Supplementary Information for "Black carbon emissions from in-use ships: a California regional assessment"

G. M. Buffaloe[1], D. A. Lack[2,3], E. J. Williams[2,3], D. Coffman[4], K. L. Hayden[5], B. M. Lerner[2,3], S-M. Li[5], I. Nuaaman[5,6], P. Massoli[7], T. B. Onasch[7], P. K. Quinn[4], C. D. Cappa[1]

[1] Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, USA

[2] NOAA Earth System Research Laboratory, Boulder, CO, 80305, USA

[3] Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, 80305, USA

[4] NOAA Pacific Marine Environment Laboratory, Seattle, Washington, 98115, USA.

[5] Air Quality Research Division, Environment Canada, 4905 Dufferin St., Toronto, Canada, M3H5T4

[6] Centre for Atmospheric Chemistry, York University, 4700 Keele St., Toronto, Canada, M3J1P3

[7] Aerodyne Research, Inc., Billerica, Massachusetts, USA, 01821

Correspondence to: C. D. Cappa (cdcappa@ucdavis.edu)

Overview

The supplementary information provides: (1) details of the correction to the light absorption coefficient measured by the PSAP (2) a description of the weighted Pearson's r^2 calculations for the instrument comparison, (3) tables showing the EF_{BC} determined for each ship plume encounter, (4) maps of the R/V *Atlantis* travel route and the locations of ship plume intercepts, and (5) a figure of the average normalized, number-weighted and mass-weighted size distributions for the rBC component of particles withe a size-independent detection efficiency.

1. Correction for the PSAP

The light absorption coefficient of the particles deposited on the glass fibre filter of the PSAP is determined from the Beer-Lambert Law, after correction for instrument response and scattering within and by particles on the filter. Specifically,

$$\boldsymbol{b_{abs}(\lambda)} = \frac{\mathbf{0.85}\cdot\left(\frac{\lambda}{\lambda_0}\right)^{-1}\cdot \boldsymbol{b_{PSAP}(\lambda_0)}}{\boldsymbol{K_2}} - \frac{\boldsymbol{K_1 b_{sp}(\lambda)}}{\boldsymbol{K_2}}, \quad \text{(S1)}$$

where 0.85 is a filter area correction factor, K_2 (=1.2 ± 0.20) is the instrument response factor to absorption, K_1 (0.02 ± 0.02) is the instrument response to scattering, $b_{sp}(\lambda)$ is the scattering coefficient measured by a nephelometer at wavelength λ, and $b_{PSAP}(\lambda)$ is the absorption coefficient reported by the PSAP at wavelength λ_0 (Bond et al., 1999). The ratio (λ/λ_0) in the first term adjusts the absorption coefficient from wavelength λ_0 (the measurement wavelength) to wavelength λ (the wavelength at which the nephelometer measured scattering), assuming an Angstrom exponent of 1 for the absorbing aerosol. This particular PSAP operated at 3 different wavelengths, 467 nm, 530 nm, and 660 nm, while the nephelometer operated at 450 nm, 550 nm and 700 nm.

2. Weighted Pearson's r^2

Weighted Pearson's r^2 values were calculated for each instrument comparison, where the uncertainties of both instruments were used to weight the average x and y values in the calculation. The r^2 value is calculated as:

$$\boldsymbol{r^2} = \left(\frac{\sum(\boldsymbol{x_i}-\bar{\boldsymbol{x}})(\boldsymbol{y_i}-\bar{\boldsymbol{y}})}{\sqrt{\sum(\boldsymbol{x_i}-\bar{\boldsymbol{x}})^2(\boldsymbol{y_i}-\bar{\boldsymbol{y}})^2}}\right)^2 \quad \text{(S2)}$$

where $\bar{x}$ and $\bar{y}$ are the uncertainty-weighted average EF_{BC} values for each of the instruments being compared, and x_i and y_i are the individual EF_{BC} values for each instrument. The uncertainty-weighted average is determined by:

$$\bar{x} = \frac{\sum w_i x_i}{\sum w_i}, \quad \text{(S3)}$$

where w_i is the weighting factor, calculated as

$$\mathbf{w_i} = \frac{\mathbf{1}}{\boldsymbol{\sigma_i}}, \quad \text{(S4)}$$

where σ_i is the uncertainty for a given EF_{BC}.

3. Vessel-specific BC Emission Factors

Vessel-specific BC emission factors were determined from each instrument measurement and then averaged and weight-averaged to get an overall EF_{BC} for each plume encounter. Not every instrument was sampling during each invidual plume intercept. Emission factors from vessels with slow speed diesel engines are shown in Table S1, from vessels with medium speed diesel engines in Table S2, and from vessels with high speed diesel engines in Table S3.

4. R/V Atlantis Ship Tracks and Location of Intercepts

The overall travel route of the R/V *Atlantis* during CalNex is shown in Figure S1, and the route near San Francisco Bay and Santa Monica Bay are shown in Figure S2. The route line is coloured by date and time to show the progression of the *Atlantis*, and the locations of the ship plume intercepts are marked as red dots on the map.

5. Black carbon size distributions

BC-specific size distributions determined from the SP2 instrument assuming a size-independent detection efficiency (= 0.7) are shown in Figure S3. These distributions can be compared with those shown in the main text, for which a size-dependent detection efficiency was used (Cappa et al., 2013).

References

Bond, T. C., Anderson, T. L., and Campbell, D.: Calibration and Intercomparison of Filter-Based Measurements of Visible Light Absorption by Aerosols, Aerosol Sci. Technol., 30, 582-600, doi:10.1080/027868299304435, 1999.

Cappa, C. D., Williams, E. J., Lack, D. A., Buffaloe, G. M., Coffman, D., Hayden, K. L., Herndon, S. C., Lerner, B. M., Li, S.-M., Massoli, P., McLaren, R., Nuaaman, I., Onasch, T. B., and Quinn, P. K.: The influence of operating speed on gas and particle-phase shipping emissions: results from the NOAA Ship Miller Freeman, Atmos. Meas. Tech., submitted, 2013.

Table S1. Black Carbon Emission Factors from Ships with Slow Speed Diesel Engines

Ship Name	Speed (kts)	PAS EF_{BC} g-BC (kg fuel)$^{-1}$	PSAP EF_{BC} g-BC (kg fuel)$^{-1}$	SP2 EF_{BC} g-BC (kg fuel)$^{-1}$	SP-AMS EF_{BC} g-BC (kg fuel)$^{-1}$	Weighted Average EF_{BC} g-BC (kg fuel)$^{-1}$	Average EF_{BC} g-BC (kg fuel)$^{-1}$
			Cargo Ships				
DREAM ORCHID	7.4	2.9 ± 0.38	2.9 ± 0.42	2.2 ± 0.55		2.9 ± 0.3	2.9 ± 0.4
DREAM ORCHID	11.2	0.52 ± 0.16	0.22 ± 0.033	0.2 ± 0.051		0.23 ± 0.03	0.37 ± 0.09
DREAM ORCHID	11		0.28 ± 0.04	0.2 ± 0.051		0.28 ± 0.04	0.28 ± 0.04
E.R. DARWIN	20		0.18 ± 0.03	0.067 ± 0.017		0.18±0.03	0.18 ± 0.03
VERRAZANO BRIDGE	8.1	0.21 ± 0.045	0.43 ± 0.063	0.21 ± 0.054		0.28 ± 0.04	0.32 ± 0.05
MOL ENDURANCE*	12	0.17 ± 0.036	0.16 ± 0.04	0.071 ± 0.018	0.16 ± 0.054	0.16 ± 0.02	0.17 ± 0.04
SUN RIGHT	12.1	0.74 ± 0.099	0.73 ± 0.11	0.49 ± 0.12	0.79 ± 0.24	0.74 ± 0.07	0.8 ± 0.2
SUN RIGHT	11.3	0.64 ± 0.095	0.66 ± 0.096	0.47 ± 0.12	0.71 ± 0.22	0.66 ± 0.07	0.7 ± 0.1
MSC CARACAS	11.6	0.42 ± 0.1	0.49 ± 0.071	0.28 ± 0.071		0.47 ± 0.06	0.45 ± 0.09
YM ORCHID*	0	6.1 ± 0.8	5.3 ± 0.76	3 ± 0.77		3.6 ± 0.4	3.6 ± 0.6
YM ORCHID	11.5		0.21 ± 0.031			0.21 ± 0.03	0.21 ± 0.03
AS PALATIA	11.4	0.25 ± 0.074	0.16 ± 0.024	0.11 ± 0.028		0.17 ± 0.02	0.21 ± 0.05
HANJIN BEIJING	11.6	0.21 ± 0.041	0.12 ± 0.017	0.072 ± 0.019		0.13 ± 0.02	0.16 ± 0.03
EVER SUMMIT	18.8			0.0042 ± 0.0025			
MARGRETHE MAERSK	12.1	0.12 ± 0.024	0.12 ± 0.017	0.05 ± 0.013	0.07 ± 0.024	0.11 ± 0.01	0.10 ± 0.02
MARGRETHE MAERSK	12.4	0.094 ± 0.015	0.079 ± 0.012	0.049 ± 0.012	0.08 ± 0.025	0.084 ± 0.009	0.08 ± 0.02
MARGRETHE MAERSK	12.3	0.1 ± 0.015	0.098 ± 0.014	0.048 ± 0.012	0.06 ± 0.019	0.092 ± 0.009	0.09 ± 0.02
MARGRETHE MAERSK	12.1	0.13 ± 0.02	0.089 ± 0.013	0.046 ± 0.012	0.08 ± 0.024	0.10 ± 0.01	0.10 ± 0.02
MARGRETHE MAERSK	12		0.25 ± 0.037	0.053 ± 0.015	0.14 ± 0.058	0.22 ± 0.03	0.20 ± 0.05
PACIFIC LINK	12	0.12 ± 0.034	0.1 ± 0.015			0.10 ± 0.01	0.11 ± 0.02
ZIM MEDITERRANEAN	8.2	0.87 ± 0.14	0.9 ± 0.23	0.86 ± 0.23		0.9 ± 0.1	0.9 ± 0.2
HORIZON TIGER*	19		0.11 ± 0.016	0.016 ± 0.016		0.08 ± 0.01	0.08 ± 0.01
LT CORTESIA	0	1 ± 0.14	1 ± 0.15	0.66 ± 0.17		1.0 ± 0.1	1.0 ± 0.1
WUXI DRAGON	10.1		0.26 ± 0.038	0.12 ± 0.031		0.26 ± 0.04	0.26 ± 0.04
STELLA PRIMA	5.7	0.47 ± 0.045	0.6 ± 0.062	0.38 ± 0.094		0.52 ± 0.04	0.54 ± 0.05
HK CHALLENGER	11.4	0.42 ± 0.088	0.085 ± 0.012	0.046 ± 0.016	0.11 ± 0.056	0.09 ± 0.01	0.20 ± 0.05
MATHILDE MAERSK	11.2		0.31 ± 0.046	0.17 ± 0.044		0.31 ± 0.05	0.31 ± 0.05

*denotes average of ships sampled consecutively, at the same speed

Table S1. Continued

Ship Name	Speed (kts)	PAS EF_{BC} g-BC (kg fuel)$^{-1}$	PSAP EF_{BC} g-BC (kg fuel)$^{-1}$	SP2 EF_{BC} g-BC (kg fuel)$^{-1}$	SP-AMS EF_{BC} g-BC (kg fuel)$^{-1}$	Weighted Average EF_{BC} g-BC (kg fuel)$^{-1}$	Average EF_{BC} g-BC (kg fuel)$^{-1}$
			Tanker				
CORPUS CHRISTI	11.7	0.21 ± 0.032	0.19 ± 0.027	0.088 ± 0.023		0.20 ± 0.02	0.20 ± 0.03
ANDES	0	0.46 ± 0.15	0.97 ± 0.15	0.26 ± 0.071		0.7 ± 0.1	0.7 ± 0.2
TAIPAN	0.1	0.89 ± 0.12	0.78 ± 0.11	0.83 ± 0.21		0.83 ± 0.08	0.8 ± 0.1
CAP ROMUALD	14.7	0.24 ± 0.099	0.2 ± 0.029	0.066 ± 0.017	0.17 ± 0.077	0.20 ± 0.03	0.20 ± 0.07
BUNGA KELANA 10	0		0.17 ± 0.025	0.097 ± 0.035		0.17 ± 0.03	0.17 ± 0.03
BUNGA KELANA 10	0		0.097 ± 0.014	0.086 ± 0.027		0.10 ± 0.01	0.10 ± 0.01
BRITISH PURPOSE*	0.1	0.21 ± 0.043	0.2 ± 0.029	0.051 ± 0.014		0.14 ± 0.02	0.17 ± 0.03
BRITISH PURPOSE	0.1		0.11 ± 0.016	0.26 ± 0.071		0.11 ± 0.02	0.11 ± 0.02

*denotes average of ships sampled consecutively, at the same speed

Table S2. Black Carbon Emission Factors from Ships with Medium Speed Diesel Engines

Ship Name	Speed (kts)	PAS EF_{BC} g-BC (kg fuel)$^{-1}$	PSAP EF_{BC} g-BC (kg fuel)$^{-1}$	SP2 EF_{BC} g-BC (kg fuel)$^{-1}$	SP-AMS EF_{BC} g-BC (kg fuel)$^{-1}$	Weighted Average EF_{BC} g-BC (kg fuel)$^{-1}$	Average EF_{BC} g-BC (kg fuel)$^{-1}$
				Fishing			
MILLER FREEMAN	11.9	0.46 ± 0.056	0.48 ± 0.053	0.15 ± 0.038	0.5 ± 0.155	0.47 ± 0.04	0.48 ± 0.09
MILLER FREEMAN	4.8	0.29 ± 0.063	0.34 ± 0.088	0.18 ± 0.049		0.31 ± 0.05	0.32 ± 0.08
MILLER FREEMAN	2.9	0.09 ± 0.0094	0.04 ± 0.0051	0.02 ± 0.006	0.08 ± 0.0248	0.052 ± 0.004	0.07 ± 0.01
MILLER FREEMAN	6.9	0.14 ± 0.022	0.18 ± 0.024	0.08 ± 0.02	0.18 ± 0.0558	0.16 ± 0.02	0.17 ± 0.03
MILLER FREEMAN	6.9	0.23 ± 0.031	0.2 ± 0.031	0.11 ± 0.03	0.16 ± 0.0496	0.21 ± 0.02	0.2 ± 0.04
MILLER FREEMAN	10.2	0.43 ± 0.054	0.48 ± 0.059	0.24 ± 0.06	0.4 ± 0.124	0.45 ± 0.04	0.44 ± 0.08
				Tow			
LAGUNA	7.5		0.34 ± 0.05	0.13 ± 0.04		0.34 ± 0.05	0.34 ± 0.05
MIKE BRUSCO	11	0.15 ± 0.021	0.22 ± 0.032	0.09 ± 0.02		0.17 ± 0.02	0.18 ± 0.03
MIKE BRUSCO	4.2	1.5 ± 0.2	2.2 ± 0.32	0.9 ± 0.2		1.7 ± 0.2	1.9 ± 0.3
ROBYN J	6	0.25 ± 0.054	0.22 ± 0.033	0.14 ± 0.04		0.23 ± 0.03	0.24 ± 0.04
REBEL2	7.9	1.5 ± 0.21	1.4 ± 0.21	0.13 ± 0.03		1.4 ± 0.2	1.4 ± 0.21
REBEL2	7.8	1.2 ± 0.18	1.2 ± 0.18	1.0 ± 0.3		1.2 ± 0.1	1.2 ± 0.2
MIKIONA	6.8		0.13 ± 0.018	0.06 ± 0.02		0.13 ± 0.02	0.13 ± 0.02
				Tug			
LEADER	7.7		0.25 ± 0.063	0.07 ± 0.02		0.25 ± 0.06	0.25 ± 0.06
TIM QUIGG	0.1		0.11 ± 0.017	0.10 ± 0.02		0.11 ± 0.02	0.11 ± 0.02
JEFFREY M*	8.6		0.48 ± 0.07	0.44 ± 0.08		0.5 ± 0.07	0.5 ± 0.07
GOLIAH	7.2	0.38 ± 0.05	0.32 ± 0.046			0.35 ± 0.03	0.35 ± 0.05
ROYAL MELBOURNE	4.4	5.4 ± 0.73	2 ± 0.28	2.4 ± 0.61		2.4 ± 0.3	3.7 ± 0.5
DELTA CAPTAIN	7.8	0.25 ± 0.033	0.71 ± 0.1	0.15 0.04		0.3 ± 0.03	0.48 ± 0.07

*denotes average of multiple plumes sampled consecutively, at the same speed

Table S3. Black Carbon Emission Factors from Ships with High Speed Diesel Engines

Ship Name	Speed (kts)	PAS EF_{BC} g-BC (kg fuel)$^{-1}$	PSAP EF_{BC} g-BC (kg fuel)$^{-1}$	SP2 EF_{BC} g-BC (kg fuel)$^{-1}$	SP-AMS EF_{BC} g-BC (kg fuel)$^{-1}$	Weighted Average EF_{BC} g-BC (kg fuel)$^{-1}$	Average EF_{BC} g-BC (kg fuel)$^{-1}$
High Speed Craft							
JET CAT EXPRESS	28.4		0.48 ± 0.07	0.21 ± 0.06		0.48 ± 0.07	0.48 ± 0.07
JET CAT EXPRESS	28.4				0.44 ± 0.45	0.4 ± 0.5	0.4 ± 0.5
JET CAT EXPRESS	32.1	0.11 ± 0.099	0.11 ± 0.02	0.1 ± 0.03		0.11 ± 0.02	0.11 ± 0.02
JET CAT EXPRESS	28.8	0.16 ± 0.078	0.12 ± 0.02	0.095 ± 0.03		0.12 ± 0.02	0.14 ± 0.05
CATALINA JET	25.5		0.5 ± 0.08	0.23 ± 0.07		0.50 ± 0.08	0.5 ± 0.08
CATALINA JET	21.4		0.74 ± 0.19			0.74 ± 0.19	0.74 ± 0.19
CATALINA JET	26.3	0.8 ± 0.1	0.44 ± 0.07	0.43 ± 0.11	0.83 ± 0.29	0.55 ± 0.05	0.69 ± 0.15
CATALINA JET	24.6	0.44 ± 0.066	0.43 ± 0.06	0.37 ± 0.09		0.43 ± 0.05	0.43 ± 0.06
CATALINA JET	29	0.25 ± 0.13	0.17 ± 0.03	0.13 ± 0.04		0.18 ± 0.03	0.21 ± 0.08
STARSHIP EXPRESS	27.7		0.18 ± 0.06	0.11 ± 0.03		0.18 ± 0.06	0.18 ± 0.06
STARSHIP EXPRESS	7		0.46 ± 0.07	0.26 ± 0.26		0.46 ± 0.07	0.46 ± 0.07
STARSHIP EXPRESS	30.1		0.69 ± 0.1	0.57 ± 0.16		0.69 ± 0.10	0.69 ± 0.10
CAPT.T.LE	15.9		1.1 ± 0.15	0.8 ± 0.2		1.1 ± 0.2	1.1 ± 0.2
Pilot Boat							
PILOT BOAT WHITE	14.8		0.71 ± 0.11			0.71 ± 0.1	0.71 ± 0.1
PILOT BOAT WHITE	0		0.19 ± 0.03	0.11 ± 0.03		0.19 ± 0.03	0.19 ± 0.03
PILOT BOAT BANNING	5.5	0.9 ± 0.2		0.63 ± 0.16		0.90 ± 0.2	0.9 ± 0.2
PILOT BOAT DRAKE	7		0.27 ± 0.04	0.031 ± 0.01		0.27 ± 0.04	0.27 ± 0.04
P/V GOLDEN GATE	19.2		0.12 0.03	0.07 ± 0.02		0.12 ± 0.03	0.12 ± 0.03

Table S3. Continued

Ship Name	Speed (kts)	PAS EF_{BC} g-BC (kg fuel)$^{-1}$	PSAP EF_{BC} g-BC (kg fuel)$^{-1}$	SP2 EF_{BC} g-BC (kg fuel)$^{-1}$	SP- AMS EF_{BC} g-BC (kg fuel)$^{-1}$	Weighted Average EF_{BC} g-BC (kg fuel)$^{-1}$	Average EF_{BC} g-BC (kg fuel)$^{-1}$
			Passenger				
ALAN T	0.2		3.3 ± 0.48			3.3 ± 0.48	3.3 ± 0.48
MAJESTIC	11.8		0.06 ± 0.02	0.034 ± 0.013		0.06 ± 0.02	0.06 ± 0.02
MARINER OF THE SEAS	18		0.05 ± 0.01	0.036 ± 0.01		0.049 ± 0.007	0.049 ± 0.007
MARINER OF THE SEAS	15.7	0.1 ± 0.014	0.1 ± 0.02	0.075 ± 0.02		0.10 ± 0.01	0.10 ± 0.01
CAT EXPRESS	26	0.51 ± 0.075	0.49 ± 0.07	0.34 ± 0.09		0.5 ± 0.05	0.5 ± 0.07
NAPA	28.9	0.24 ± 0.032	0.17 ± 0.03	0.1 ± 0.03		0.20 ± 0.02	0.21 ± 0.03
SOLANO	33.4	0.51 ± 0.07	0.49 ± 0.07	0.32 ± 0.08		0.5 0.05	0.5 ± 0.07
MARIN	22.1	0.49 ± 0.064	0.45 ± 0.07	0.31 ± 0.08		0.47 ± 0.05	0.47 ± 0.06
ENCINAL	22.9	1 ± 0.14	0.83 ± 0.12	0.63 ± 0.16		0.91 ± 0.09	0.93 ± 0.13
			Cruise Ship				
CARNIVAL SPLENDOR	20.6	0.11 ± 0.022	0.08 ± 0.01	0.024 ± 0.008	0.067 ± 0.03	0.08 ± 0.01	0.09 ± 0.02
CARNIVAL SPLENDOR	11.1	0.047 ± 0.016	0.04 ± 0.01	0.022 ± 0.006		0.044 ± 0.006	0.05 ± 0.01
CARNIVAL PARADISE	12.3	0.2 ± 0.059	0.07 ± 0.01	0.05 ± 0.01	0.14 ± 0.05	0.08 ± 0.01	0.14 ± 0.04

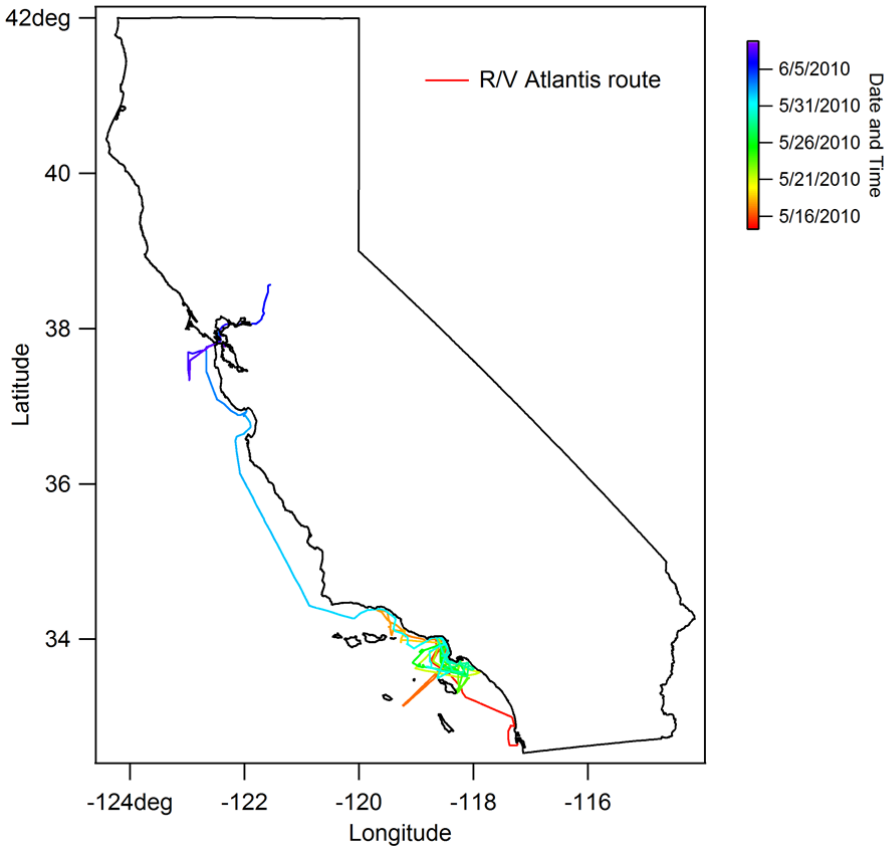

Figure S1. Map of California, with *R/V* Atlantis travel route colored by date and time

.

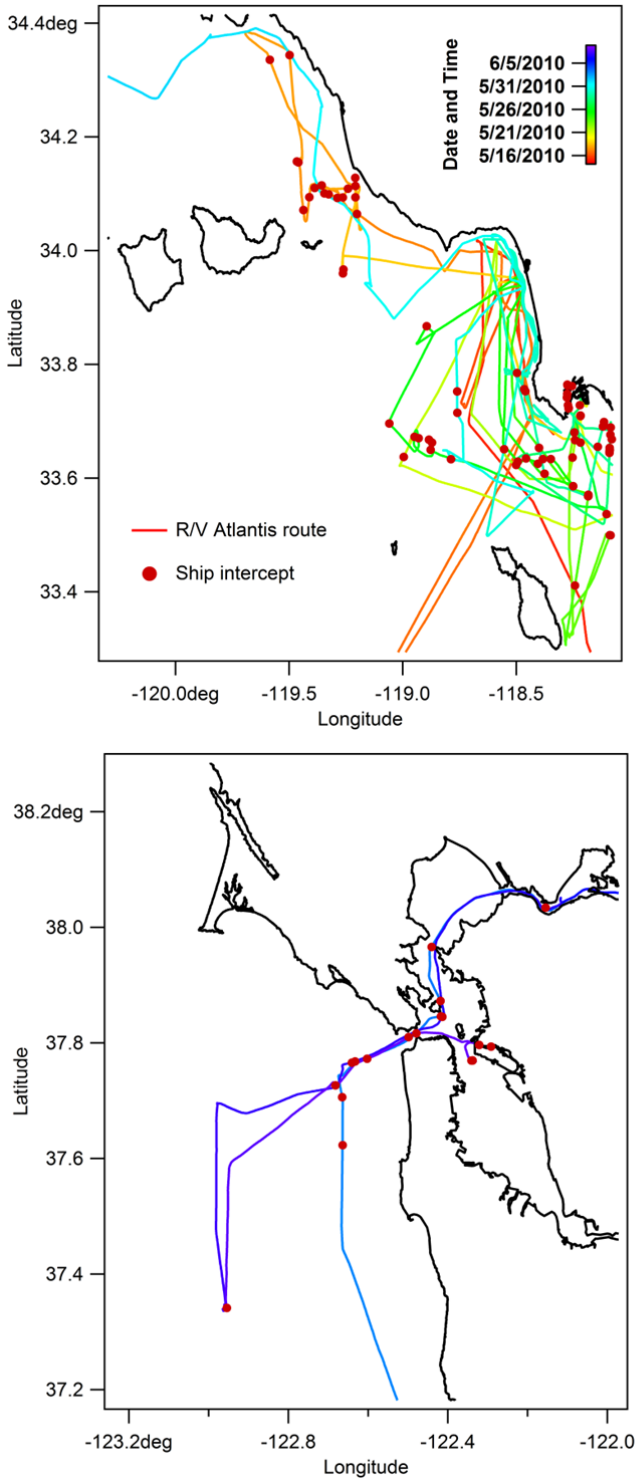

Figure S2. (Top) Map of the California coast near Los Angeles, showing R/V *Atlantis* travel route as rainbow colored line (where color indicates the date and time) and the location of ship plume intercepts by red dots. (Bottom) Same as top map, but for the California coast near San Francisco.

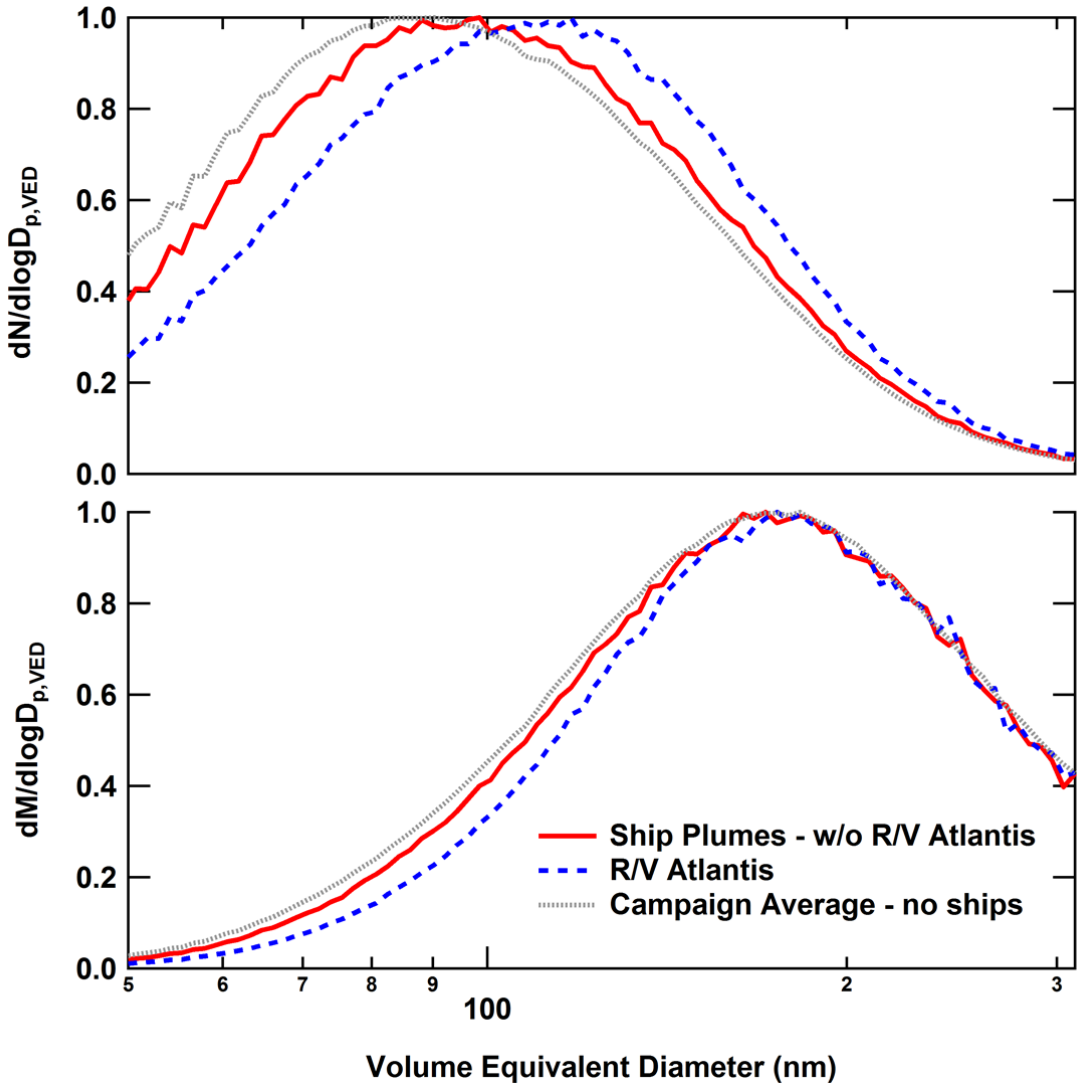

Figure S3. Average normalized, number-weighted (top) and mass-weighted (bottom) size distributions for the rBC component of particles. These are the same size distributions as shown in Error! Reference source not found. in the main text, but where a size-independent detection efficiency of 0.7 has been applied.