

US EPA ARCHIVE DOCUMENT

CHARACTERIZATION OF PARTICULATE EMISSIONS FROM SHIPS FROM IN SITU MEASUREMENTS (WITH A SPECIAL FOCUS ON BLACK CARBON)

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Why Ships?



- ca. 8% of primary organic particulate emissions from all global fossil and biofuels
- 2% of global black carbon emissions globally
- Emissions into
 - Pristine marine environments
 - Sea-ice
 - Ship tracks
 - Near large population centers (e.g. ports)
 - Estimated 60,000 premature deaths/year worldwide
- Traffic expected to increase substantially
- **Limited characterization of PM emission factors from in use vessels**

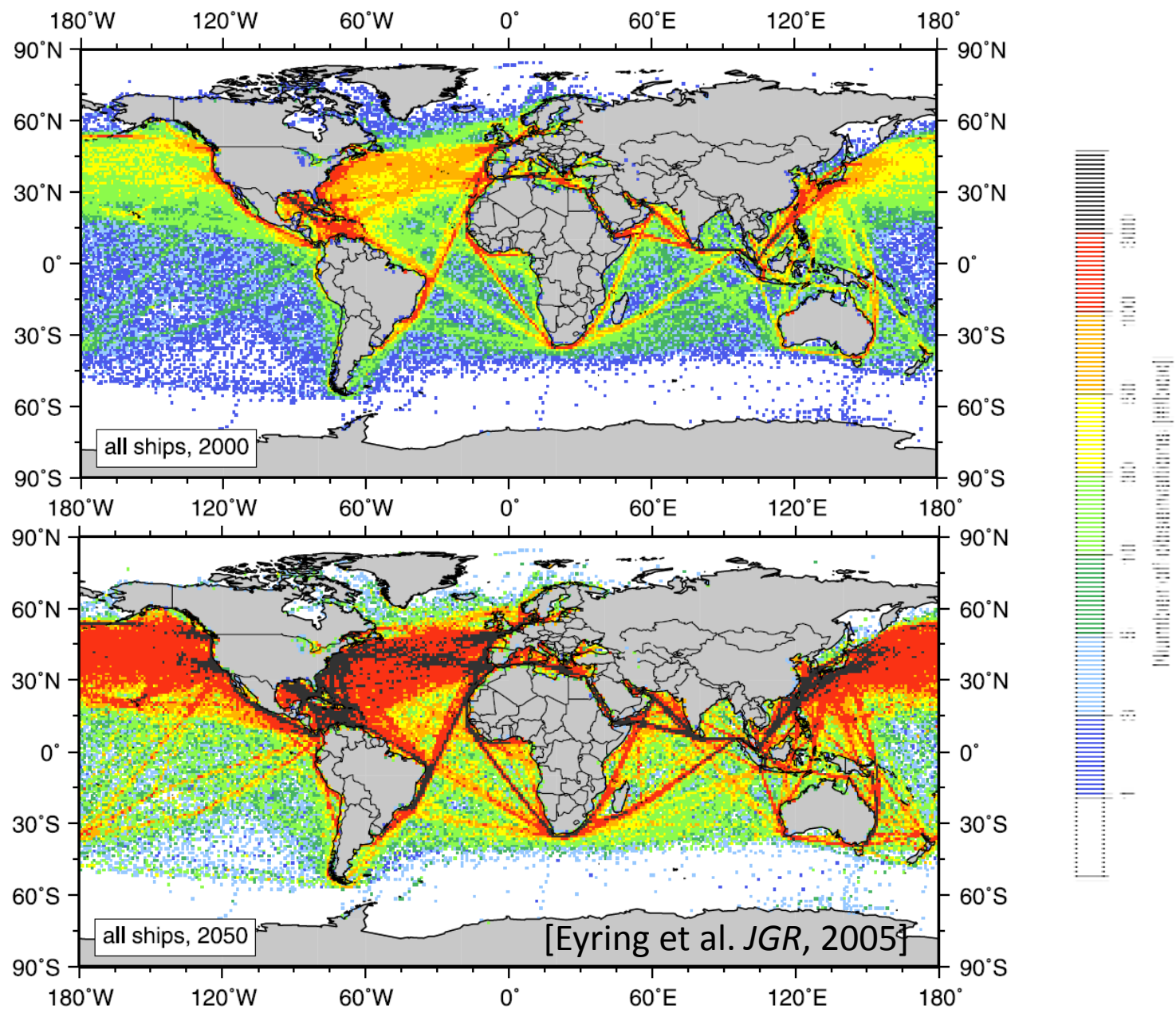
[Corbett et al., *ES&T*, 2007]

[Lack et al., *GRL*, 2008]

[Ito & Penner, *GBC*, 2005]

[Eyring et al. *JGR*, 2005]

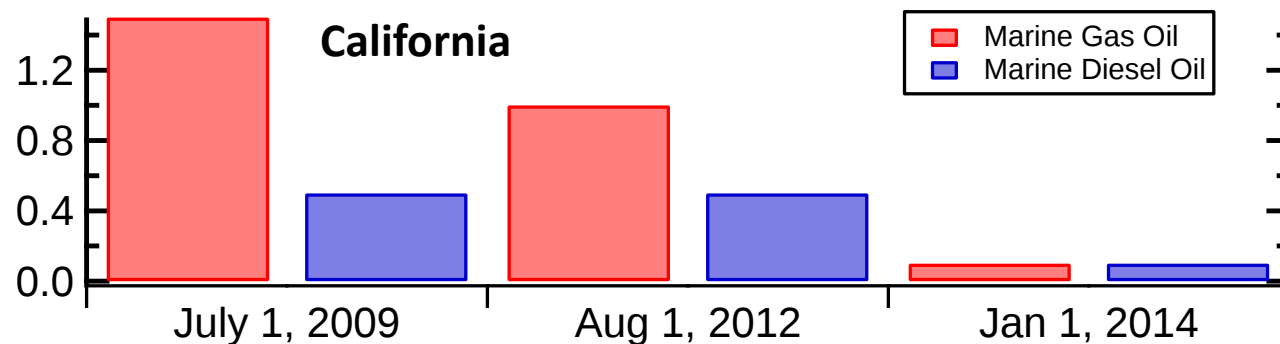
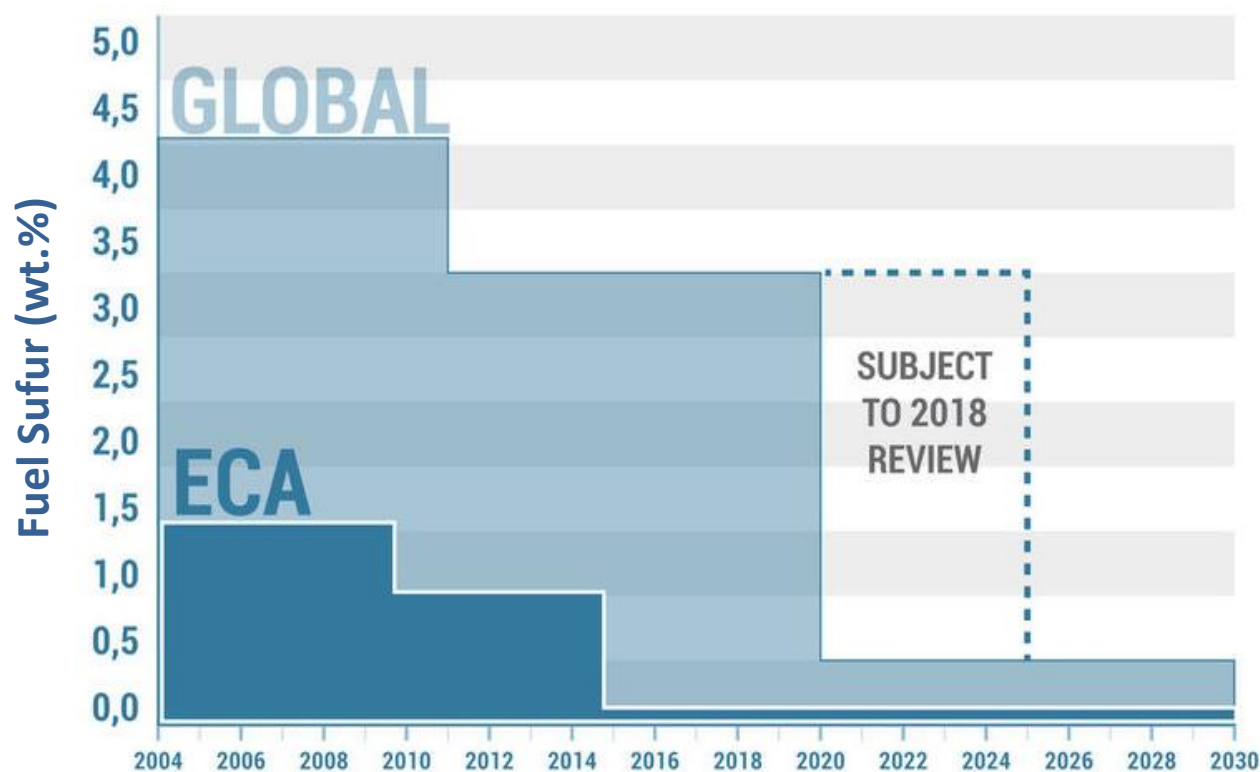
Ocean-going vessel traffic density



Fuel Sulfur Regulations



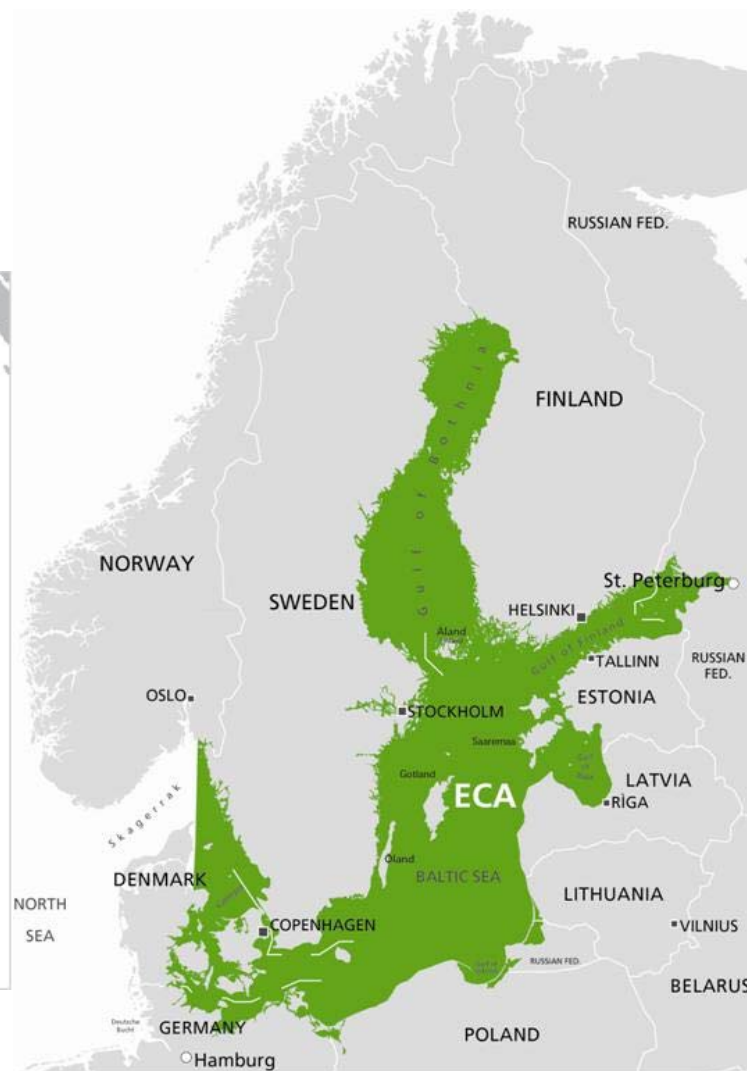
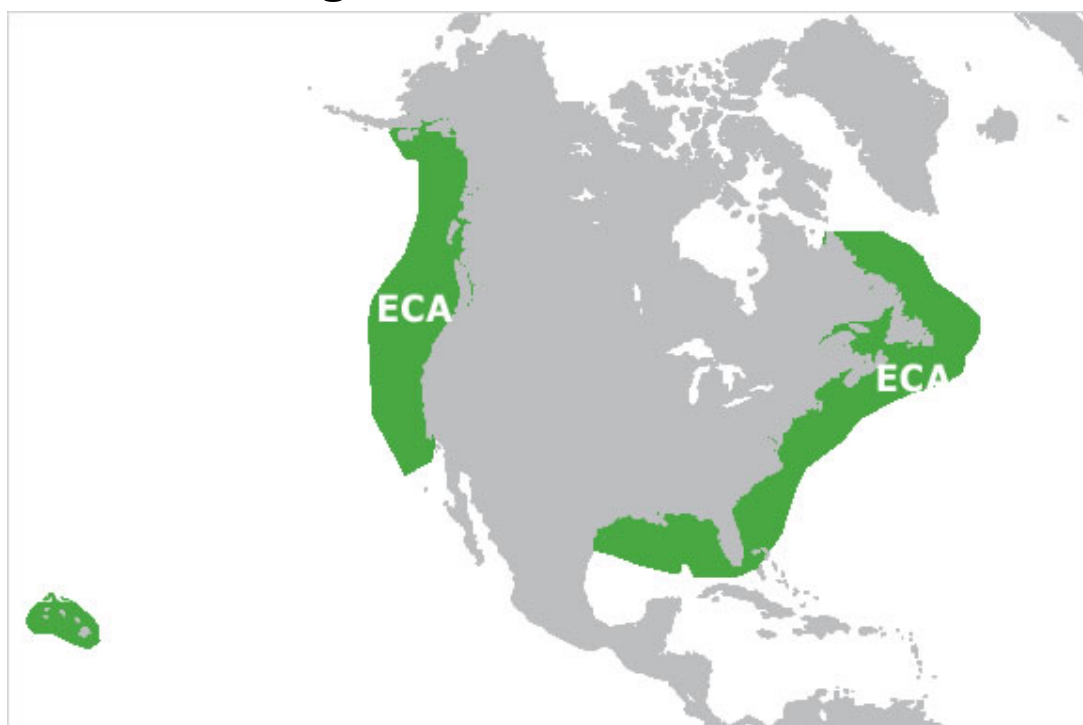
- Allowable fuel sulfur content decreasing in **Emission Control Areas** and in global fuels
- Regulations in CA even more stringent/being implemented sooner
- Fuel sulfur content is often related to overall fuel quality (e.g. ash content)



Emission Control Areas



As of 1 August, 2012



Vessel Speed Reduction



- Various (mostly voluntary) vessel speed reduction efforts
- Typically provide incentives for vessels to reduce speed to ~12 knots (from a typical ~25 knots) within ~40 nm of the coast
- Decreased CO₂ and NO_x emissions; effects on PM?
- VSR in effect around Port of Los Angeles and Long Beach (our study area)



Objective



Characterize and quantify emissions of particulate matter in plumes from a suite of ocean going vessels around CA by:

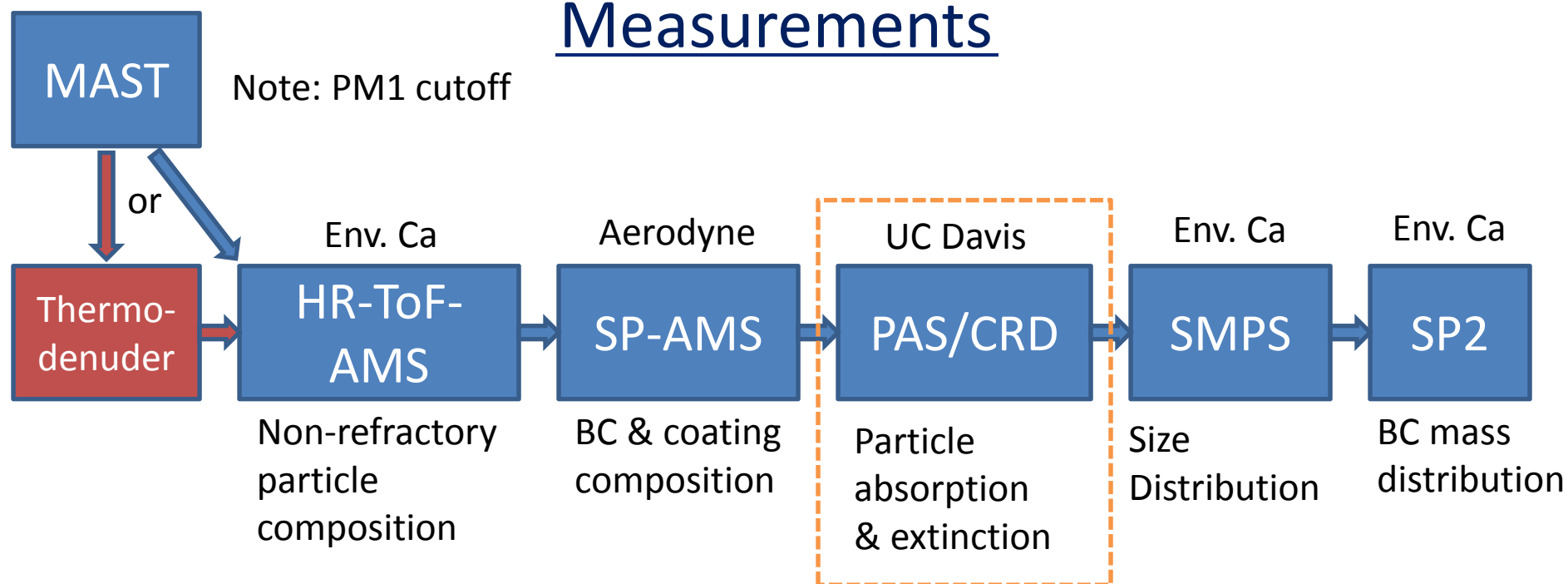
- Vessel type
- Fuel type (new CA regulations requiring low sulfur fuel were in effect)
- Vessel speed



Our Research Platform during CalNex 2010: The Woods Hole R/V Atlantis



Measurements



Other particle measurements:

Particle Number (< 5 nm; < 13 nm; < 50 nm; < 100 nm), CPC, 1 second

Particle Size Distributions, SMPS, 3 minute

Cloud Condensation Nuclei (CCN), 1 second

Particle Scattering, Nephelometer, 1 second

Particle Absorption, PSAP, 1 second (w/ 30 second running mean)

Optical hygroscopicity, CRD-AES, 5 seconds

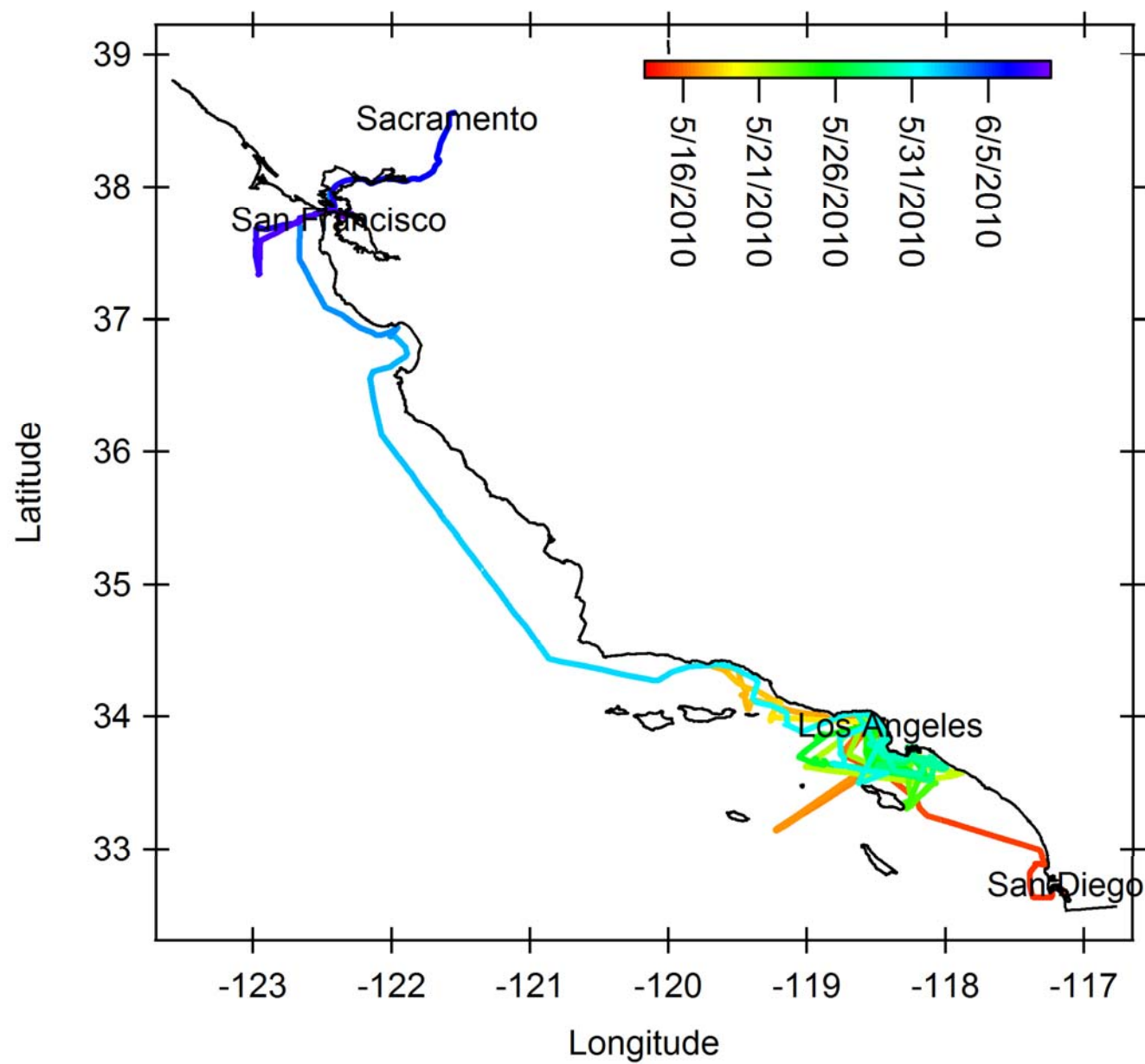
Single particle composition, ATOFMS, fast

Gas Phase:

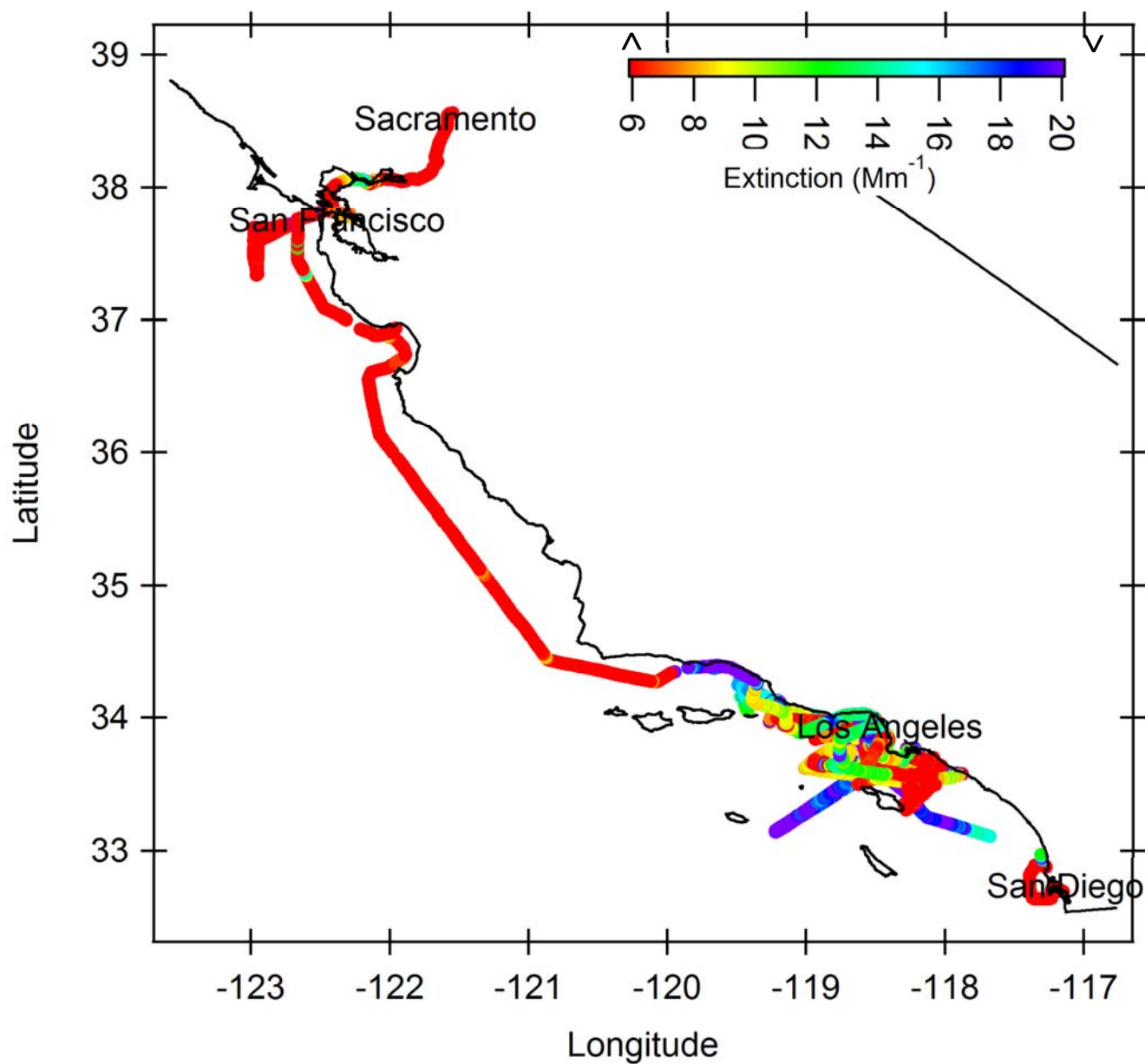
SO₂, 1 second CO, 1 second NO_x, 1 second

CO₂, 1 second O₃, 1 second

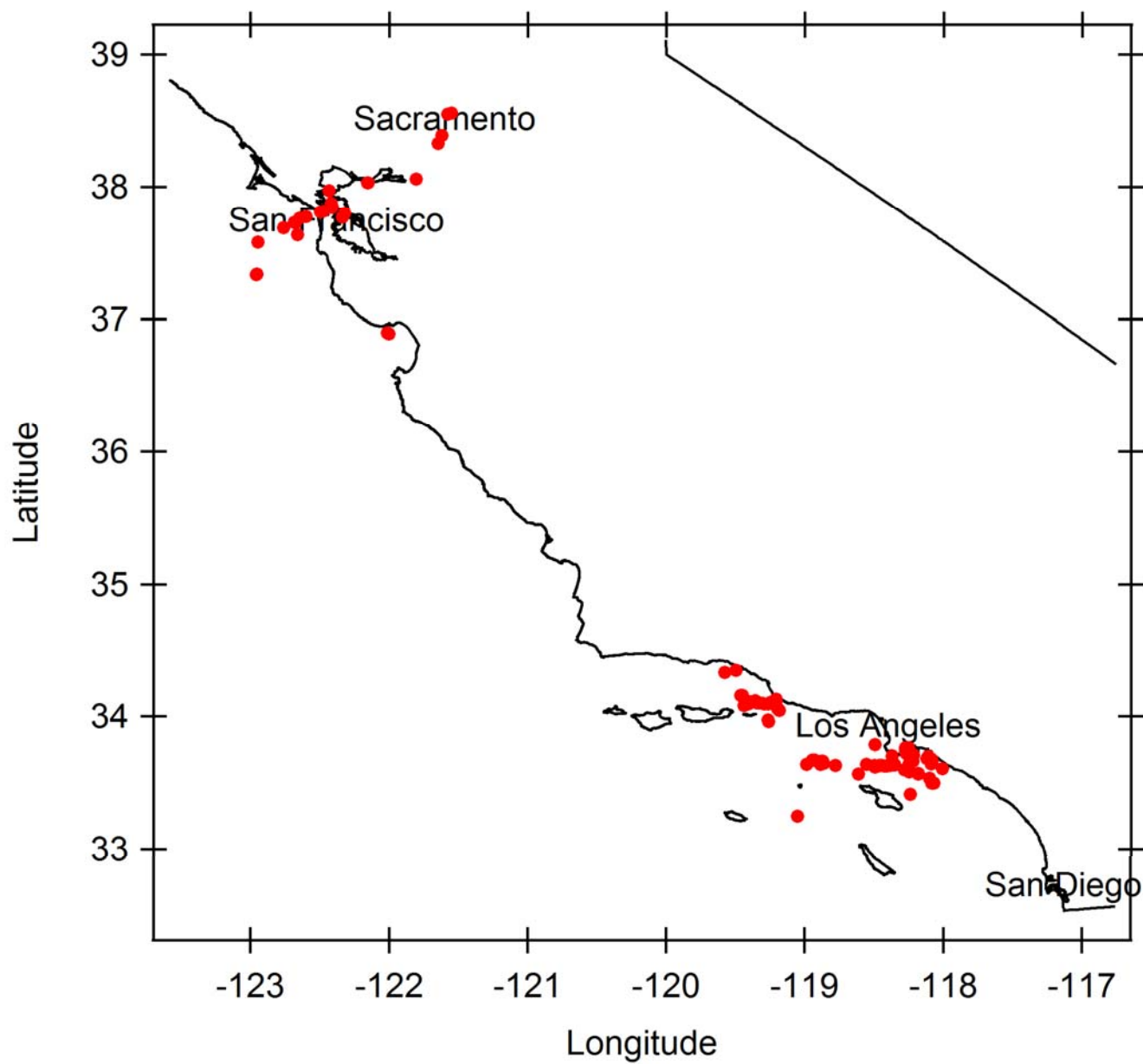
CalNex 2010 Study Area



Sub 1 μm Particle Extinction (532 nm)



Ship Encounters

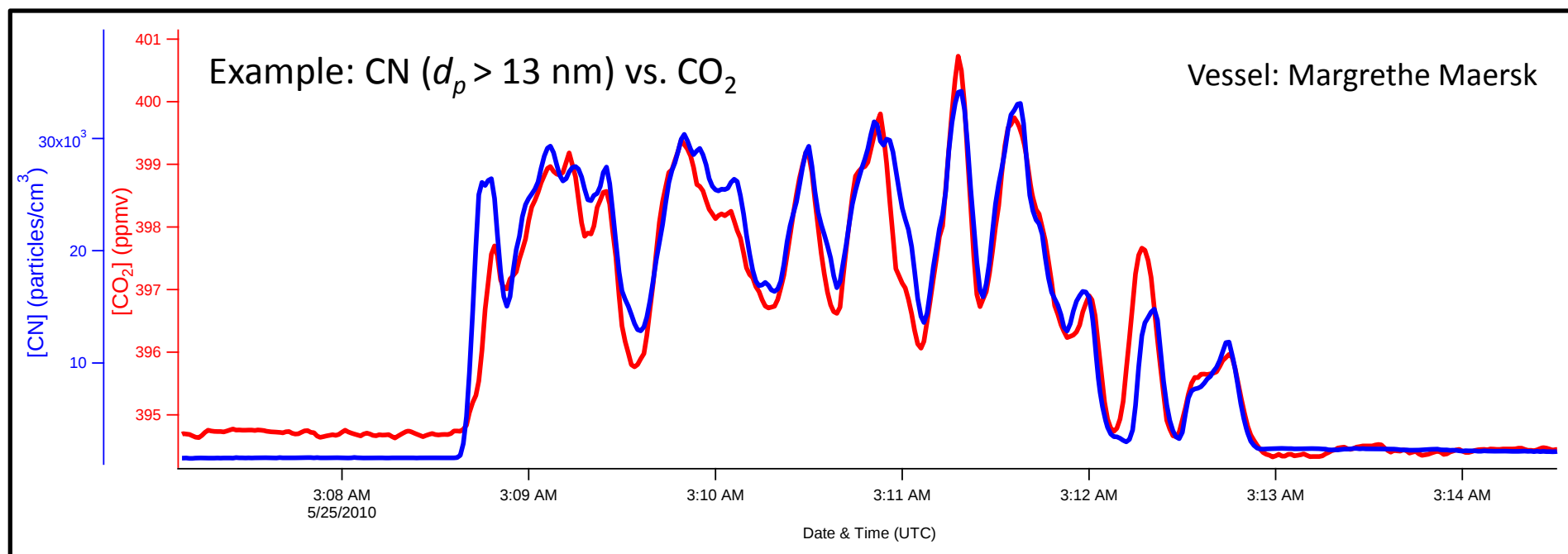




Quantifying Ship Emissions

- Determine **emissions factors** from measurements of species X and CO₂ in intercepted plumes from **in use** ships
- Plume ages range from < 1 min to 10 minutes

$$EF_X = \frac{([X]_{plume} - [X]_{bgd})}{([CO_2]_{plume} - [CO_2]_{bgd})} \cdot f_{fuel} = \frac{amt. X \text{ emitted}}{kg \text{ fuel consumed}}$$



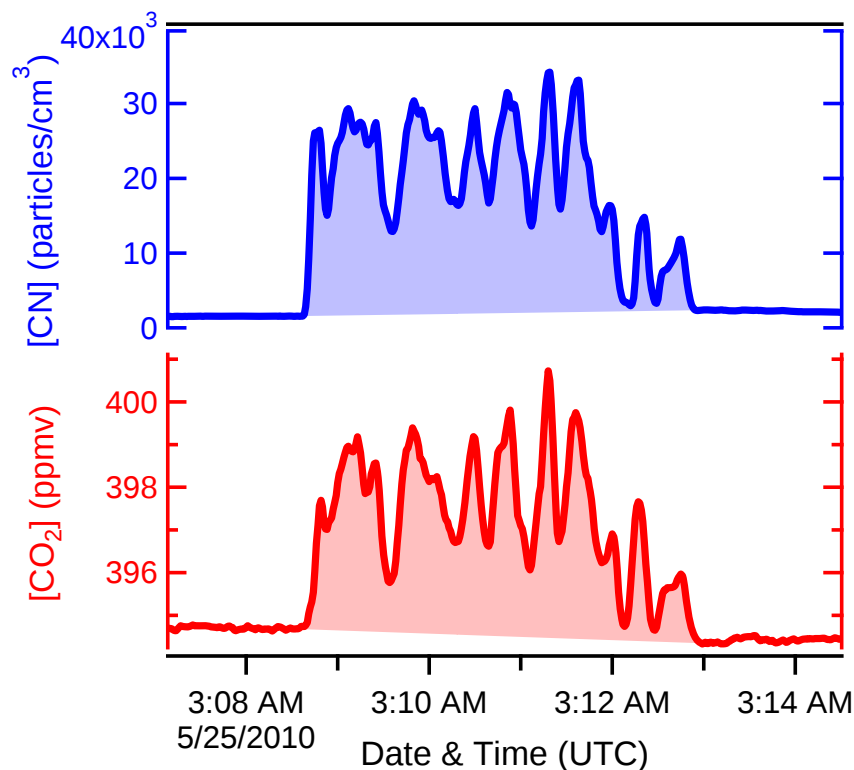
f_{fuel} = conversion factor accounting for fuel carbon content and MWs

Quantifying Ship Emissions

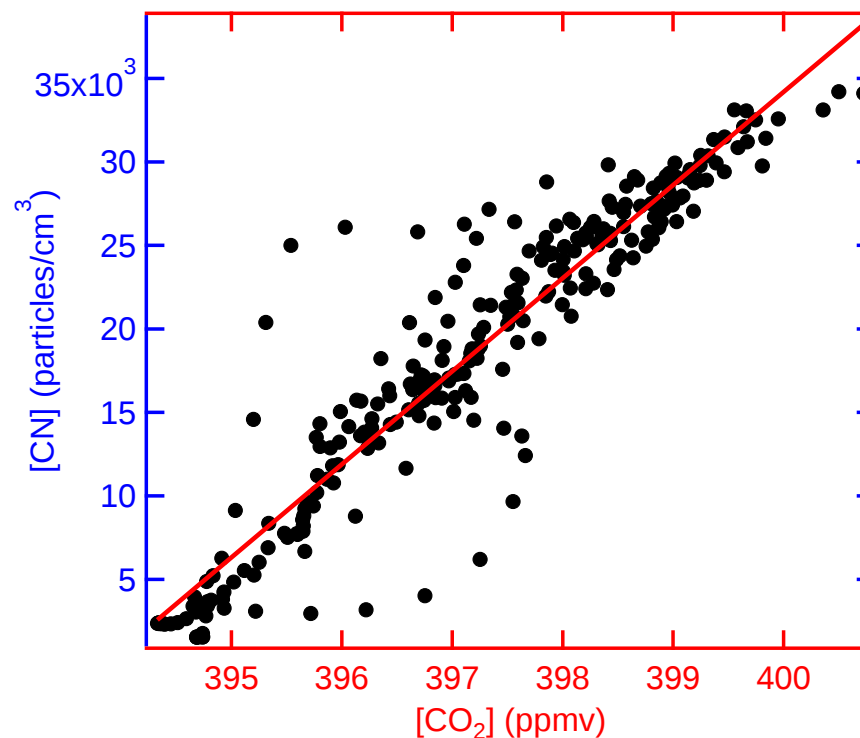


$$EF_X = \frac{([X]_{plume} - [X]_{bgd})}{([CO_2]_{plume} - [CO_2]_{bgd})} \cdot f_{fuel} = \frac{amt. X \text{ emitted}}{kg \text{ fuel consumed}}$$

Area-Ratio Method



Slope Method



Three Stories



1. Emissions of black carbon from the in use fleet in the CA coastal waters [Buffaloe et al., 2014]



2. Case Study: Influence of fuel quality (fuel sulfur content) on PM emissions from an in use slow speed diesel container ship [Lack et al., 2011]



3. Case Study: Influence of vessel speed on PM emissions from an research vessel/fishing boat [Cappa et al., 2014]



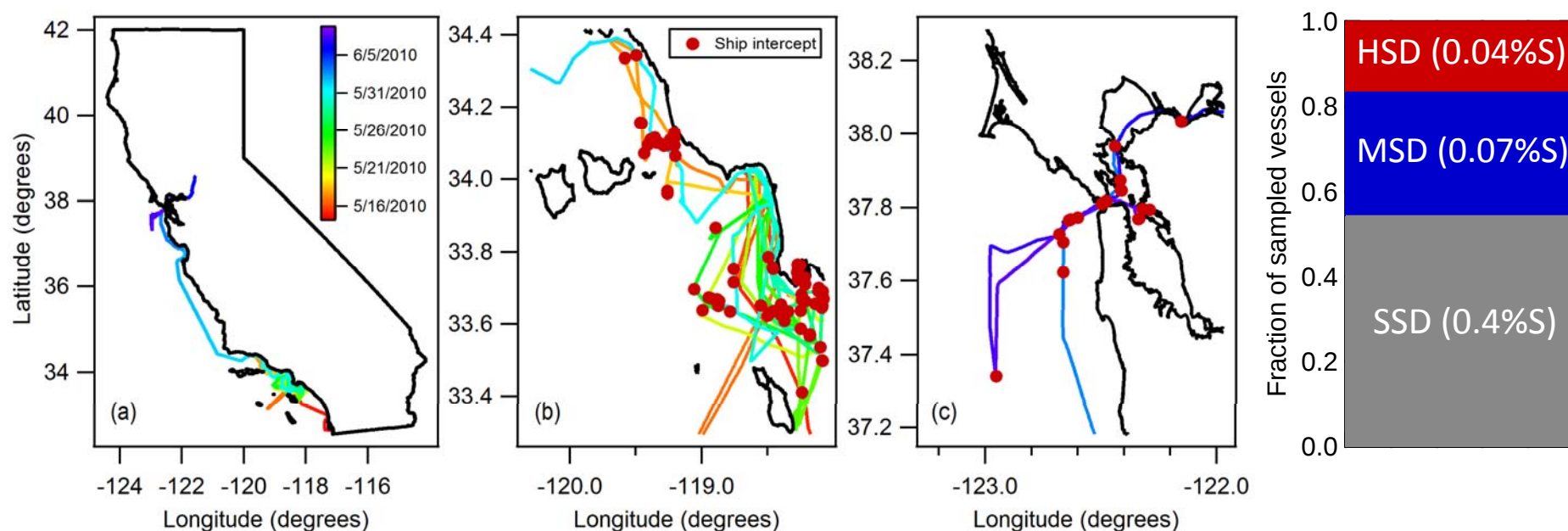
Emissions of black carbon from the in use fleet in the CA coastal waters

FIRST STORY



Black Carbon Emissions from the CA Fleet

- Primarily target of opportunity study (i.e. sampled ship plumes when we could!)
- Total of 71 vessels and 135 plumes encountered
- Combination of *slow speed*, *medium speed* and *high speed* diesels
- All vessels operating on low sulfur fuels
- Multiple measurement methods (PAS, PSAP, SP2 and SP-AMS)

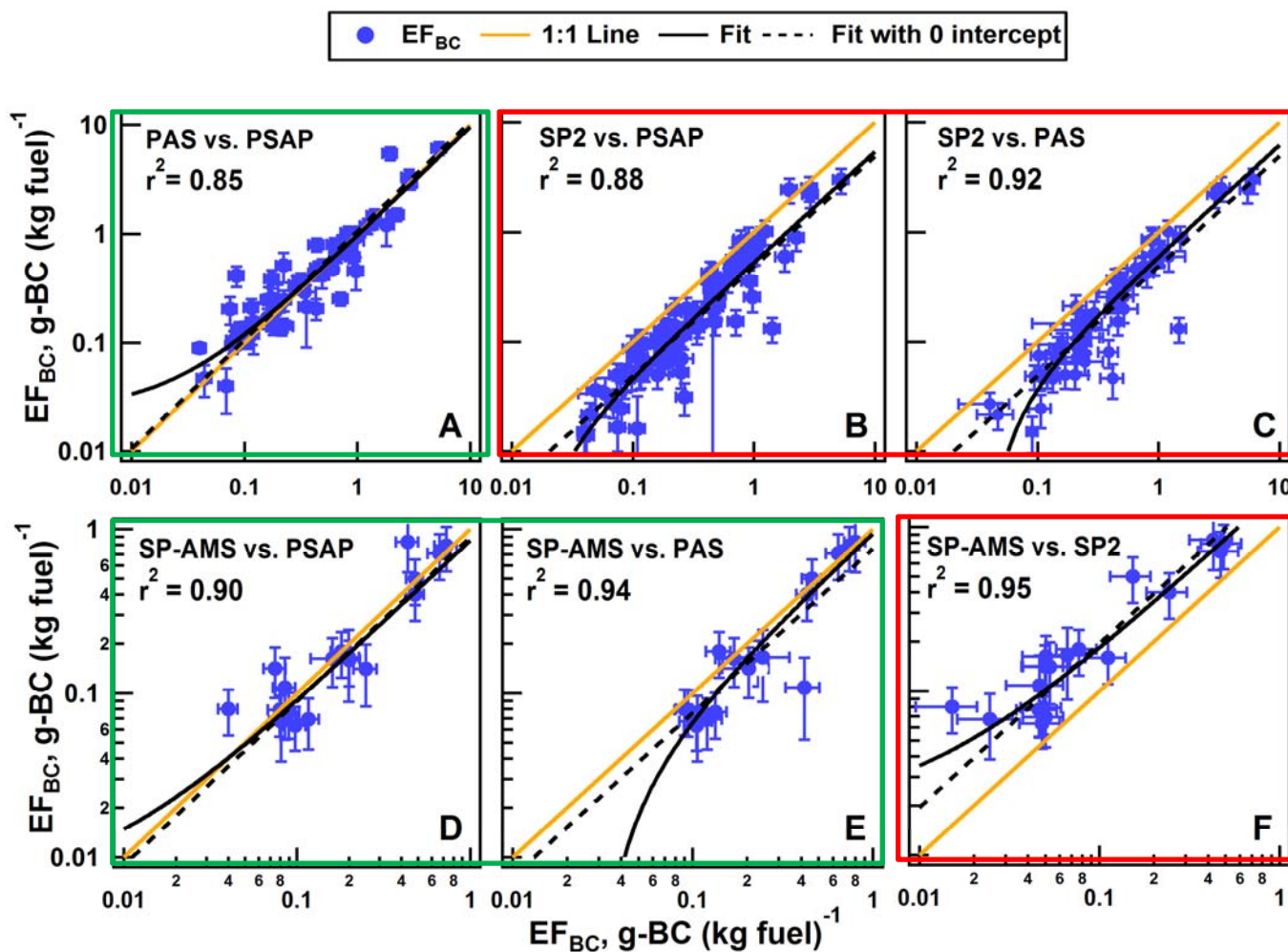


[Buffaloe et al., ACP, 2014]



BC Emissions: Technique Comparison

- Good agreement between PAS, PSAP and SP-AMS
- SP2 biased low relative to other methods

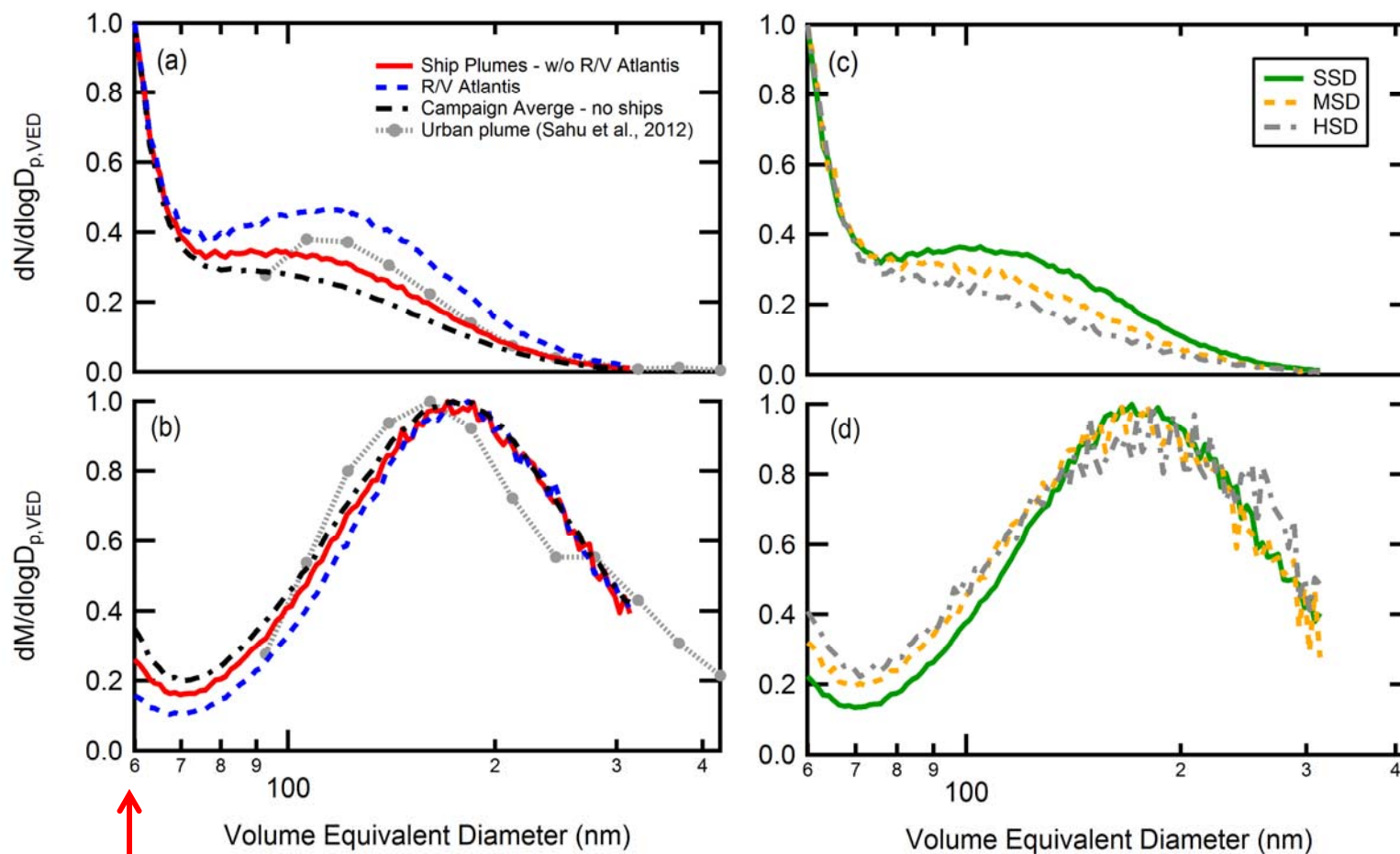


[Buffaloe et al., ACP, 2014]



Bias in SP2?

- Evidence for small particle mode not captured by SP2
- Limitations in BC source testing with SP2?

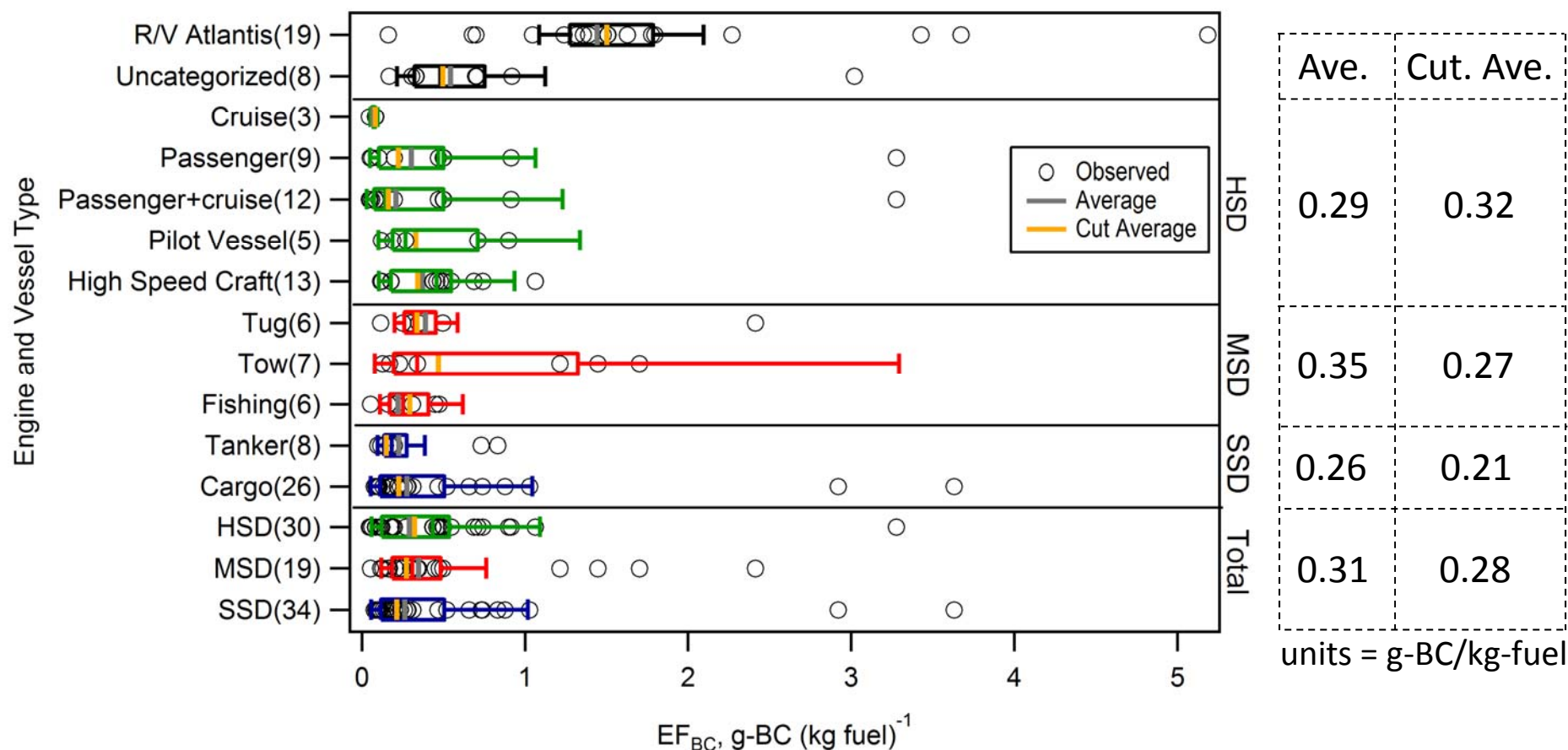


SP2 lower limit



BC Emission Factors during CalNex

- Good amount of ship-to-ship variability
- Little difference b/t ships with different engine types on average



Notes: - logarithmic averages (Parrish et al., JGR, 1998)
 - cut averages exclude statistical outliers

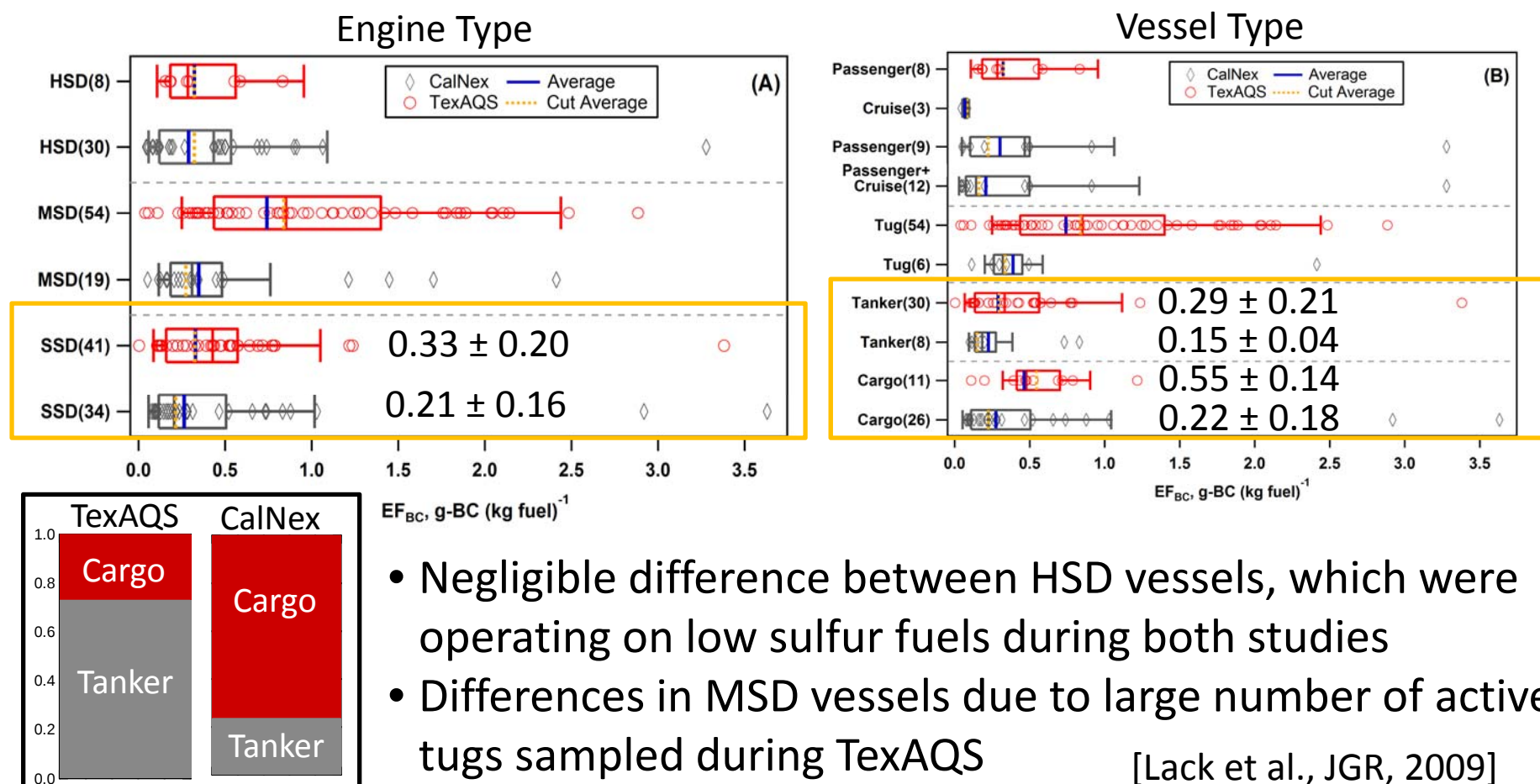


Can we use the CalNex dataset to say something about the influence of fuel sulfur?



BC Emission Factors: CalNex vs. TexAQS

- SSD vessels during CalNex (2010) operated on a much lower sulfur fuel than during TexAQS (2006) – 0.4%S vs. 1.6%S
- BC emission factors in CalNex statistically lower than in TexAQS for Tankers and Cargo SSD vessels ($p \leq 0.001$)



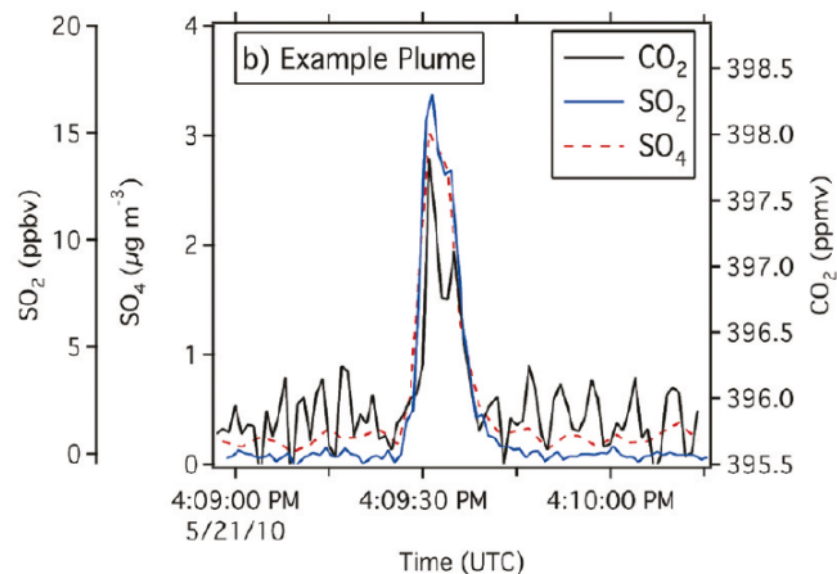
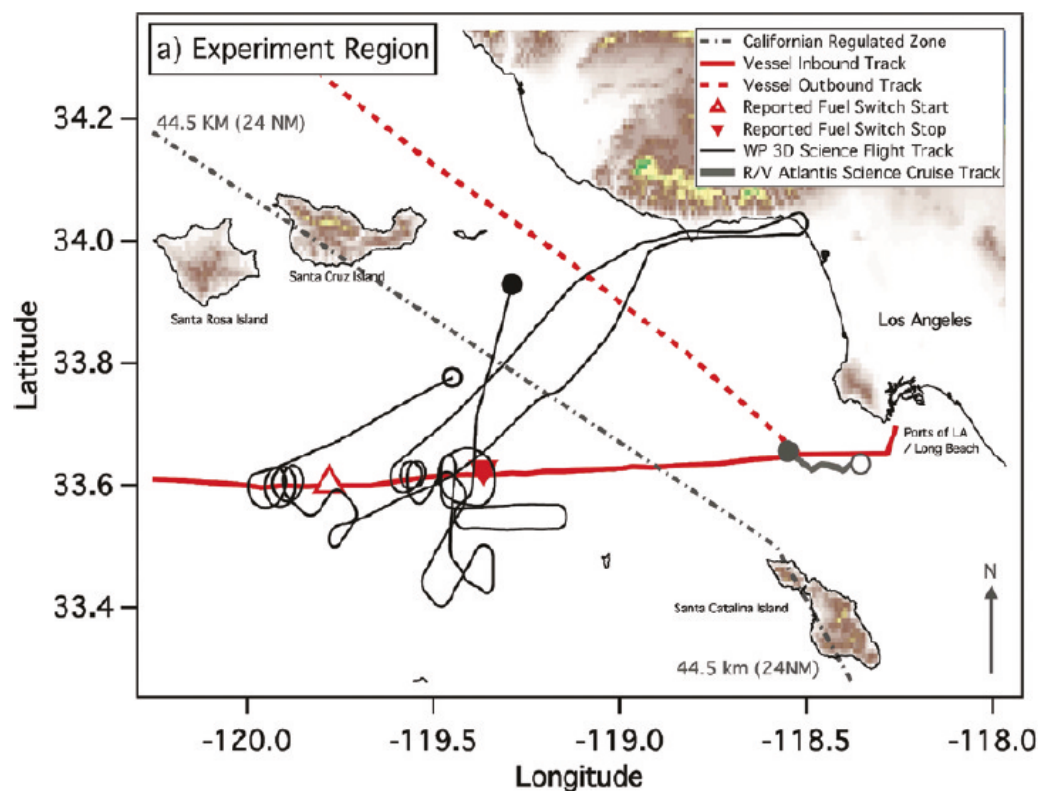
Case Study: Influence of fuel quality (fuel sulfur content) on PM emissions from an in use slow speed diesel container ship

SECOND STORY



Fuel Sulfur and the Margrethe Maersk

- Coordinated study between R/V *Atlantis*, the NOAA P-3B and the Margrethe Maersk (MM)
- MM switched from high sulfur (3.15% S, 0.05% ash) to low sulfur (0.07% S, <0.01% ash) over a period of 60 minutes
- Sample multiple times during the switch from the P-3B and after the switch was complete from the *Atlantis*

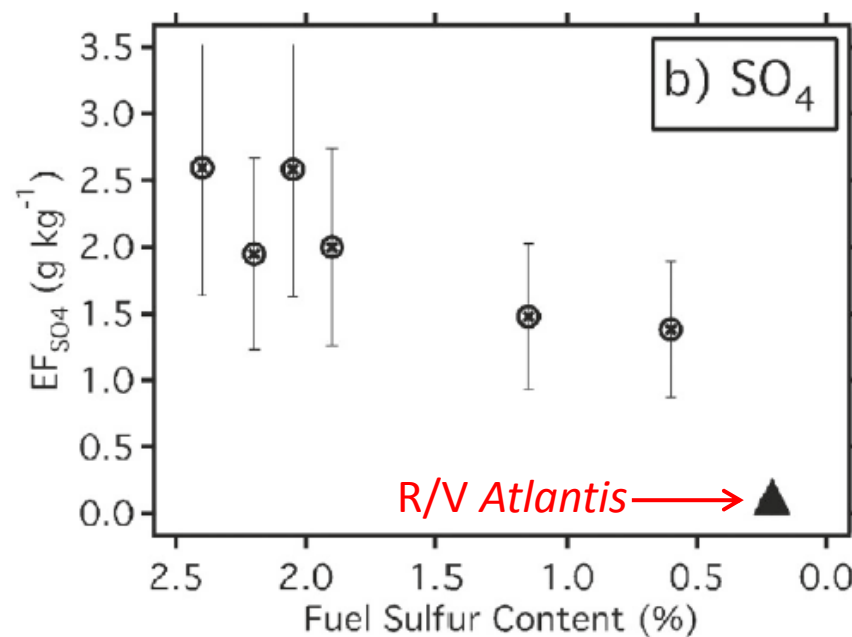
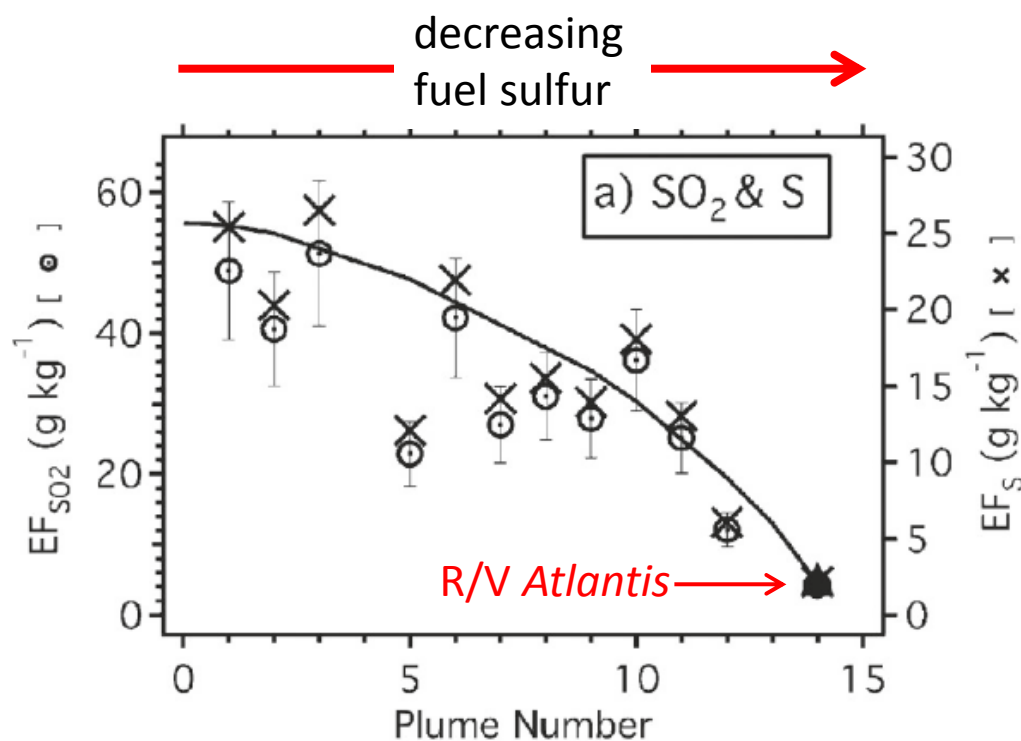


[Lack, Cappa et al., *ES&T*, 2011]



Fuel Sulfur and the Margrethe Maersk

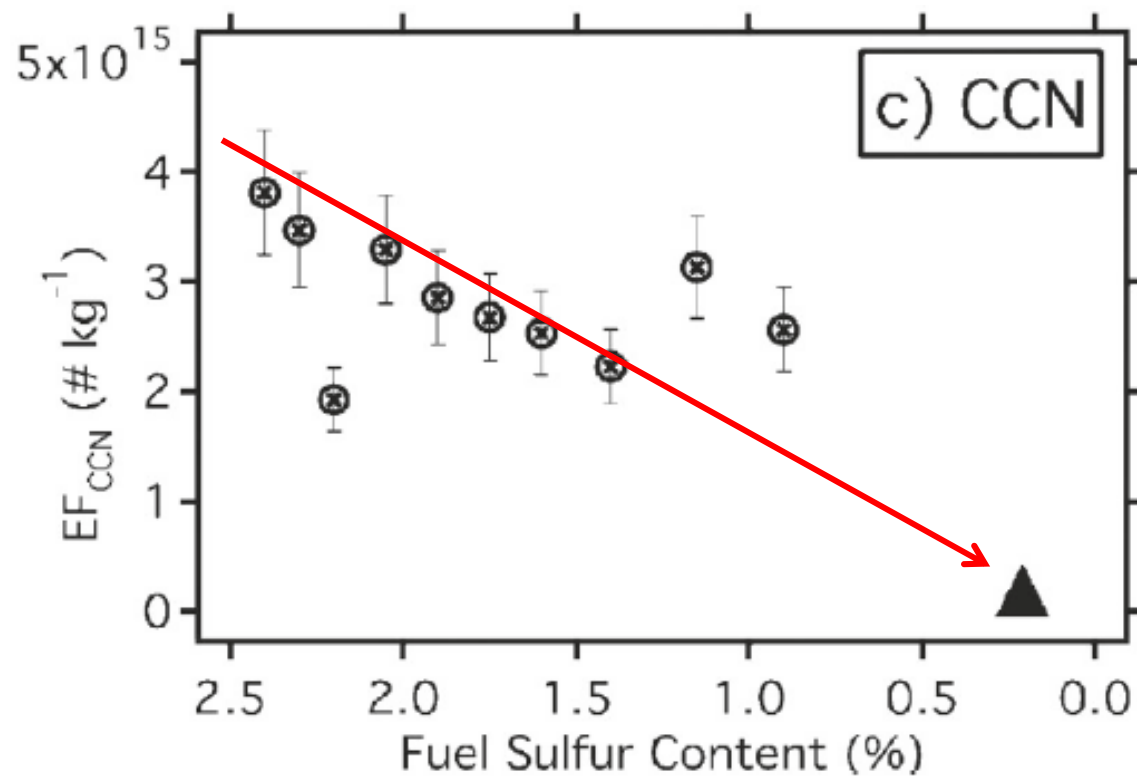
- SO_2 emissions decrease as fuel sulfur decreases
- p-SO_4^{-2} emissions decrease as fuel sulfur decreases



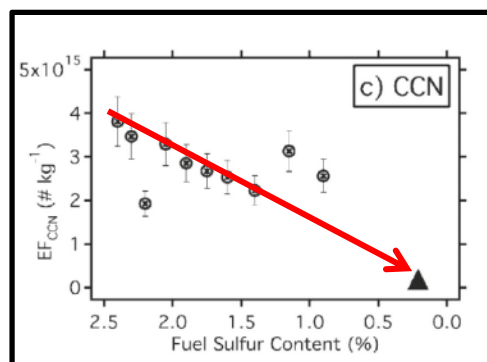
Fuel Sulfur and the Margrethe Maersk



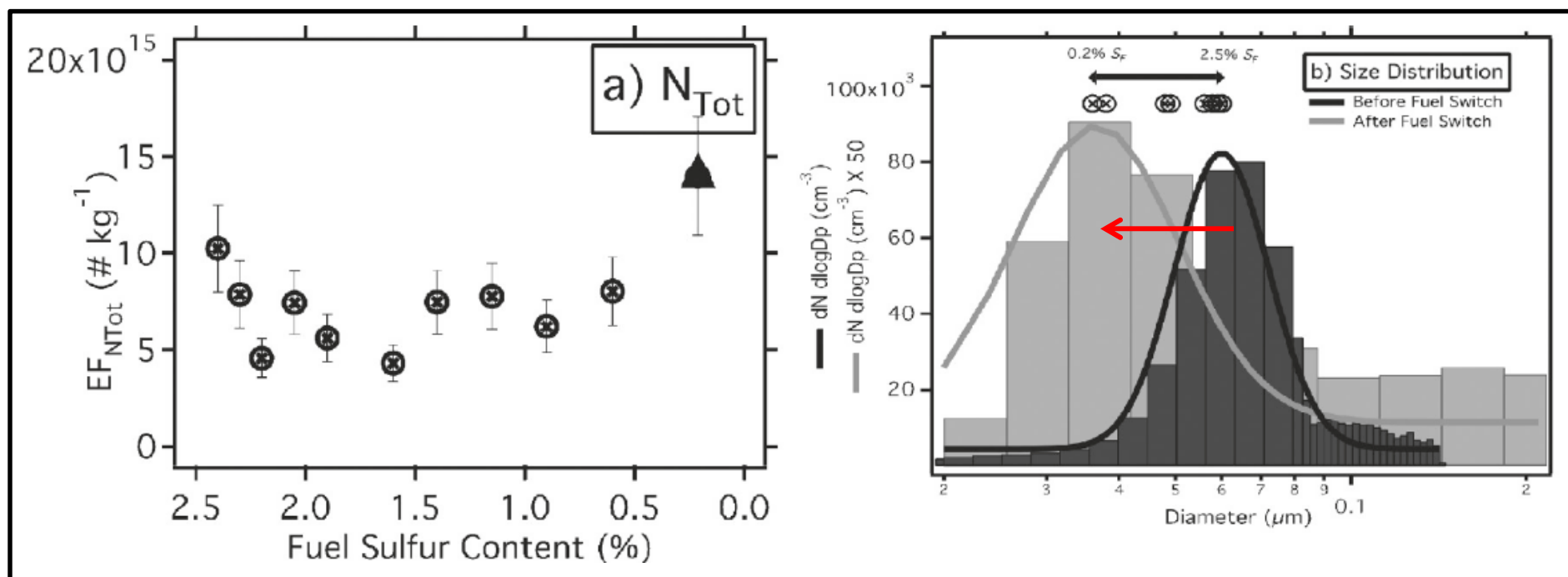
- Number of Cloud Condensation Nuclei decreases



Fuel Sulfur and Margrethe Maersk



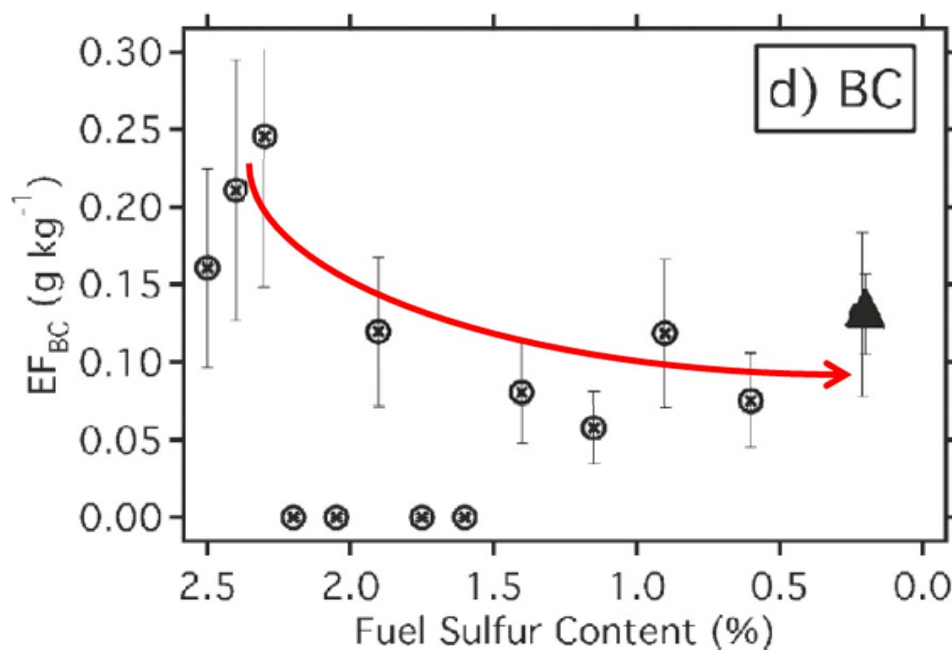
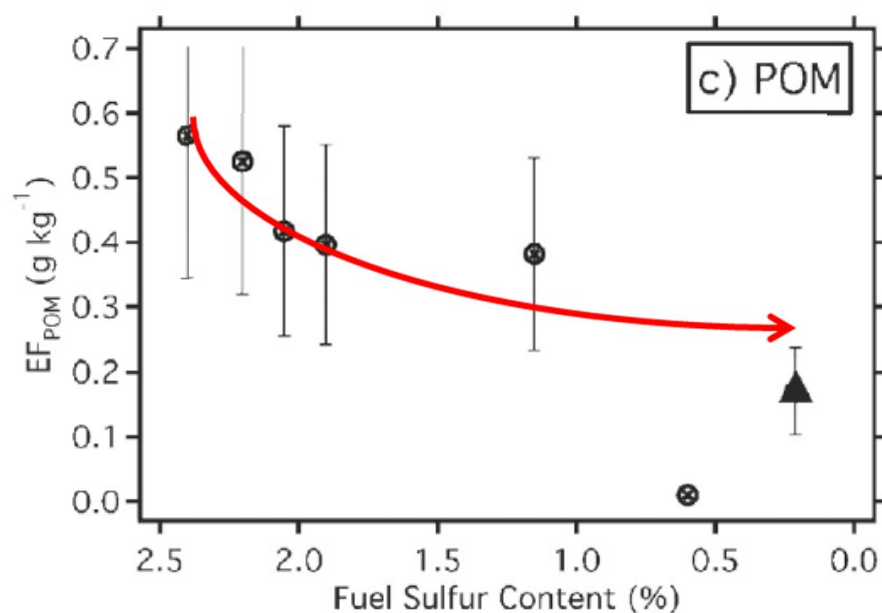
- Change in CCN driven more by size/composition changes than particle number



Fuel Sulfur and Margrethe Maersk



- Decrease in POM and (slight) decrease in BC emission factors
- May be related to concurrent decrease in vessel speed, but most likely a result of fuel change



Case Study: Influence of vessel speed on PM and gas-phase emissions
from a research vessel/fishing boat

THIRD STORY

Influence of Vessel Speed: the Miller Freeman



- Coordinated study with NOAA ship R/V *Miller Freeman*
- Intercepted plumes emitted at different steady-state operating speeds
- Characterize changes in PM and gas emission factors



Ship Details

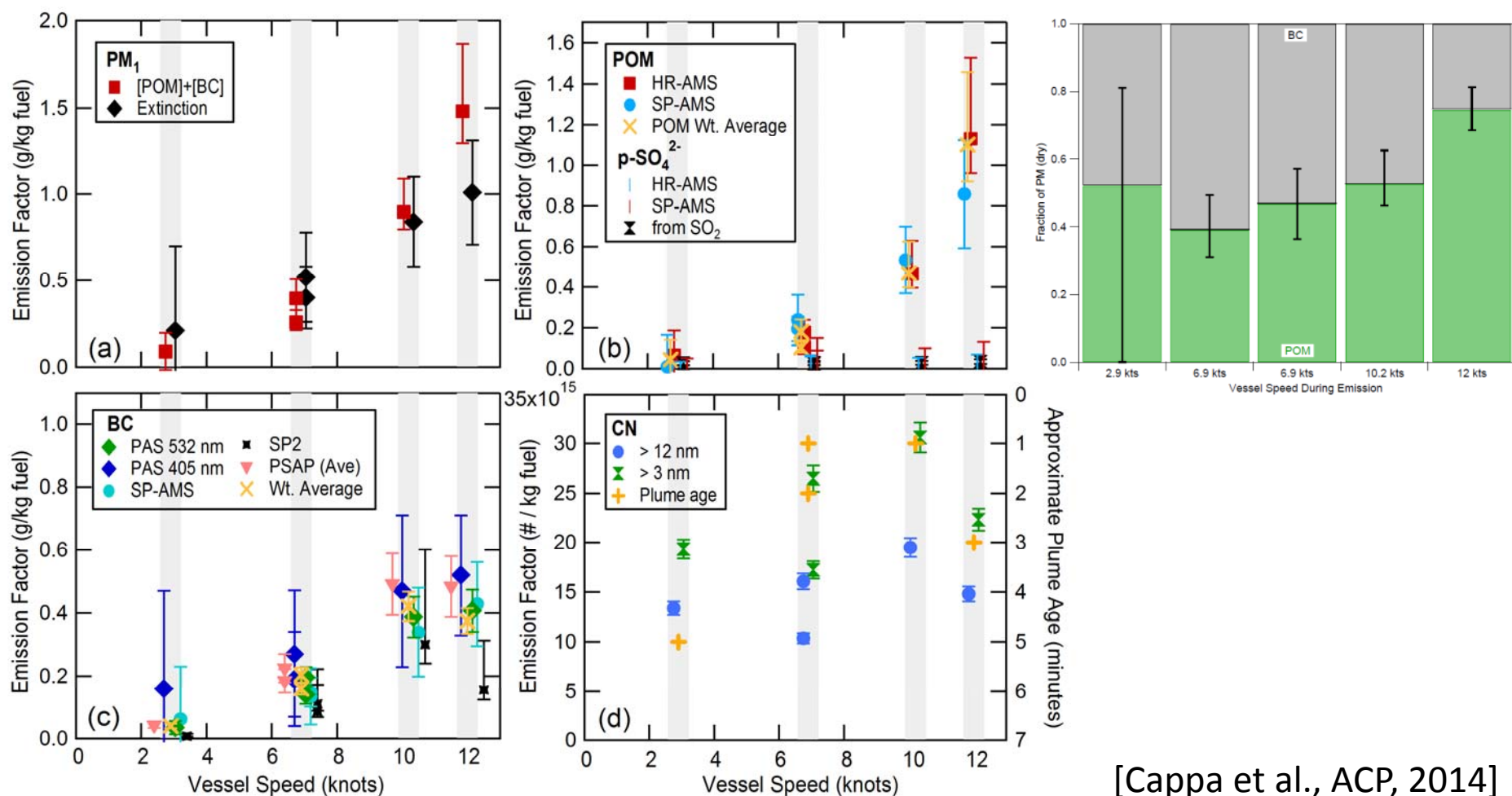
- 65.5 m vessel
- 11 knots cruising speed
- Medium Speed Diesel
- 2-stroke, 1.64 MW
- *Variable Pitch Propeller*
- $F_S \sim 0.1$ wt.%

[Cappa et al., ACP, 2014]

Influence of Vessel Speed: the Miller Freeman



- Decrease in PM, BC and POM EFs with decreasing vessel speed
- Slight increase in POM fraction as vessel speed increases
- No clear dependence of CN EF on vessel speed

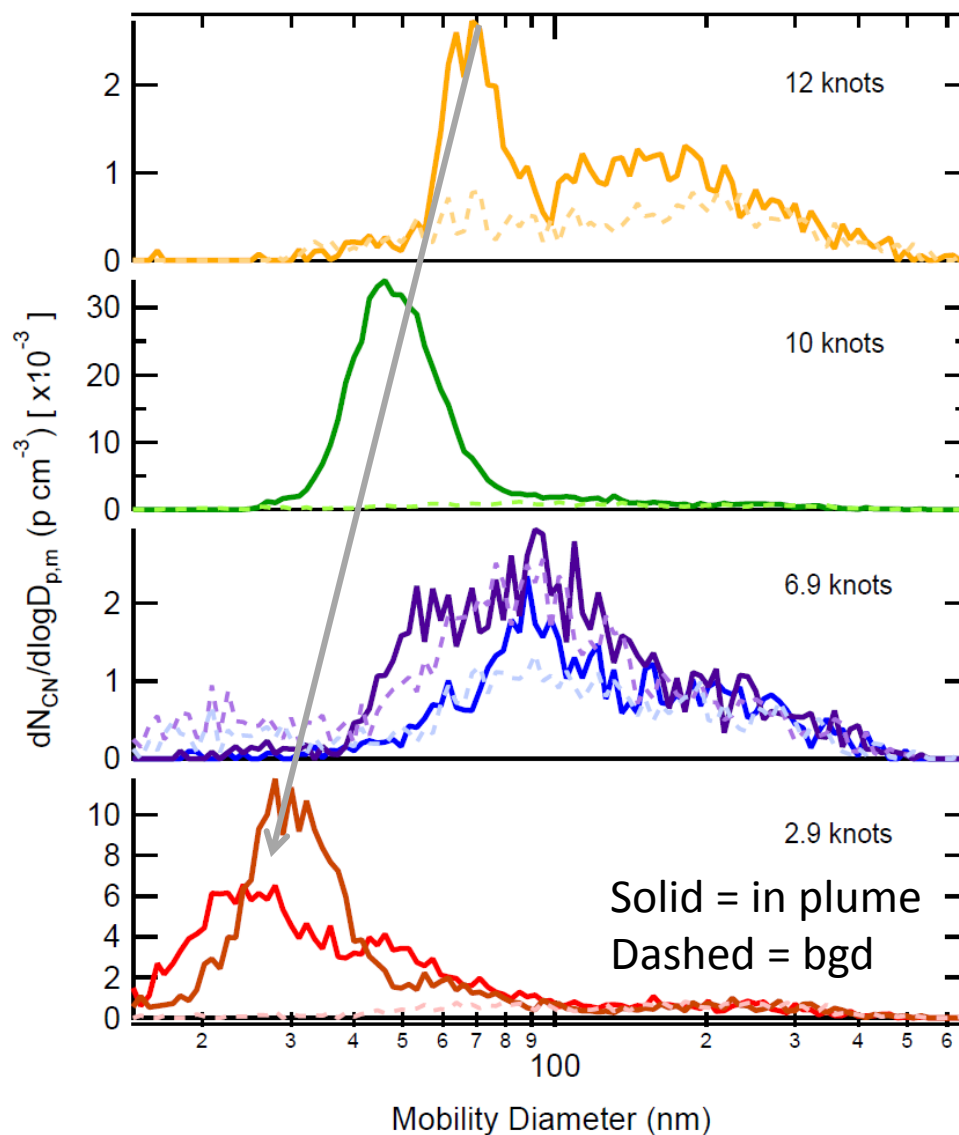
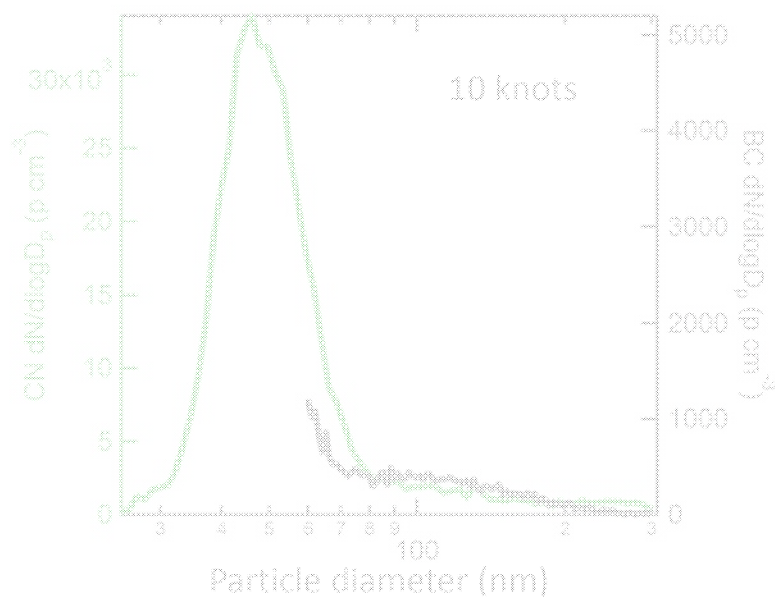


[Cappa et al., ACP, 2014]

Influence of Vessel Speed: the Miller Freeman



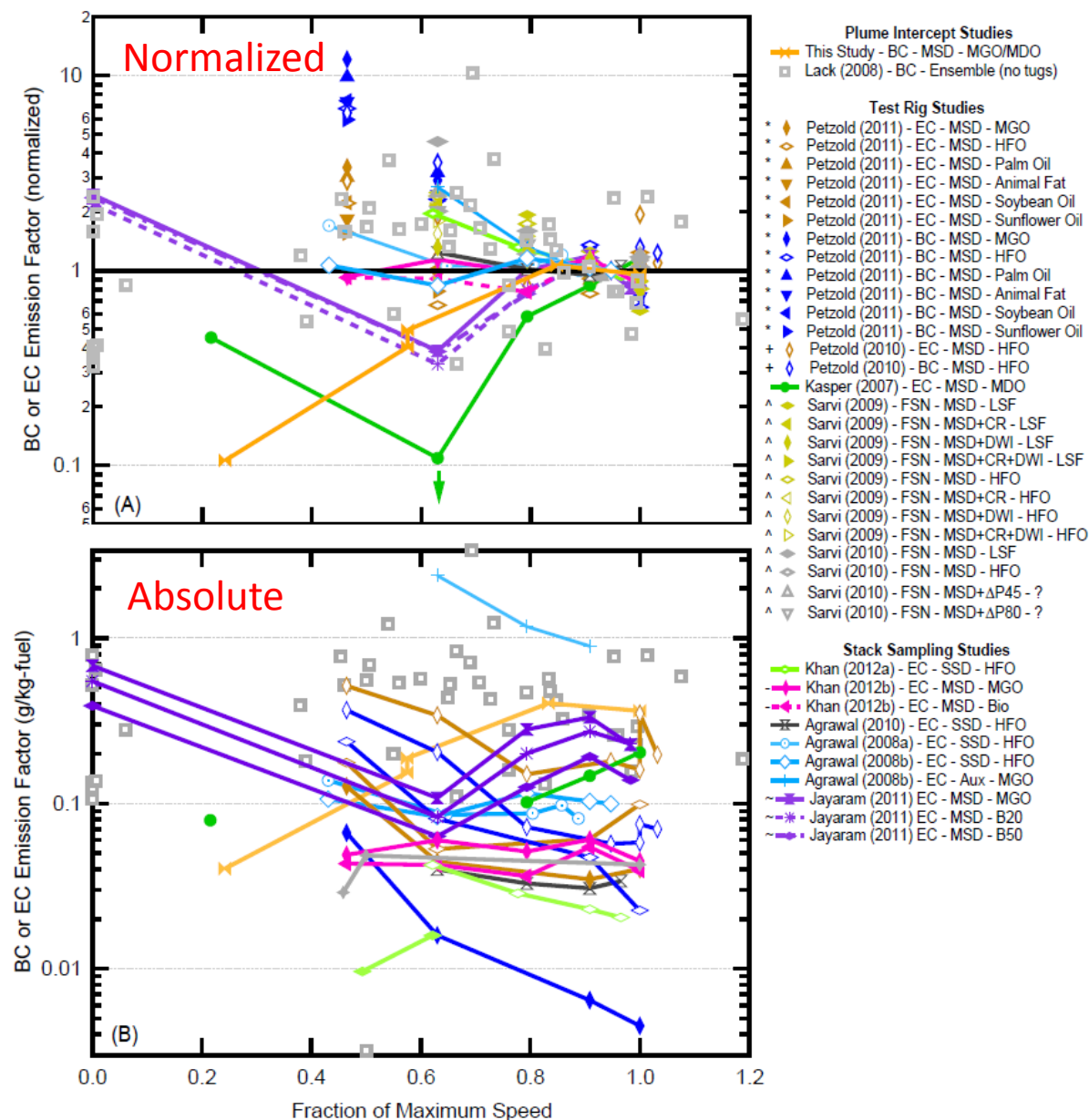
- Decrease in particle size with decreasing speed
- Consistent with decrease in PM concentration
- Comparison b/t SMPS size distribution and SP2 (BC) size dist'n consistent with small BC mode



Influence of Vessel Speed: Broader View for BC



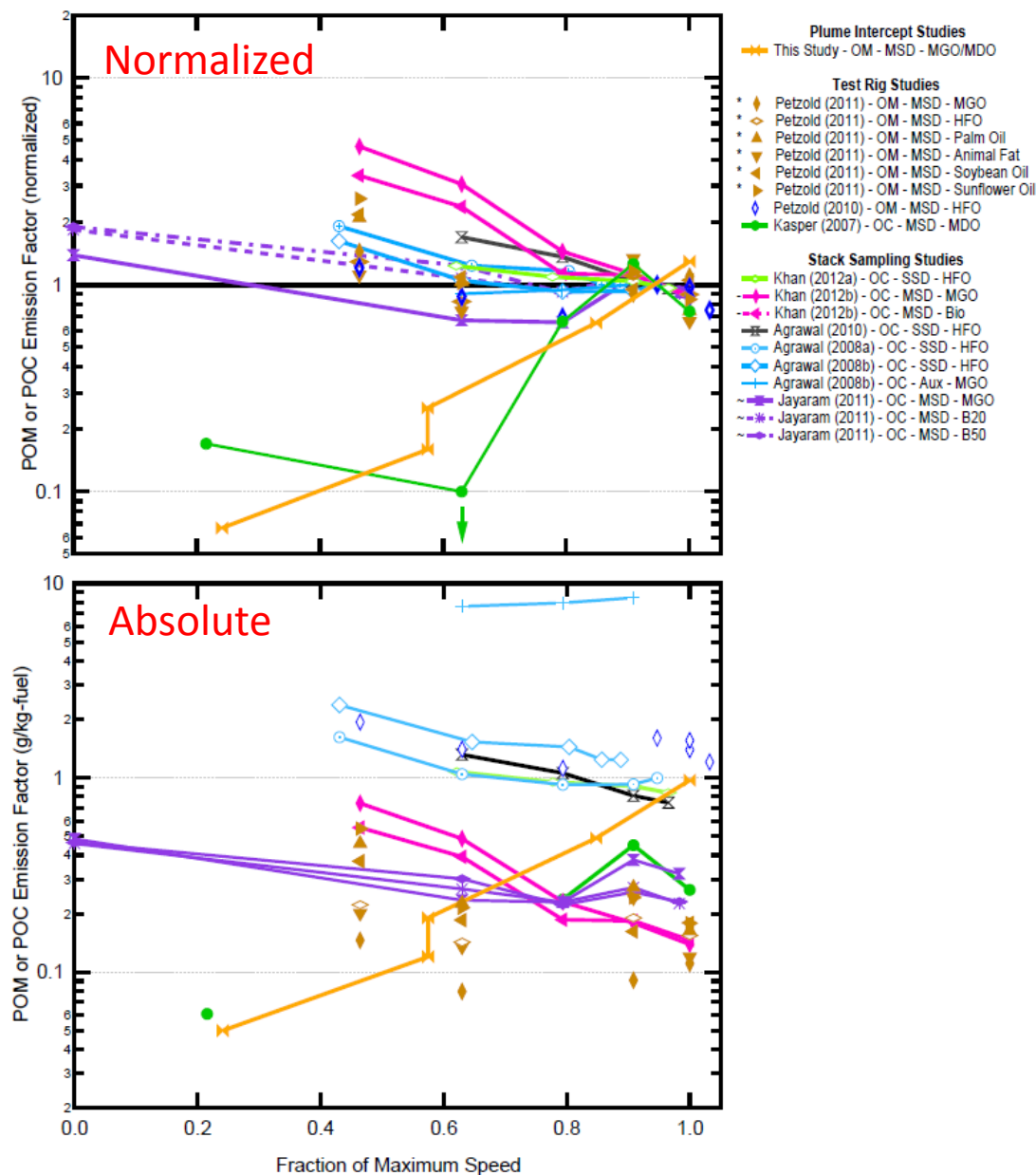
- Variation in EF_{BC} with vessel speed is not consistent between different studies
- Both increases and decreases in EF_{BC} with decreasing speed
- No clear engine dependence
- Wide range of absolute EF_{BC} between different vessels/studies



Influence of Vessel Speed: Broader View for POM



- Variation in EF_{POM} with vessel speed is not consistent between different studies
- Wide range of absolute EF_{POM} between different vessels/studies



Summary and Conclusions



- Characterized BC emissions factors for multiple vessels
 - No difference between engine types (SSD vs. MSD vs. HSD)
- Lowering sulfur in fuels (equivalent to cleaner fuels)...
 - Decreases overall PM emissions (primarily from sulfur ↓)
 - Decreases BC emission factors
 - May decrease POM emission factors
- Clear decrease in PM emissions as vessel speed decreases for R/V *Miller Freeman*
 - Substantial variability between different studies of individual vessels or test rig engines
 - *Miller Freeman* particular dependence may result from use of variable pitch propeller
- Follow-on work: Comprehensive characterization of broader suite of PM characteristics (number, composition) from vessels intercepted during CalNex

Gina Buffaloe (UC DAVIS)
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Brian Lerner (NOAA)

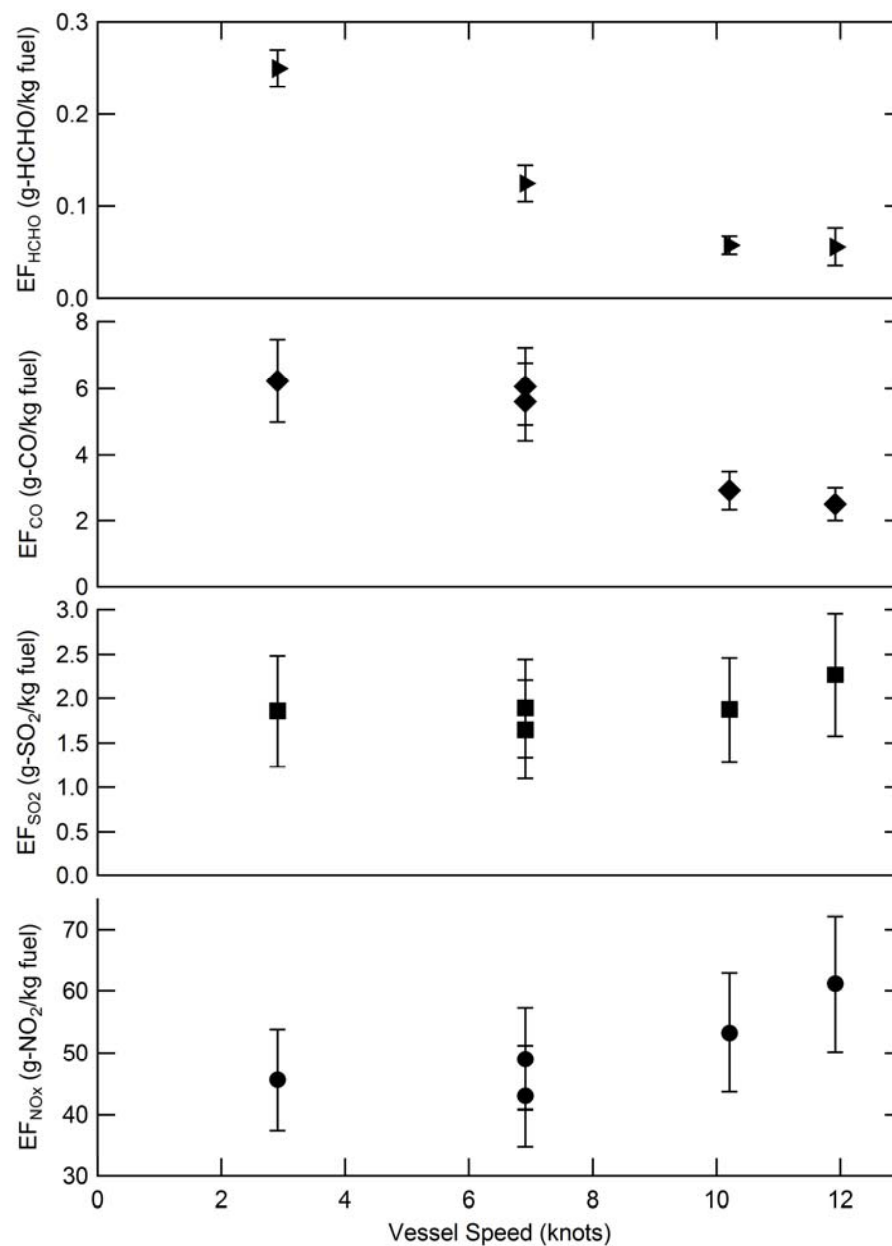
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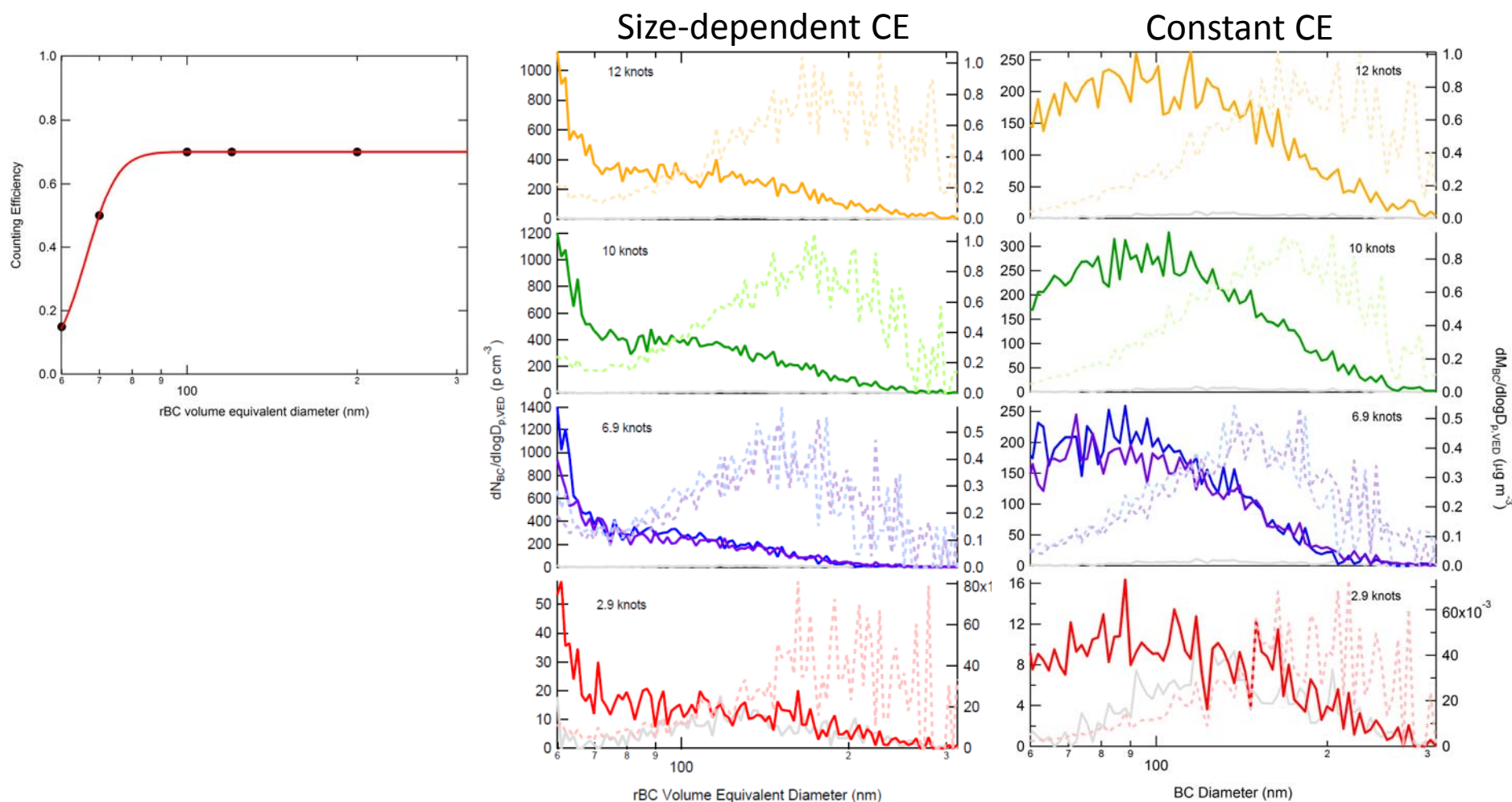
Vessel Speed: Gas Phase



Bias in SP2?



- Some evidence for small particle mode not captured by SP2
- Limitations in BC source testing with SP2?
- Need to account for size-dependent counting efficiency



Acknowledgments



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