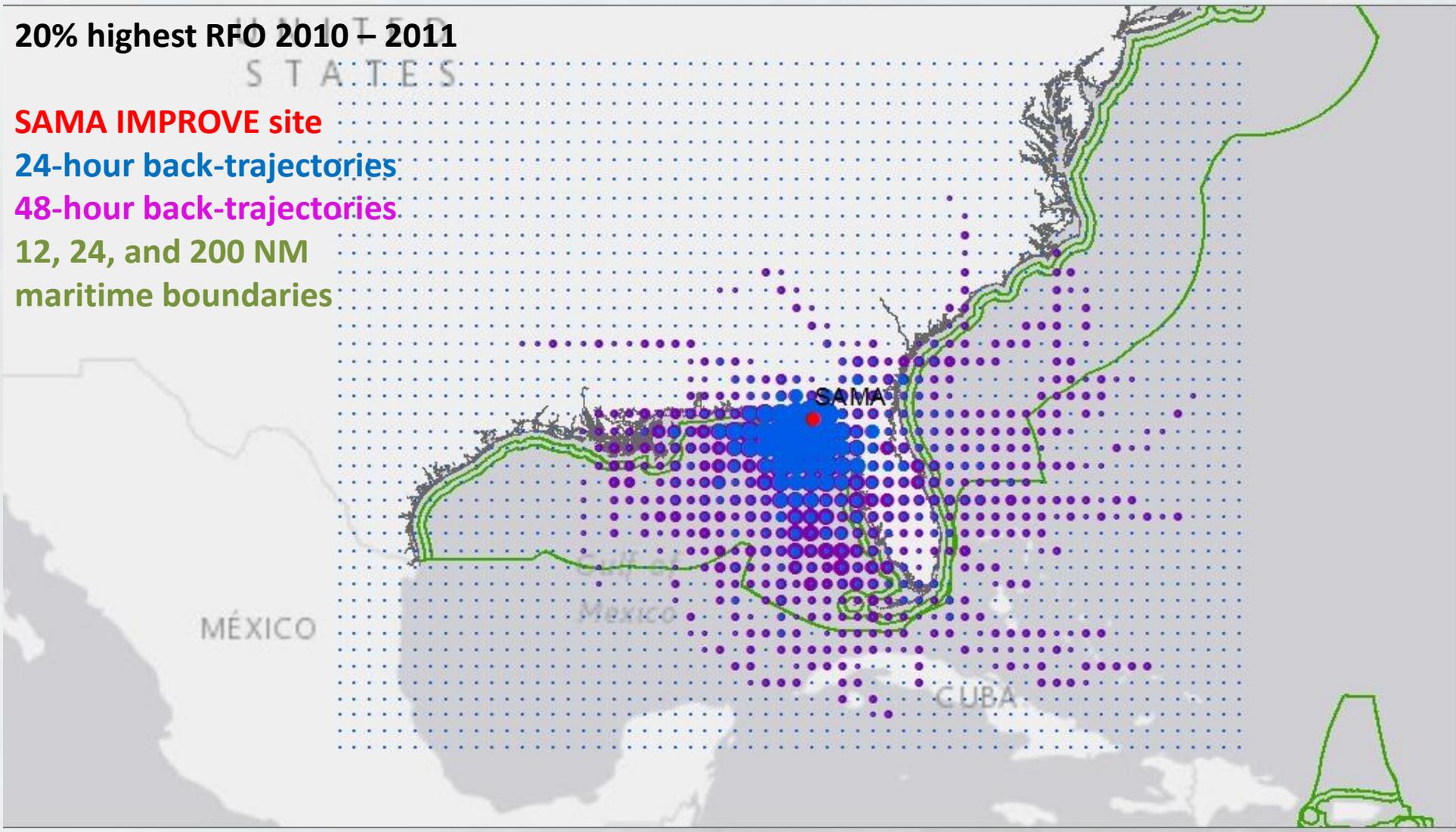
SAMA IMPROVE site

24-hour back-trajectories

48-hour back-trajectories

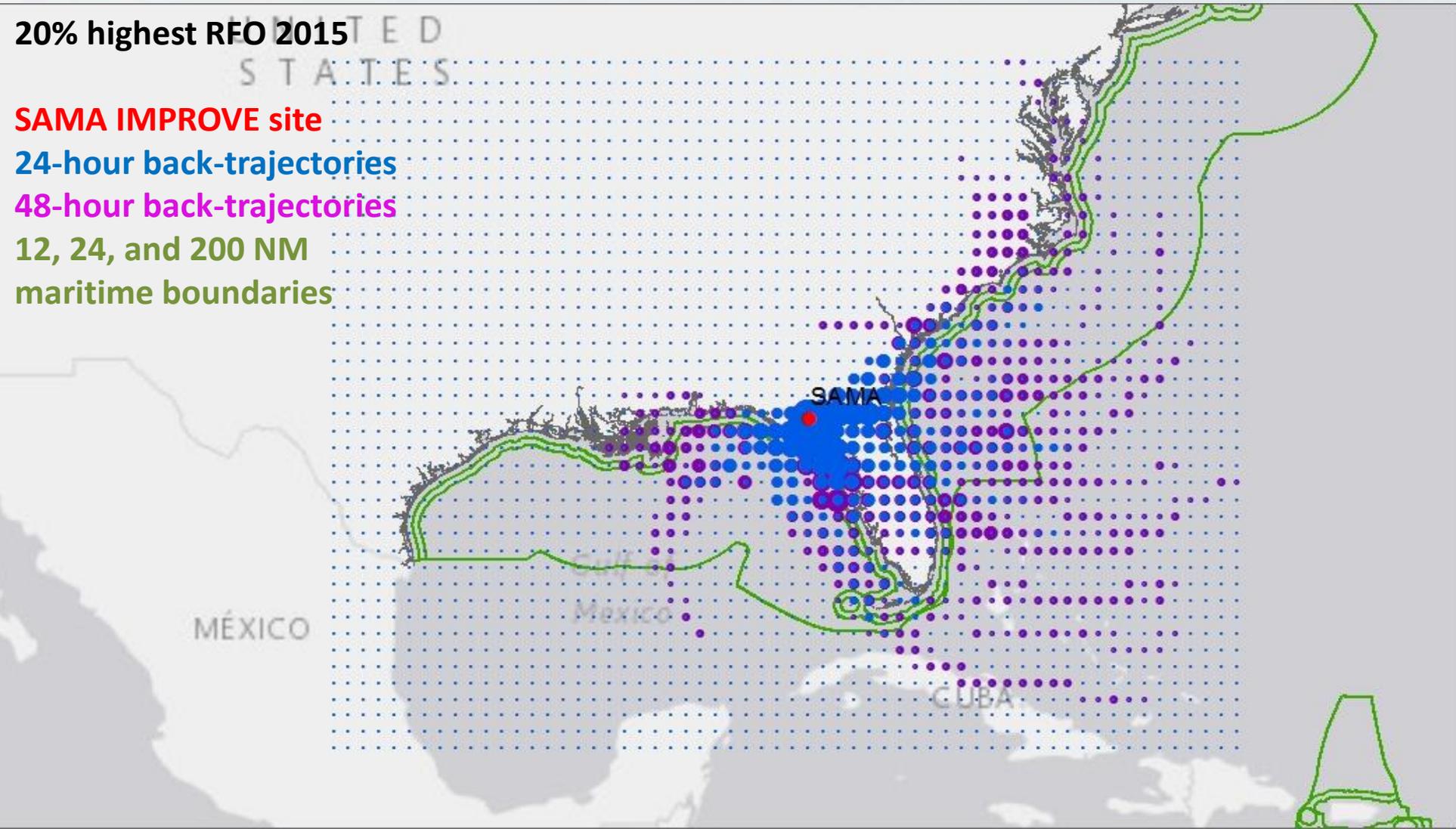
12, 24, and 200 NM

maritime boundaries



# Back-trajectory endpoint analysis.

Now showing the 24 and 48-hour back-trajectories for the 20% highest RFO impact days at SAMA in 2015.



# Back-trajectory endpoint analysis.

## Notable differences: 2015 compared to 2010-2011

- Less transport from the west, notably, from the region of oil operations.
- More transport from the east, notably, from the area near the port of Savannah.
- Less 48-hour transport from outside the ECA zone.

20% highest RFO 2015

SAMA IMPROVE site

24-hour back-trajectories

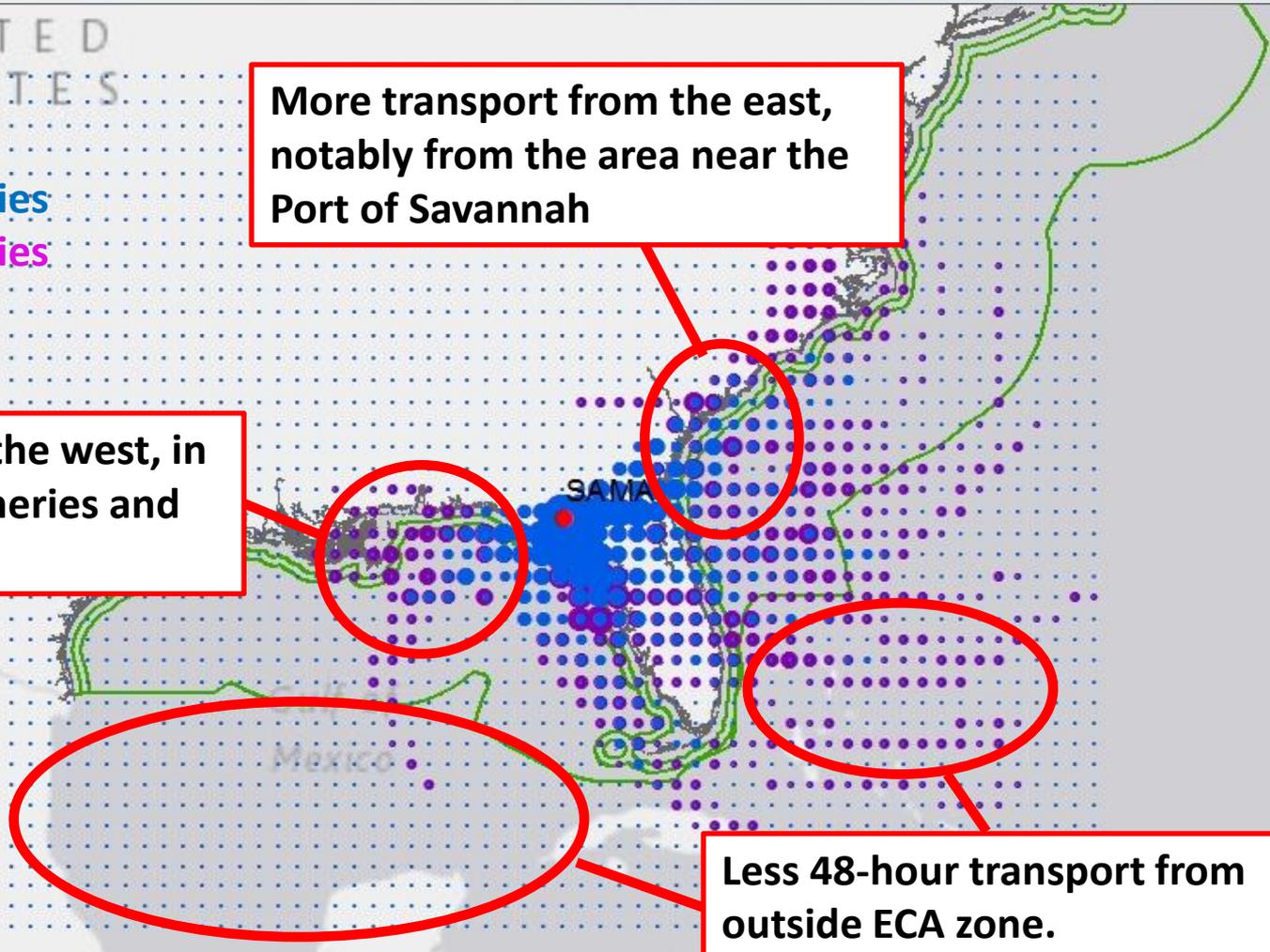
48-hour back-trajectories

12, 24, and 200 NM maritime boundaries

More transport from the east, notably from the area near the Port of Savannah

Less transport from the west, in the region of oil refineries and operations.

Less 48-hour transport from outside ECA zone.

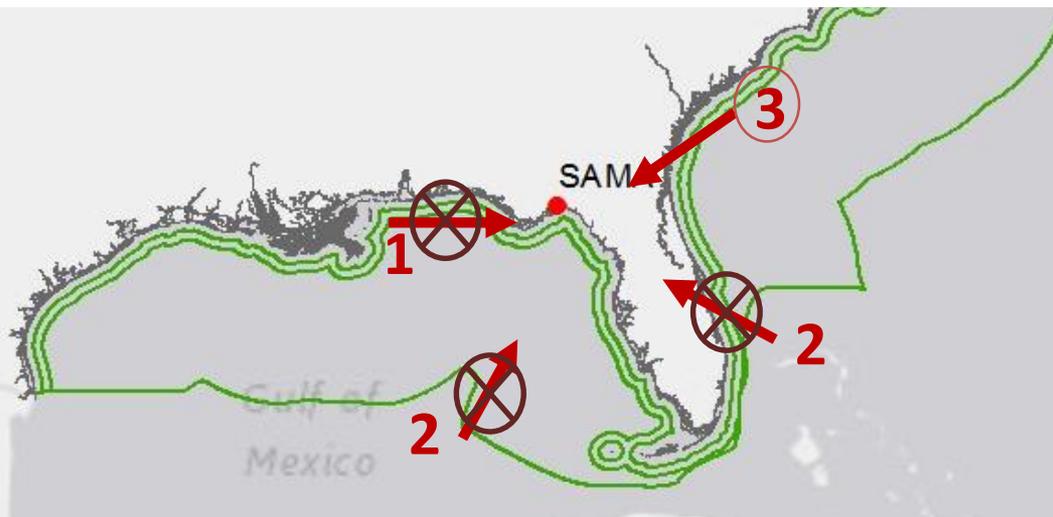


# Back-trajectory endpoint density analysis.

## Conclusions for the SAMA IMPROVE site:

Why does SAMA not see the same level of 2015 reductions as the other IMPROVE sites (besides CHAS)?

1. Less transport from the west in 2015 suggests emissions from refinery operations are not a significant reason.
2. Less 48-hour transport in 2015 from areas outside the ECA suggests transport from regions outside the ECA zone are not a significant reason.



3. More transport from the NE, a region of significant marine vessel activity around the Port of Savannah, suggests increased transport in 2015 from a high activity area may be contributing.