

1 **Size-resolved observations of refractory black carbon particles in cloud droplets at a**
2 **marine boundary layer site.**

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14

15 **Abstract**

16

17 Size resolved observations of aerosol particles and cloud droplet residuals were studied at a
18 marine boundary layer site (251 m a.m.s.l.) in La Jolla, CA during 2012. A counterflow virtual
19 impactor (CVI) was used as the inlet to sample cloud residuals while a total inlet was used to
20 sample both cloud residuals and interstitial particles. Two cloud events totaling ten hours of in-
21 cloud sampling were analyzed. Based on bulk aerosol particle concentrations, mass concentrations of
22 refractory black carbon (rBC) and back trajectories, the two air masses sampled were classified as
23 polluted marine air. Since the fraction of cloud droplets sampled by the CVI was less than 100
24 %, the measured activated fractions of rBC should be considered as lower limits to the total
25 fraction of rBC activated during the two cloud events. Size distributions of rBC and a coating
26 analysis showed that sub-100 nm rBC cores with relatively thick coatings were incorporated
27 into the cloud droplets. For example, 95 nm rBC cores with median coating thicknesses of at
28 least 65 nm were incorporated into the cloud droplets. Measurements also show that the coating
29 volume fraction of rBC cores is relatively large for sub-100 nm rBC cores. For example, the
30 median coating volume fraction of 95 nm rBC cores incorporated into cloud droplets was at
31 least 0.9, a result that is consistent with kappa-Köhler theory. Measurements of the total
32 diameter of the rBC containing particles (rBC core + coating) suggest that the total diameter of

1 rBC containing particles needed to be at least 165 nm to be incorporated into cloud droplets
2 when the core rBC diameter is ≥ 85 nm. This result is consistent with previous work that has
3 shown that particle diameter is important for activation of non-rBC particles. The activated
4 fractions of rBC, determined from the measurements ranged from 0.01 to 0.1 for core rBC
5 diameters ranging from 70 to 220 nm. This type of data is useful for constraining models used
6 for predicting rBC concentrations in the atmosphere.

7 8 **1. Introduction**

9
10 Black carbon (BC) is a subset of the aerosol population that is emitted as a result of
11 incomplete combustion. Since BC particles strongly absorb solar radiation, they can modify
12 the climate directly. Based on the current best-estimates the BC direct radiative forcing from
13 all present day sources is $+0.88 \text{ W m}^{-2}$; however, this the uncertainty associated with this
14 number is approximately 90%. The uncertainty in the BC direct radiative forcing estimates
15 stems from several factors, which include the removal rates of BC from the atmosphere
16 through wet or dry deposition (Bond et al., 2013). BC particles can also potentially act as
17 cloud condensation nuclei (CCN) and contribute to the indirect effects of aerosols on climate
18 (Bond et al., 2013). The current best estimates of the indirect radiative forcing of BC is $+0.23$
19 W m^{-2} (Bond et al., 2013). However, similar to the direct radiative forcing estimate, this
20 indirect radiative forcing estimate is also highly uncertain, with an uncertainty of
21 approximately 90% (Bond et al., 2013). The uncertainty in the indirect effect radiative forcing
22 estimate is partially due to an uncertainty in BC-cloud interactions (Bond et al., 2013). To
23 better understand the direct and indirect effects of BC on climate, a better understanding of
24 the activation of BC into cloud droplets is needed.

25 Despite the importance of activation of BC particles into cloud droplets there have only
26 been a small number of studies that have investigated the activation of BC particles into cloud
27 droplets under real atmospheric conditions (see Table 1 in (Cozic et al., 2007) as well as Pratt
28 et al., 2010 and Granat et al., 2010). Of these studies, most have been carried out at mid to
29 high altitude mountain sites (Cozic et al., 2007; Hittenberger et al., 2000, 2001; Kasper-Giebl
30 et al., 2000; Sellegri et al., 2003). Only a few studies have investigated the activation of BC
31 particles at a marine or coastal site (Gieray et al., 1997; Granat et al., 2010). In addition,
32 almost all of the previous studies have focused on the fraction of total BC mass activated into

1 cloud droplets. For example, (Hallberg et al., 1992) measured the mass scavenging of BC into
2 fog droplets at a polluted site in the Po Valley (Italy). They found that the mass fraction of
3 scavenged BC (0.06) was statistically smaller than the scavenged fraction of sulphate (0.18).
4 Similar results were obtained when sampling stratocumulus clouds at a mountaintop site at
5 Kleiner Feldberg Germany. There a statistically significant difference in scavenging was also
6 observed; the scavenged fraction of sulphate at this site was 0.52 while the scavenged fraction
7 of BC was 0.15 (Hallberg et al., 1994). In this latter case, observations showed that BC
8 particles found as cloud droplet residuals were of mixed composition, often having a water-
9 soluble component that varied as a function of size. These studies are not able to determine
10 the relative contribution of particle size and composition to the activation of BC into clouds.
11 Although, the fraction of total BC mass activated is useful for validating models, the CCN
12 properties of rBC containing particles are more closely linked to number and particle size.

13 Recent studies have compared concentrations of BC particles measured over the central
14 Pacific from 85°N to 67°S during the HIAPER (High-Performance Instrumented Airborne
15 Platform for Environmental Research) Pole-to-Pole Observations (HIPPO) campaign, with
16 predictions using a global chemical transport model (Wang et al., 2014). The authors
17 concluded that most models may not be accurately simulating the scavenging of BC particles
18 into cloud droplets (Wang et al., 2014). To help better constrain these models, additional
19 studies on the activation of BC into cloud droplets under real atmospheric conditions and at
20 different locations and times would be helpful.

21 The single particle soot photometer (SP2) is an instrument recently developed to determine
22 the refractory black carbon (rBC) mass of individual particles. With this instrument, size
23 distributions of rBC can be obtained in real time. In addition, this instrument provides
24 information on coating thicknesses of the rBC containing particles. The SP2 has now been
25 used extensively to determine the size distribution and coating thicknesses of rBC particles in
26 the atmosphere. Here, we apply this technique to investigate the activation of rBC particles in
27 stratocumulus clouds at a marine boundary layer site. Specific questions to be addressed
28 include the following: (1) what is the activated fraction of rBC as a function of particle size in
29 the marine stratocumulus clouds studied? (2) Do small (sub-100 nm) rBC cores get
30 incorporated into the cloud droplets? (3) What is the thickness of the coating on the rBC cores
31 that are incorporated into the cloud droplets? (4) Is the rBC coating volume fraction and the

1 total diameter (rBC core + coating thickness) important for activation of rBC into cloud
2 droplets? (5) Are the results consistent with kappa-Köhler theory, which is used in advanced
3 modelling studies to describe the activation of rBC particles into cloud droplets (e.g. (Fierce et
4 al., 2013; Riemer et al., 2010)).

5

6 **2. Site, sampling and analysis**

7

8 **2.1. Site description**

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10 The sampling site was located below the peak of Mt. Soledad (251 m a.m.s.l.) which is ~ 2 km
11 off the coast of the Pacific Ocean in La Jolla, CA (32.8400° N, 117.2769° W) with mostly light
12 commercial and residential activities in the area. The city of La Jolla is predominately residential
13 with a population of approximately 43,000 people and is situated 24 km north of San Diego
14 (population 1.3 million), the closest urban center (Zhao et al., 2014). The cloud periods
15 occurred primarily at night when these activities are at a minimum.

16

17 Data was collected from 27 May to 18 June 2012 using instruments housed in a modified
18 shipping container. A total of three stratocumulus cloud events were sampled during this time
19 frame. The first cloud event was excluded from this analysis due to an instrumental error. The
20 second cloud event occurred from 12 June 2012 20:43 to 13 June 2012 11:35 PDT, and
21 hereinafter called Cloud 2. The third cloud event took place from 17 June 2012 20:36 to 18 June
22 2012 07:52 PDT, and called Cloud 3 for the remainder of the document.

23

24 **2.2. Inlets**

25

26 Two inlets, referred to as the total inlet and residual inlet, were used during this study (Fig. 1).
27 The total inlet measured both interstitial and cloud residual particles during cloud events. This
28 heated inlet was designed and built following the specifications reported by Bates et al. (2002)
29 and therefore assumed to have the same transmission efficiency, namely > 95% for particles less
30 than 6.5 μm , using a ~900 LPM bypass flow. The instruments sampling from the plenum of the
31 total inlet (Fig.1) were connected sequentially to a common sampling line (0.25 inch stainless steel
32 tubing). A pump was placed at the end of this sampling line creating a bypass flow of ~2 LPM.

33

34 The intake of the residual inlet was a counterflow virtual impactor (see Sect. 2.3 and

1 Supplementary Material Sect.S1) that enabled the sampling of cloud droplets without
2 contamination from interstitial particles, or ambient gases, thus only the residual particles of the
3 cloud droplets were sampled. This inlet was used only during cloudy periods and was
4 connected to a branch of the total inlet by a 3-way valve (Fig.1). During a cloud event, the valve
5 was manually switched so that cloud droplets were sampled through the counterflow virtual
6 impactor (CVI) and cloud residuals were measured by instrumentation connected downstream
7 of the valve. At times when no clouds were present the valve was switched such that all
8 instruments were sampling ambient particles. All instruments downstream of the 3-way valve
9 were sequentially connected to a common sampling line (0.25 inch stainless steel tubing). A
10 pump was also placed at the end of the sampling line creating a bypass flow of ~2 LPM.

11
12 Since much of the analysis used in this paper is based on a measured ratio of particle
13 number concentrations it was necessary to ensure that there were no significant losses of
14 particles due to the inlet configurations. Therefore, particle losses from diffusion,
15 sedimentation, turbulent inertial deposition and inertial deposition from both bends and
16 contractions for the total and residual inlets (assuming cloud free sampling) were calculated
17 using the Particle Loss Calculator (Von der Weiden et al., 2009) and found to be < 2% for
18 particles with diameters between 0.07 and 1 μm , covering the size range used for this analysis.

19 20 **2.3. Counterflow virtual impactor sampling**

21
22 The CVI was based on the design of Noone et al., 1988., where droplet laden air was drawn into
23 the CVI using a high velocity air intake vacuum ($\approx 92 \text{ m s}^{-1}$). Only those droplets with enough
24 inertia to overcome a counterflow of zero air with an average flow rate of $\approx 5 \text{ LPM}$ made it past the
25 region known as the stagnation plane and were entrained into the sample flow and transported to the
26 instruments downstream. Water from these droplets began evaporating upon impact with the
27 warm dry counterflow air, held at a constant temperature of 40 °C, and particles were further
28 dried by a heated section of the sampling tube, also at 40 °C, leaving only the droplet residuals
29 to be sampled downstream. If the droplets were completely evaporated, any volatile gases in the
30 cloud droplets, such as nitric acid, likely evaporated and were not part of the residual particles
31 (Zhao et al., 2014) . If some water was retained by the residual particles at this temperature, a
32 fraction of highly soluble volatile components may have also remained.

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The smallest droplet diameter for which 50% of the droplets are sampled is considered to be the CVI cut-size (CVI-D₅₀) and is the diameter for which a droplet's stopping distance is greater than the CVI inlet diameter and the length to the end of the stagnation plane (Anderson et al., 1993; Noone et al., 1988). For the clouds sampled in this study a CVI-D₅₀ of $11.5 \pm 0.7 \mu\text{m}$ and $11.6 \pm 0.7 \mu\text{m}$ for Cloud 2 and Cloud 3, respectively, were calculated (see Supplementary Material Sect. S1 for details).

Due to the properties of a CVI, particle concentrations are enhanced at the exit of the CVI compared to ambient conditions. Enhancement factors (EF) of 7.1 and 7.4 for Cloud 2 and Cloud 3, respectively, were calculated based on the flow rates used during sampling (see Supplementary Material Sect. S1).

2.4. Black carbon measurements

Refractory black carbon (rBC) was measured from the total inlet and the residual inlet using two separate single particle soot photometers (SP2, DMT, Boulder, CO). These instruments are referred to as the total SP2 (SP2_{Tot}) and the residual SP2 (SP2_{Res}). The location of these instruments is shown in Fig.1. The SP2 has been described in detail elsewhere (Moteki and Kondo, 2007; Schwarz et al., 2006; Stephens et al., 2003). Briefly, particles are sampled at $\approx 0.12 \text{ LPM}$ and carried directly into a chamber housing a high intensity ($\approx 1 \text{ MW cm}^{-2}$) intra-cavity Nd:YAG laser operating at $\lambda = 1064 \text{ nm}$. BC particles are rapidly heated, through absorption, to incandescence, where the emitted visible light is detected by two photomultipliers. The mass of individual rBC particles can be determined using a calibration plot, where the amplitude of the detector response is proportional to the mass of a reference material. The two SP2s used in this study were calibrated pre and post-campaign with Aquadag[®] (Moteki et al., 2009), using effective densities reported by Gysel et al., 2011. Based on the recommendations by Baumgardner et al., 2012, the average peak heights determined for each of the Aquadag[®] sizes were scaled downward by 0.75 since Aquadag[®] has been shown to cause a higher SP2 signal response per unit mass than ambient BC.

The calibration parameters used to determine mass were taken from a linear fit of the combined pre and post-campaign data. The uncertainty in the rBC mass (at the 95% confidence

1 limit) stemming from uncertainty in the fit of the calibration was 1-16% for SP2_{Res} (depending
2 on particle mass) and 3-25% for SP2_{Tot} (depending on particle mass). A volume equivalent
3 diameter was also determined from the measured mass assuming a black carbon density of 1.8
4 g cm⁻³ (Bond and Bergstrom, 2006). The SP2_{Res} was a 4 channel instrument with a detection
5 range of approximately 70 to 220 nm, whereas the SP2_{Tot} was an 8 channel instrument with a
6 detection range of 70 to 558 nm.

7 It is well known that the detection efficiency of an SP2 decreases when the diameter of rBC
8 cores becomes small (i.e. <~70-90 nm) (Laborde et al., 2012; Schwarz et al., 2010). Since the
9 main conclusions about black carbon in this manuscript are based on relative measurements
10 taken with two SP2s (i.e. the residual SP2 and the total SP2) the detection sensitivities of the
11 two instruments as a function of size need to be similar. To ensure that this was the case, we
12 carried out the following test: We measured the rBC size distributions with both SP2s from side
13 by side ambient sampling of room air during the post-campaign calibration. Since the two
14 instruments gave slightly different results, we applied a size dependent correction factor to the
15 SP2 connected to the total inlet to bring the two results in agreement. Shown in Fig. S 1 are rBC
16 size distributions measured during cloud free sampling conditions before the corrections were
17 applied, the size dependent correction factor applied to the total SP2, and the rBC size
18 distributions measured during cloud free sampling after the correction factors were applied.
19 After applying the correction factors to the total SP2, the two SP2s agreed to within 6% for the
20 total number concentration of rBC particles having diameters between 70 and 220 nm.

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22 **2.5. Refractory black carbon coating thickness measurements**

23 In addition to measuring the incandescence signal, the SP2 measures the elastically scattered
24 light from rBC and non-rBC containing particles with two avalanche photodiodes (APDs). Both
25 APDs were set to the high gain setting for collection, and one of the APDs was a split detector.
26 The APDs generate a time dependent signal as particles pass through the Gaussian laser beam.
27 The split detector APD can be used to obtain position information, whereas the APD without
28 the split detector is used to obtain information on the elastic scattering intensity from particles
29 (Gao et al., 2007). The information from the two APDs combined can be used to determine the
30 coating thickness on rBC cores as described by Gao et al., 2007. However, in the Soledad
31 studies a large fraction of rBC particles evaporated before the notch position in the split

1 detector, due to poor alignment of the split detector. As a result, position information could not
2 be obtained reliably for a large fraction of the rBC particles. A similar observation has
3 previously been reported (Taylor et al., 2014). Since position information could not be
4 determined reliably for a large fraction of rBC particles, coating thicknesses were not
5 determined using the approach described by Gao et al., 2007. Instead, we used the maximum
6 intensity in the elastic scattering signal from the non-split APD detector to determine lower
7 limits to the coating thickness on the rBC particles. A similar approach has been previously
8 used (Subramanian et al., 2010). This coating analysis was only performed on the data from the
9 residual SP2. In other words, we only extracted coating information for rBC containing particles
10 sampled from the residual inlet. When a rBC containing particle intersects with the laser beam
11 the particles are heated, and any coating material can evaporate. As a result, the maximum
12 elastic scattering signal measured with the non-split APD detector may not represent the
13 original size of the coated rBC particle. Because of the evaporation process, the maximum
14 intensity from the non-split APD detector only provides a lower limit to the coating thicknesses
15 of rBC containing particles (Gao et al., 2007; Subramanian et al., 2010).

16
17 The signal from the non-split detector was calibrated using polystyrene latex (PSL) beads (200
18 and 300 nm in diameter). This gives a calibration curve that relates the amplitude of the
19 measured scattering signal to the scattering intensity determined from Mie calculations. These
20 Mie calculations involved calculating the scattering intensity for each PSL size over the solid
21 angle of the SP2 detector (a full-angle cone of 65° at 45° and 135° from the laser axis (Gao et al.,
22 2007; Schwarz et al., 2008b) using a Mie code (Leinonen) based on that of (Mätzler, 2002a,
23 2002b). The refractive index used for the PSL Mie calculations was $1.59-0.0i$.

24
25 Since the mass of the rBC core is known from the incandescence signal and the scattering
26 amplitude is known from the non-split APD detector, a core-shell Mie model can be employed to
27 determine what coating thickness would give the measured scattering signal for that particular
28 particle (Gao et al., 2007; Schwarz et al., 2008b). In this work a core-shell Mie model was used to
29 construct a lookup table for core diameters of 60 to 220 nm (in 1 nm increments) and shell
30 thicknesses from 0 to 360 nm (in 1 nm increments). The complex index of refraction used for the
31 core was $2.26-1.26i$ (Moteki et al., 2010; Taylor et al., 2014) and for the shell was $1.5-0.0i$,

1 which is consistent with that of dry sulfate or sodium chloride (Metcalf et al., 2012; Schwarz et
2 al., 2008a, 2008b). The PSL calibration was used to scale all calculated values to measured
3 values. The elastic scattering amplitudes and the rBC core diameters were then used with this
4 lookup table to determine lower limits to the coating thicknesses for each rBC containing
5 particle. It should be noted that the coating thicknesses have not been validated experimentally,
6 but merely provide consistency between the observed optical scattering and Mie theory.

7 For small particles, although the incandescence measurements can size rBC cores down to
8 ~70nm, the SP2 elastic scattering optical detection limit means that scattering from bare rBC
9 cores below ~110 nm cannot be measured. As particle size decreases below 110 nm, thicker
10 and thicker coatings are required to produce a measureable scattering signal. In this analysis
11 any particle with no measureable scattering signal was assumed to have a coating thickness of 0
12 (i.e. they were assumed to be bare rBC cores), even though they may actually have had a thin
13 coating. This also leads to a lower limit for coating thicknesses for particles below ~110 nm.
14 The fraction of particles with no detectable scattering was 33% for Cloud 2 and 17% for Cloud
15 3.

16 For large rBC cores the optical detector became saturated when even relatively modest
17 coatings are present. For example, the scattering from a 220 nm rBC core with a coating
18 thickness of 40 nm would saturate the SP2 optical detector. In this analysis, the coatings for
19 particles with saturated scattering signals were calculated using the saturation limit of the
20 detector, again resulting in a lower limit for coating thickness. The fraction of particles with
21 saturated scattering signals was 6% for cloud event 2 and 4% for cloud event 3.

22 In summary, due to the optical detection limits of the non-split detector and due to
23 evaporation of the coatings in the laser beam, the coating thicknesses determined in this work,
24 are lower limits to the true coating thicknesses.

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28 **2.6. Size distribution measurements of the bulk aerosol**

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30 Two instruments were used to measure size distributions of the bulk aerosol (see Fig.1). Size
31 distributions of the bulk aerosol sampled from the total inlet were determined with a scanning
32 electrical mobility spectrometer (SEMS, model 2002, BMI, Hayward, CA) coupled to a

1 condensation particle counter (CPC, model 3781, TSI, St. Paul, MN), which counted particles
2 into 61 discrete size bins from 0.01-1 μm with a 5 min scan time interval. Size distributions of
3 bulk aerosol, sampled from the residual inlet, were determined with a scanning mobility particle
4 sizer (SMPS, model 3034, TSI, St. Paul, MN), which recorded particle counts into 55 size bins
5 from 10-487 nm with a 3 min scan time interval. Both the SEMS and SMPS operate based on
6 the coupling of a size selecting differential mobility analyzer and a condensational growth
7 particle counter. During cloud free sampling periods the total number concentration of particles
8 between 70 and 400 nm measured with the SMPS and SEMS agreed to within 4%.

9 10 **2.7. Aerosol mass spectrometry**

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12 To characterize the chemical composition of the cloud droplet residuals an online aerosol mass
13 spectrometer (HR-ToF-AMS, Aerodyne Research Inc., Billerica, MA) was operated
14 downstream of the CVI on the residual inlet. The HR-ToF-AMS measures non-refractory, sub-
15 micrometer aerosol chemical composition at high time resolution (DeCarlo et al., 2006). Here
16 we only consider data measured by the HR-ToF-AMS in its mass-spectrum and V-modes of
17 operation. These data were recorded as 2 minute averages every 4 – 6 minutes, depending on
18 how many other modes of operation (W-mode, light scattering) the instrument was alternating
19 between. Size-resolved composition data for the residual particles measured by the HR-ToF-
20 AMS in time-of-flight mode are not considered here since the signal was generally at or below
21 the detection limit. Standard quantification procedures (Allan et al., 2004) were applied to the
22 mass spectra measured by the HR-ToF-AMS to determine the relative concentrations of the
23 non-refractory species (organic, nitrate, sulfate, ammonium and chloride) typically reported by
24 aerosol mass spectrometry.

25 26 **2.8. Back trajectories**

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28 Air mass back trajectories were calculated using the NOAA Hybrid Single Particle Lagrangian
29 Integrated Trajectory Model (HYSPLIT) (Draxler and Rolph, 2013; Rolph, 2013). All trajectory
30 calculations used the National Centers for Environmental Predictions EDAS meteorological
31 dataset. Trajectories were calculated starting at 10m a.g.l., 96 h backwards in time, and at
32 hourly intervals throughout the entire period of cloud sampling.

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2.9. Cloud properties

A fog monitor (FM-100, model 100, DMT, Boulder, CO), which is a forward scattering optical spectrometer, was located approximately 50 cm above the top of the container, 1 m from the residual inlet, and 1.5 m from the total inlet. The instrument was mounted on a freely rotating board allowing it to be turned into the wind when the wind direction was obvious. Details of the operational theory of the FM-100 can be found in Eugster et al., 2006 and Spiegel et al., 2012. Briefly, ambient droplet laden air is pumped through a wind tunnel and carried to a sizing region where droplets pass a laser beam (wavelength = 658nm). Light that is scattered in the forward direction from a droplet crossing the laser beam is collected by photodetectors and the signals measured are used to assign which size bin within which the droplet falls. From the measured cloud droplet size distribution both the total cloud droplet number concentration (CDNC) and the amount of liquid water content (LWC) present can be determined (Spiegel et al., 2012). The FM-100 used in this study collected droplet counts from droplets with the diameters from 2-50 μm using the manufacture's predefined 20 size bins. The size bin widths using this configuration were 2 μm for droplets $<20\mu\text{m}$ and 3 μm for droplets $> 20\mu\text{m}$. Calibrations of the FM-100 were performed by Droplet measurement Technologies prior to installation.

3. Results and discussion

3.1. Back trajectories

The back trajectories for Cloud 2 (Fig. 2a and c) show that the air mass spent most of the previous 96 h over the Pacific Ocean and arrived at the sampling site from a northwesterly direction. During the first part of Cloud 2 (from 12 June 21:00 to 13 June 08:00 PDT) the back trajectories became progressively more northerly and the air mass began traveling near large populated urban regions. Towards the end of the cloud event (at $\approx 09:00$ PDT on 13 June) the winds shifted to southwesterly. Based on the back trajectories the air mass for Cloud 2 traveled $\approx 40\text{-}50$ km over land before reaching the sampling site. In addition, the air mass spent a significant amount of time close to the ocean surface prior to being lifted up to the sampling site (Fig. 2c).

The back trajectories for Cloud 3 (Fig. 2b and d) also show that the air mass spent the majority of the previous 96 h over the Pacific Ocean before arriving at the site. At the start of Cloud 3 (17 June 21:00 to 22:00 PDT) the air mass arrived from the northwest. Throughout the remainder of the cloud event (17 June 23:00 to 18 June 08:00 PDT) the air mass continued to shift farther north and by the end of the cloud event (18 June 08:00 PDT) the air mass was traveling south along the coastline before arriving at the sampling site. The back trajectories indicate that the air mass traveled $\approx 10\text{-}20$ km over land prior to arriving at the sampling site. Similar to Cloud 2, the air spent a significant amount of time close to the ocean surface prior to being lifted up to the sampling location (Fig. 2d). Since the trajectories during both clouds are close to the coastline for a period of time, it is likely these air masses contained both marine

1 particles and anthropogenic emissions.

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3 **3.2. Meteorological conditions and cloud properties**

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5 For the purposes of this study, the data were classified as in-cloud and included for analysis if
6 they met the following criteria: (1) the five minute averaged CVI counterflow was within $\pm 6\%$
7 of the mean counterflow (i.e. $\pm 5\sigma$, where σ is standard deviation) to ensure only periods of stable CVI flows
8 were included; and (2) the five minute averaged LWC was greater than 0.05 g m^{-3} to remove
9 periods of entrainment, or "patchy" regions of the cloud as much as possible (Cozic et al., 2007).

10 The measured cloud properties as a function of time are shown in Fig. 3a-c, where Cloud 2
11 is shown on the left side and Cloud 3 is shown on the right side of the plot. Cloud 2 was
12 characterized by a median temperature of 13.4°C , a median wind velocity of 0.5 (10^{th} and 90^{th}
13 percentiles of 0.3 and 0.8) m s^{-1} and median wind direction of 126° (10^{th} and 90^{th} percentiles of 60 and
14 297°), and a median LWC of 0.10 g m^{-3} . During the middle portion of Cloud 2 (13 June 01:00 to
15 02:00 PDT) the droplet distributions clearly show an interval where the number of droplets
16 above the CVI–D50 (black trace overlaid on panel C) increases significantly, which coincides, in
17 time, with a sharp increase in LWC. Cloud 3 was characterized by a median temperature of 15.2
18 $^\circ\text{C}$, a median wind velocity of 1.4 m s^{-1} (10^{th} and 90^{th} percentiles of 1.1 and 2.0 m s^{-1}), a median
19 wind direction of 328° (10^{th} and 90^{th} percentiles of 322 and 341°) and a median LWC of
20 0.09 g m^{-3} .

21 The cloud droplet number and volume size distributions, averaged over the entire event, are
22 shown in Fig. 4, and further summarized in Table 1. Cloud 3 had a CDNC of 146 cm^{-3} , a factor
23 of two higher than during Cloud 2 (68 cm^{-3}).

24 From the calculated CVI–D50 and the fits to the droplet size distribution (Fig. 4) the number and
25 volume fraction of droplets sampled by the CVI were determined. The results are summarized
26 in Table 1. During Cloud 2 the number fraction of droplets larger than the CVI–D50 was about
27 38% and for Cloud 3 the fraction sampled was about 24% . Since only the larger droplets were
28 sampled by the CVI during these two cloud events, the results presented herein are only
29 representative of the larger droplet population.

30

3.3. Size Distributions

Average size distributions of the bulk aerosol particles and rBC particles measured from the total and residual inlets for both cloud 2 and cloud 3 are shown in Fig. 5. Data are plotted in two ways; on a log scale, in panels A and B and normalized to the respective maximum, in panels C and D. Table 2 summarizes the results obtained from the size distribution analysis. All size distributions shown in Fig. 5 have been corrected for differences in instrument sensitivity, and all residual distributions have been corrected for the CVI enhancement factor (see Supplementary Material Sect. S1) and droplet transmission through the CVI (see Supplementary Material Sect. S4).

3.3.1. Size distributions measured from the total inlet ($BulkAero_{Tot}$ and rBC_{Tot})

The average size distributions of the bulk aerosol measured with the total inlet (referred to as $BulkAero_{Tot}$ for the remainder of the document) and the average size distributions of the refractory black carbon measured with the total inlet (referred to as rBC_{Tot} for the remainder of the document) are shown in Fig. 5. A single mode lognormal distribution function was fit to the $BulkAero_{Tot}$ data yielding mean geometric diameters (D_g) of 108 and 81nm with geometric standard deviations (σ_g) of 1.58 and 1.70 for Cloud 2 and 3 respectively. Integration of the number distribution during Cloud 2 results in a total number concentration (N_{Tot}) for the bulk aerosol of 981 cm^{-3} . Likewise, N_{Tot} during cloud 3 were measured to be 994 cm^{-3} . Previous measurements in the marine boundary layer have classified the environment as "clean" marine if the number of particles is $\leq 300\text{-}500 \text{ cm}^{-3}$ and "polluted" marine if the number concentrations are $\geq 400\text{-}1500 \text{ cm}^{-3}$ (Andreae, 2009; Bates et al., 2000; Glantz and Noone, 2000; Hawkins et al., 2010; O'Dowd et al., 2001; Pirjola and O'Dowd, 2000; Twohy et al., 2005). Thus the particle concentrations measured at Mt. Soledad, in addition to the back trajectories, suggest that for both clouds the air masses can be classified as polluted marine aerosols. The size distributions of $BulkAero_{Tot}$ as a function of time are also included in Fig. 3d for comparison.

The rBC_{Tot} size distributions for each cloud are shown in Fig. 5. The D_g for rBC_{Tot} (assuming the number distributions are lognormal) during both events lies somewhere in the nucleation mode at $<70 \text{ nm}$, which is outside the detection range for the SP2. Integration of the rBC_{Tot}

1 distributions, from 70-220 nm, yields an N_{Tot} of 75 cm^{-3} during Cloud 2 and 62 cm^{-3} in Cloud 3.
2 Assuming a black carbon density of 1.8 cm^{-3} the total mass concentrations of rBC (M_{Tot}) are 73 and
3 62 ng m^{-3} for Clouds 2 and 3 respectively (Table 2). The $r\text{BC}_{\text{Tot}}$ mass concentrations observed at Mt.
4 Soledad were higher than concentrations measured in clean marine air (Cooke et al., 1997;
5 Shank et al., 2012), but considerably lower than concentrations measured in most urban
6 environments (see Table 1 in Metcalf et al., 2012).

7

8 **3.3.2. Size distributions measured from the residual inlet ($\text{BulkAero}_{\text{Res}}$ and $r\text{BC}_{\text{Res}}$)**

9

10 Average size distributions of the bulk aerosol measured from the residual inlet (referred to as
11 $\text{BulkAero}_{\text{Res}}$ for the remainder of the document) are also shown in Fig. 5. The size distributions
12 of the $\text{BulkAero}_{\text{Res}}$ indicate that it was mostly the larger particles of the $\text{BulkAero}_{\text{Tot}}$
13 distributions that were incorporated into the sampled cloud droplets. The size distributions of
14 $\text{BulkAero}_{\text{Res}}$ as a function of time for both cloud events are included in Fig. 3e for comparison.

15

16 The size distributions for $\text{BulkAero}_{\text{Res}}$ shown in Fig. 5 have a local minimum at 110 nm for
17 Cloud 2 and 90 nm for Cloud 3. The particles observed at sizes less than the local minima may
18 be due droplet shattering, or due to a leak in the CVI (Pekour and Cziczo, 2011;
19 Schwarzenboeck, 2000; Vidaurre et al., 2011), or possibly due to entrainment or precipitation
20 processes in the clouds (Targino et al., 2007).

21 Figure 5 also shows the size distributions of the rBC residuals measured with the CVI. Figure
22 5 shows that rBC cores smaller than 100 nm are incorporated into cloud droplets. In addition,
23 they are overall larger than the $r\text{BC}_{\text{Tot}}$. Fitting the $r\text{BC}_{\text{Res}}$ size distributions (assuming these
24 distributions are lognormal) results in mean geometric diameters of 87 and 81 nm for Cloud 2
25 and 3 respectively.

26

27 **3.4. Size resolved activated fraction**

28

29 The size resolved activated fraction [$\text{AF}(D_p)$] for rBC and the bulk aerosol were calculated by
30 taking the ratio of the number distributions measured with the residual inlet to the number
31 distributions measured with the total inlet. Prior to calculating $\text{AF}(D_p)$, a spline interpolation
32 algorithm was applied to the rBC and bulk aerosol size distributions. After a spline interpolation
33 was applied to the data, the following equation was used to calculate the size resolved activated

1 fraction:

$$2 \quad AF_{D_p} = \frac{N_{Res}(D_p) \times CF(D_p)}{N_{Tot}(D_p) \times EF \times DT} \quad (1)$$

3

4 where $N_{Res}(D_p)$ is the number of residual particles as a function of size, $CF(D_p)$ is the size-
5 resolved instrument sensitivity correction factor, $N_{Tot}(D_p)$ is the number of particles measured
6 with the total inlet as a function of size, EF is the CVI enhancement factor (Supplementary
7 Material Sect. S1) and DT is the droplet transmission factor through the CVI. Calculations of
8 the droplet transmission factor are given in the Supplementary Material Sect. S4 and plotted in
9 Fig. S3. $CF(D_p)$, which correct for variances in instrument detection efficiencies, were
10 determined from a 12 h period of cloud free air on 5 June 2012 for the bulk aerosol and from
11 side by side ambient sampling of room air during the post-campaign for rBC. Additional
12 information on the measurement of $CF(D_p)$ for rBC is given in the Supplementary Material
13 (Sect. S2).

14

15 The median $AF(D_p)$ for the bulk aerosol and rBC are presented in Fig.6, where the error bars
16 represent the 10th and 90th percentiles for each 10 nm bin. Uncoated rBC particles with sizes < 100 nm are
17 not expected to be incorporated into cloud droplets by nucleation for typical supersaturations reached in
18 stratocumulus clouds. Figure 6 a and b show that the AF of rBC cores is significant, even for core diameters
19 ≤ 100 nm. These results can be explained by the presence of large coatings surrounding the core
20 (See Sect. 3.6 below). Since the rBC size distributions were normalized to differences in
21 instrument sensitivity, the decreased rBC AF at smaller diameters is not a result of the different
22 detection efficiencies of the SP2 instruments. Figure a and b also show that during both clouds
23 the AF for rBC cores is larger than the AF for the bulk aerosol at diameters less $< \approx 150$ nm.
24 Again, this can be explained by the presence of thick coatings on the rBC cores. Since the
25 fraction of cloud droplets sampled by the CVI was < 100 %, the calculated AF should be
26 considered as lower limits to the total fraction activated during the two cloud events.

27

28 **3.5. Mechanism of incorporating rBC into cloud droplets**

29 Two possible mechanisms exist for incorporating rBC containing particles into cloud droplets:
30 nucleation scavenging and coagulation between the rBC containing particles and cloud droplets.

1 Results and calculations suggest that the dominant mechanism for incorporating rBC particles
2 into the cloud droplets studied was nucleation scavenging. First, the fraction of rBC containing
3 particles activated into cloud droplets increases as the size of the rBC cores increases (see Fig. 6a
4 and b). If coagulation dominated we would expect to see an opposite trend. Second, calculated
5 coagulation rates, together with estimated lifetimes of the cloud droplets cannot explain the
6 fraction of rBC containing particles activated into the cloud droplets - the calculated coagulation
7 rates are too small (see Supplementary Material Sect. S3).

8 9 **3.6. Lower limits to coating thickness of rBC residuals**

10 Lower limits to the coating thicknesses on the rBC cores were determined using a core and shell
11 Mie model. The median values from this analysis are shown in Fig. 6c and d, where the error
12 bars represent the 10th and 90th percentiles and the symbols represent the medians for each size
13 bin. When calculating lower limits to the coating thicknesses, the particles were idealized as a pure BC core
14 uniformly coated with a non-absorbing material, although the actual particle morphology may
15 be more complicated (Sedlacek et al., 2012). The results shown in Fig. 6c and g give a
16 qualitative explanation for why we see activation of rBC cores with sizes < 100 nm: these rBC
17 cores have relatively thick coatings, which can lower the critical supersaturation required for
18 activation. For example, 95 nm rBC cores incorporated into the cloud droplets had a median
19 coating thickness of 65 nm.
20

21 Figure 6c and d shows that as the rBC core diameter increased from 75 to approximately 100
22 nm the lower limit to the coating thickness also increased. This is likely because as the rBC core
23 diameter increased from 75 to 100 nm, the fraction of particles above the optical detection limit
24 increased. Recall, that for rBC containing particles with diameters < \approx 100 nm a relatively large
25 fraction of the coated particles are below the optical detection limits and hence are assigned a
26 coating thickness of zero (see Sect. 2.5). After the median coating thickness reached a maximum
27 at an rBC core diameter of approximately 100 nm, the lower limit to the coating thickness
28 decreased with an increase in rBC core diameter. This may suggest that the larger rBC cores had
29 thinner coatings than the smaller rBC cores that were incorporated into the cloud droplets. Part of
30 the decrease in the lower limit to the coating thickness with an increase in rBC core diameter
31 could be due to saturation of the optical detector. As mentioned in Sect. 2.5, the optical detector
32 became saturated when the rBC cores were relatively large and contain a modest coating. For

1 example, the scattering from a 220 nm rBC core with a coating thickness of 40 nm will saturate
2 the detector.

3 In Fig. 6c and h we plotted the overall diameter of the rBC containing particles. In other
4 words, we plotted the sum of the rBC core diameter plus 2 x the coating thickness. If we
5 disregard the point at 75 nm (which is likely strongly influenced by the fact that a large fraction
6 of the rBC containing particles, with this core size, are below the optical detection limit) we
7 conclude that in order for the rBC containing particles to be incorporated into the cloud droplets
8 the overall median diameter of rBC containing particles must be at least 165 nm in diameter.
9 Figure 6c and h suggest that the overall diameter of the rBC containing particles is important for
10 activation. This finding is consistent with previous work that has shown that particle diameter is
11 important for activation of non-rBC containing particles (e.g. see Wang et al., 2008).

12 To further investigate the factors that control activation of the rBC containing particles we
13 plotted the coating volume (Fig. 6d and h) and coating volume fraction (Fig. 6e and j) as a
14 function of rBC core diameter. For discussion purposes we focus on the coating volume fraction
15 as a function of size and rBC core diameters ≥ 85 nm. As discussed above, coating volume
16 fraction at 75 nm rBC core diameter, is likely strongly influenced by the fact that a large fraction
17 of rBC containing particles, with this core size, are below the optical detection limit. Figure 6e
18 and j show that for rBC core diameters from 85 to 95 nm, the median coating volume fraction is
19 at least 0.9. This finding also gives a qualitative explanation for why we see relatively large
20 activated fractions of small rBC cores in the cloud residuals.

21 As the rBC core diameter increased past approximately 100 nm, the lower limit to the coating
22 volume fraction decreased. This could be because larger rBC cores need less coating material in
23 order to be incorporated into cloud droplets. Part of the decrease in coating volume fraction at
24 rBC core diameters above 100nm could also be due to the saturation limit of the optical
25 scattering detectors, as discussed above.

26

27 **3.7. In-cloud aqueous phase chemistry**

28 In the discussion above, we assume the coatings on the rBC cores were present before
29 incorporation into the cloud droplets. However, some of the coating material may have formed
30 after the rBC cores were incorporated into the cloud by aqueous phase chemistry. As mentioned
31 in the Supplementary Material, the upper limit to residence times of air parcels in the clouds

1 sampled at Soledad were likely 1 h. Whether significant aqueous phase chemistry can occur on
2 this time scale depends on the level of SO₂ and oxidants. When SO₂ is absorbed by a cloud
3 droplet, it partitions in different forms as a function of pH: at lower pH values, the primary
4 aqueous phase oxidant of dissolved SO₂, or S(IV) is H₂O₂; for higher pH values, ozone and
5 catalyzed aerobic oxidation are important oxidation pathways. Depending on the pH and
6 available oxidants, conversion of the dissolved S(IV) to S(VI) can be fast or slow. The
7 absorption of large amounts of HNO₃ or N₂O₅ can reduce the pH significantly, which will
8 require the presence of H₂O₂ in order to significantly convert S(IV) to S(VI). Since the clouds at
9 Soledad were mostly overnight, the primary oxidant (H₂O₂) was likely lower (and probably near
10 zero). Also, analysis of the cloud water indicated that nitrate was high, and thus the pH was
11 probably low. Based on these factors, we suspect that aqueous phase production of sulfate was
12 not large. However, a quantitative estimate of the sulfate produced is not possible since the
13 measurements of SO₂ and H₂O₂ were not performed at this site. Based on the discussion above,
14 we assumed that a large fraction of the coatings were present before rBC particles were
15 incorporated into the cloud droplets. However, the production of coating material from in-cloud
16 aqueous phase chemistry cannot be ruled out.

17

18

19 **3.8. Comparison of rBC_{Res} as a function of size with predictions based on κ-Köhler theory**

20

21 Sections 3.4 and 3.6 provide a qualitative explanation for how small rBC cores are
22 incorporated into cloud droplets – the rBC cores have thick coatings which leads to overall
23 particles diameters greater than approximately 165 nm. In the following we expand on this
24 qualitative explanation by carrying out a quantitative analysis that shows that the presence of
25 small rBC cores in the cloud residuals is consistent with kappa-Köhler theory. This quantitative
26 analysis consists of the following steps: (1) an estimation of the bulk aerosol composition; (2)
27 an estimation of the critical diameter for activation of the cloud droplets sampled; (3) an
28 estimation of the critical supersaturation required to form the droplets sampled, and (4) a
29 prediction of the critical diameter for activation of rBC cores. Steps 1-3 are required to carry out
30 the predictions in step 4.

31

32 **3.8.1. Bulk aerosol composition**

33

1 A HR-ToF-AMS was used to measure the bulk aerosol composition in residual particles
 2 downstream of the CVI. Five species (organic, nitrate, sulfate, ammonium and chloride) were
 3 quantitatively differentiated. Then, based on a simplified ion-pairing scheme similar to (Gysel
 4 and Crosier, 2007) (see Supplementary Material Sect. S5), the mass fractions of ammonium
 5 nitrate, ammonium sulfate, ammonium bisulfate, sulfuric acid, and ammonium chloride were
 6 calculated. The results of these calculations are shown in Fig.7. In order to determine the bulk
 7 aerosol hygroscopicity (see Eq. 3) mass fractions, of these individual components, were first
 8 converted to volume fractions using an organic density of 1.4 g cm^{-3} (Moore et al., 2012) and
 9 densities report in Lide, 2001 for the inorganic salts.

10
 11 **3.8.2. The critical diameter for activation of the bulk aerosol in the cloud droplets**
 12 **sampled**

13
 14 The critical diameter for activation (D_{crit}) of the bulk aerosol is often calculated by integrating
 15 the droplet number distribution from the largest to smallest diameters until the number
 16 concentration equals the CDNC sampled (see for example Hersey et al., 2013). Using this
 17 method, D_{crit} was found to be 241 nm and 239 nm for Cloud 2 and Cloud 3, respectively. Note
 18 these D_{crit} values apply only to the cloud droplets sampled (i.e. cloud droplets greater than ≈ 11
 19 μm). Different D_{crit} values would be expected if the entire cloud droplet population were
 20 sampled.

21
 22 **3.8.3. Critical supersaturation for the cloud droplets sampled during the two cloud**
 23 **events.**

24
 25 To estimate the critical supersaturation (S_C) for the formation of the cloud droplets sampled
 26 during the two cloud events (i.e. cloud droplets greater than $\approx 11 \mu\text{m}$) the single parameter
 27 kappa-Köhler model (Petters and Kreidenweis, 2007) was used. This model describes the relationship
 28 between the water vapor saturation ratio (S) over an aqueous solution droplet, and can be
 29 calculated using the following equation:

30
 31
$$S = \frac{D^3 - D_p^3}{D^3 - D_p^3(1 - \kappa_{\text{Bulk}})} \exp \frac{4\sigma M_w}{\rho_w R T D} \quad (2)$$

32
 33 where D is the droplet diameter; D_p is the dry particle diameter; σ is the droplet surface tension,

1 and is assumed to be that of water, 0.072 J m^{-2} ; M_w is the molecular mass of water; ρ_w is the
2 density of water; R is the universal gas constant; T is the temperature; and κ_{Bulk} is a compositionally
3 specific parameter that describes the bulk aerosol's hygroscopicity. Equation (2) was used to find
4 the S_C needed for a particle of dry diameter D_p to activate (Petters and Kreidenweis, 2007).

5
6 The overall hygroscopicity of a particular aerosol follows a simple mixing rule and can be
7 calculated from:

$$\kappa_{Bulk} = \sum_i \varepsilon_i \kappa_i \quad (3)$$

10
11 where ε_i is the volume fraction and κ_i is the hygroscopicity parameter for each component i discussed
12 in Section 3.8.1. The individual component κ values used in equation 2 were; 0.1 for organic (Lance et al.,
13 2013; Moore et al., 2012; Rose et al., 2010); 0.67 for ammonium nitrate (Petters and Kreidenweis,
14 2007); 0.61 for ammonium sulfate and ammonium bisulfate (Petters and Kreidenweis, 2007;
15 Wu et al., 2013); and 0.71 for sulfuric acid, which is the average of the range reported in Shantz
16 et al., 2008. The value for ammonium chloride κ was calculated according to Eq. (A28) in (Rose et al.,
17 2008) using a Van't Hoff factor of 2.

18
19 Using the above κ_i values and the ε_i values discussed in Section 3.8.1 in Eq. (3), κ_{Bulk} values of 0.50 and 0.41
20 were calculated for Cloud 2 and Cloud 3 respectively. The values determined during this study
21 are consistent with the values suggested by Andreae and Rosenfeld, 2008 for Cloud 2 and lower
22 than the values suggested for Cloud 3.

23
24 Shown in Fig.8a are plots of S_C as a function of dry diameter for Cloud 2 (solid line) and
25 Cloud 3 (dashed line) calculated using Eqs. (2) and (3). Combining D_{crit} (see Section 3.8.2)
26 with the results plotted in Fig. 8, S_C for the cloud droplets sampled can be determined. The
27 points at which D_{crit} intersect with the calculated S_C traces shown in Fig 8, result in estimations
28 of S_C values of 0.05% for both clouds. Note these critical supersaturations apply only to the
29 cloud droplets sampled by the CVI. Different S_C values would be expected if the entire droplet
30 population had been sampled. Theory predicts that the largest droplets in the distribution should

1 have been the first to form, thus formed on particles activated at the lowest supersaturations.
2 During this study a CCN instrument was also connected to the residual inlet and sampled
3 residual particles during the cloud events. Data from this instrument were used to derive an upper
4 limit to the cloud supersaturation applicable to the cloud droplets sampled by the CVI
5 (manuscript in preparation), and was found to be approximately 0.1%. This upper limit to the
6 cloud supersaturation is consistent with the S_C values reported here using the estimation
7 technique discussed above.

8
9
10 In this determination of S_C several assumptions were made, which are addressed separately
11 below: (1) the predominant mechanism for incorporation of particles into droplets was
12 nucleation scavenging, and influences by impaction were negligible (see Sect. 3.5); (2) the
13 contribution from sea salt aerosols could be neglected. Based on sea salt mass concentrations
14 measured by the HR-Tof-AMS behind the CVI and calibrated against collocated ion
15 chromatography measurements following a procedure similar to that introduced by Ovadnevaite
16 et al., 2012, we estimated an upper limit of approximately 15% for the sea salt mass fraction of
17 the cloud residuals (these results will be discussed in detail in a future publication). A
18 sensitivity study (not shown here) indicated a $< 8\%$ decrease in the estimated S_C when a sea
19 salt fraction of 15% was include; (3) we assumed that the particles were internally mixed and
20 the composition did not depend on size. Since, during this study, the size dependent AMS data
21 were at or below the detection limit we could not determine if the composition was size
22 dependent. Additionally, no measurements of bulk aerosol mixing state were carried out; and
23 (4) we assumed that the entire fraction of organics was water soluble and represented by a κ of
24 0.1. To determine if S_C was sensitive to this value, κ for organics was varied from 0-0.2, which is roughly
25 consistent with the range of κ values reported in the literature for organics (Chang et al., 2010; Latham et al.,
26 2013; Mei et al., 2013). Over this range of κ values, S_C varied by $< 4\%$.

27 **3.8.4. Predictions of the critical diameter for activation of rBC cores**

28
29 In Fig.8b the critical diameter for activation of rBC cores for the cloud droplets sampled is
30 calculated using kappa-Köhler theory and assuming coating thicknesses ranging from 0-200nm, which
31 covers the range of coating thicknesses measured. In these calculations the composition of the
32 coating was assumed to be the same as determined by the AMS (see Section 3.8.1), and the rBC
33 cores were assumed to be insoluble with a $\kappa=0$ (Rose et al., 2010). As expected, in Fig.8b, S_C
34 decreases as the coating thickness increases at a constant rBC core diameter. Figure 8b also
35 suggests, that if the S_C is $\approx 0.05\%$, and the diameter of the rBC core is 95 nm, the coating thickness must be
36 between 50 and 75 nm. Our lower limits to the coating thicknesses for an rBC core diameter of 95 nm shown in
37 Fig. 6b and g are consistent with these predictions.

1 In Fig. 8c we plotted S_C as a function of the rBC coating volume fraction assuming rBC
2 core diameters of 75 nm, 100 nm and 200 nm. This figure illustrates that in order to activate 75
3 and 100 nm rBC cores at a S_C of 0.05% the rBC coating volume fraction must be greater than
4 0.9. Figure 9c also shows that for an rBC core diameter of 200 nm, the coating volume fraction
5 needs to be approximately 0.6. For 100 nm rBC cores the measurements are in good agreement
6 with the predictions (compare Fig. 9c with Fig. 6e and j). For 75 nm cores and 200 nm cores
7 the measurements are lower than the predictions. However, the measurements are not
8 inconsistent with the calculations since the measurements are lower limits.

9 10 **4. Summary and conclusions**

11
12 Cloud residuals were measured during two cloud events at the top of Mt. Soledad in La
13 Jolla, CA. Back trajectories showed that air masses for both cloud events spent at least 96
14 h over the Pacific Ocean and traveled near, or over populated regions before arriving on
15 site. Based on measured bulk aerosol concentrations the two air masses sampled were classified as
16 polluted marine air, a classification consistent with the back trajectories and measured
17 concentrations of black carbon. Size distributions of the bulk aerosol residuals were shifted
18 to larger sizes for both cloud events compared to size distributions measured with the total
19 inlet. The size distributions of rBC cloud residuals were also shifted towards larger
20 diameters when compared to the size distributions of rBC measured with the total inlet.
21 The activated fractions of rBC determined from the measurements ranged from 0.01 to
22 0.1 for rBC core diameters ranging from 70 to 220nm. This type of data will be useful for
23 constraining models used to predict rBC concentrations in the atmosphere. Since the
24 fraction of cloud droplets sampled by the CVI was less than 100 %, the measured
25 activated fractions of rBC are lower limits to the total fraction of rBC activated during the
26 two cloud events.

27 To investigate the factors that control the incorporation of rBC into cloud droplets, we
28 determined lower limits to the coating thickness, the total diameter (rBC core + coating),
29 the coating volume and the coating volume fraction of the rBC cores incorporated into
30 cloud droplets. Uncoated rBC particles with diameters < 100 nm are not expected to be
31 incorporated into the cloud droplets sampled at Mt. Soledad due to the high
32 supersaturations required for nucleation of uncoated 100 nm rBC particles and the low

1 critical supersaturations often observed for stratocumulus clouds. The coating thicknesses
2 give a qualitative explanation for why we see relatively large activated fraction of rBC
3 cores with sizes < 100 nm – the rBC cores with sizes < 100 nm have relatively thick
4 coatings, which increases the overall size of the rBC containing particles and provides
5 soluble material to the particle which can lower the critical supersaturation required for
6 activation. The measurements of the coating volume fraction show the median coating
7 volume fraction was at least 0.9 for rBC core diameters ranging from 85-95 nm, a result
8 consistent with kappa-Köhler theory. The measurements of the total diameter (rBC core +
9 coating) suggest that the total diameter must be at least 165 nm in diameter in order for
10 rBC cores with diameters ≥ 85 nm to be incorporated into cloud droplets. The results also
11 suggest that the total particle diameter (core + coating thickness) is important for
12 determining if rBC particles are incorporated into the cloud droplets. This finding is
13 consistent with previous work that has shown that particle diameter is important
14 activation of non-rBC containing particles (Wang et al., 2008).

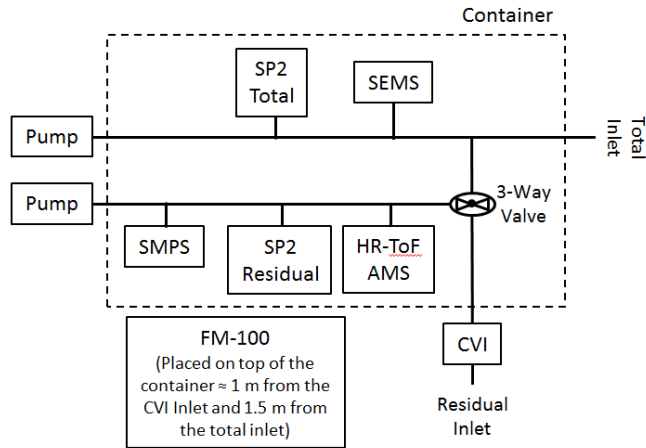
15

16 **Acknowledgements**

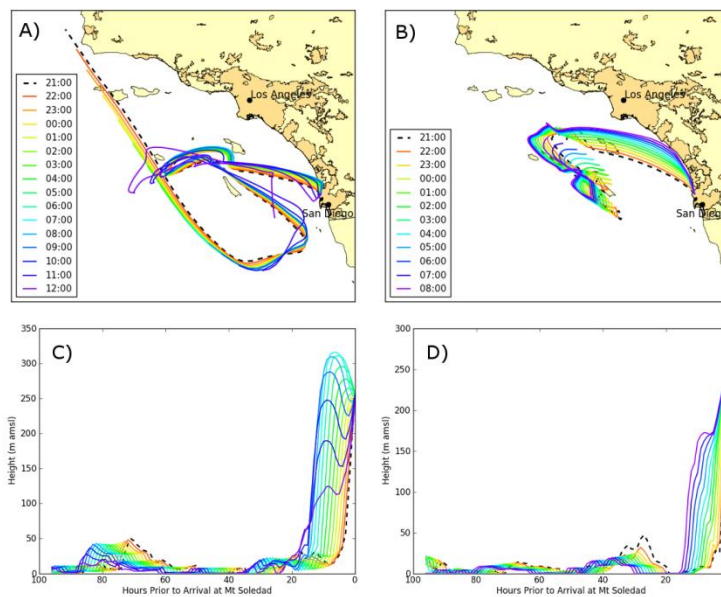
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23

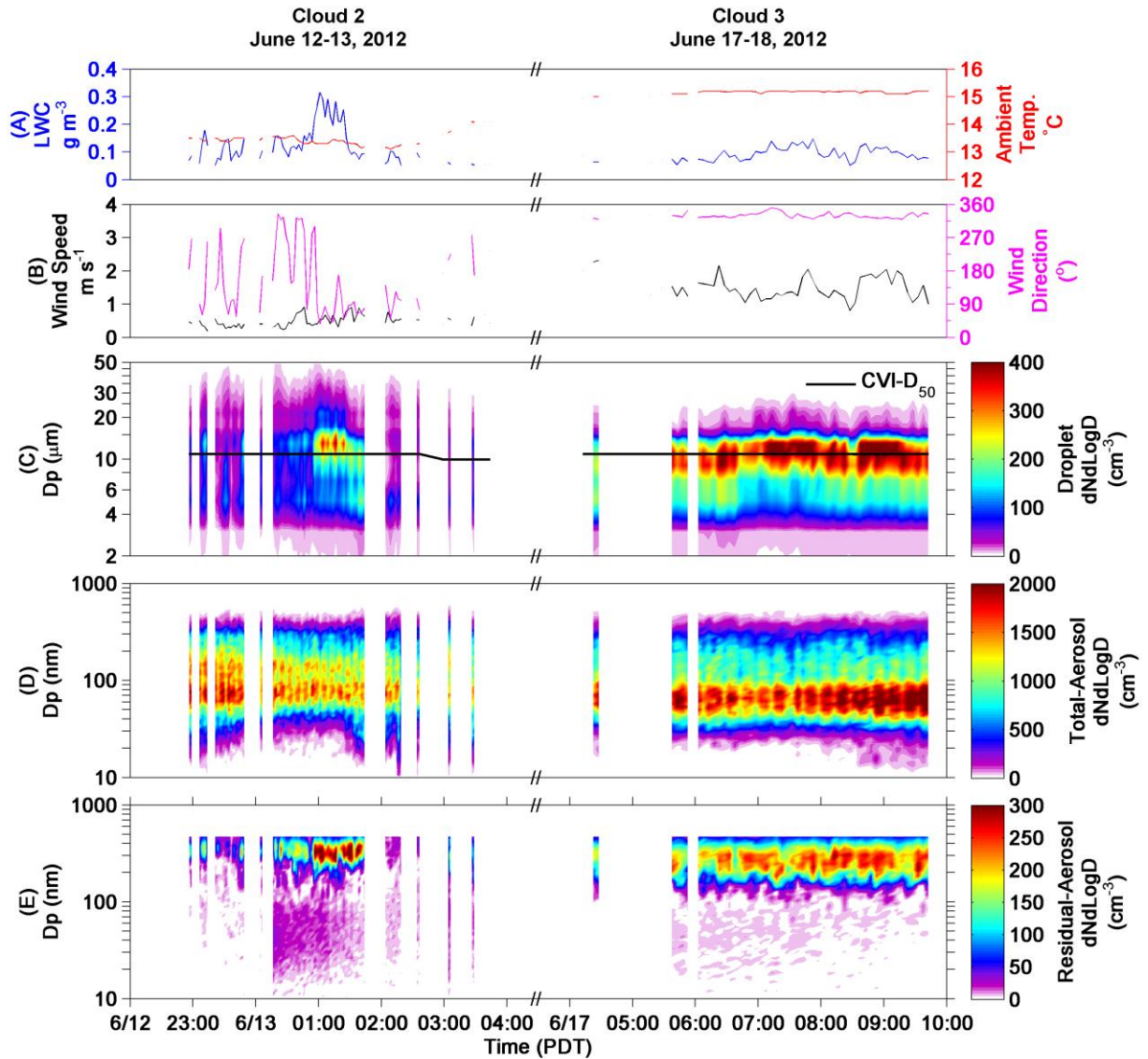
24 **Figures**



1
 2 **Fig. 1.** Schematic showing the configuration of the inlets and instrumentation housed in the shipping
 3 container
 4

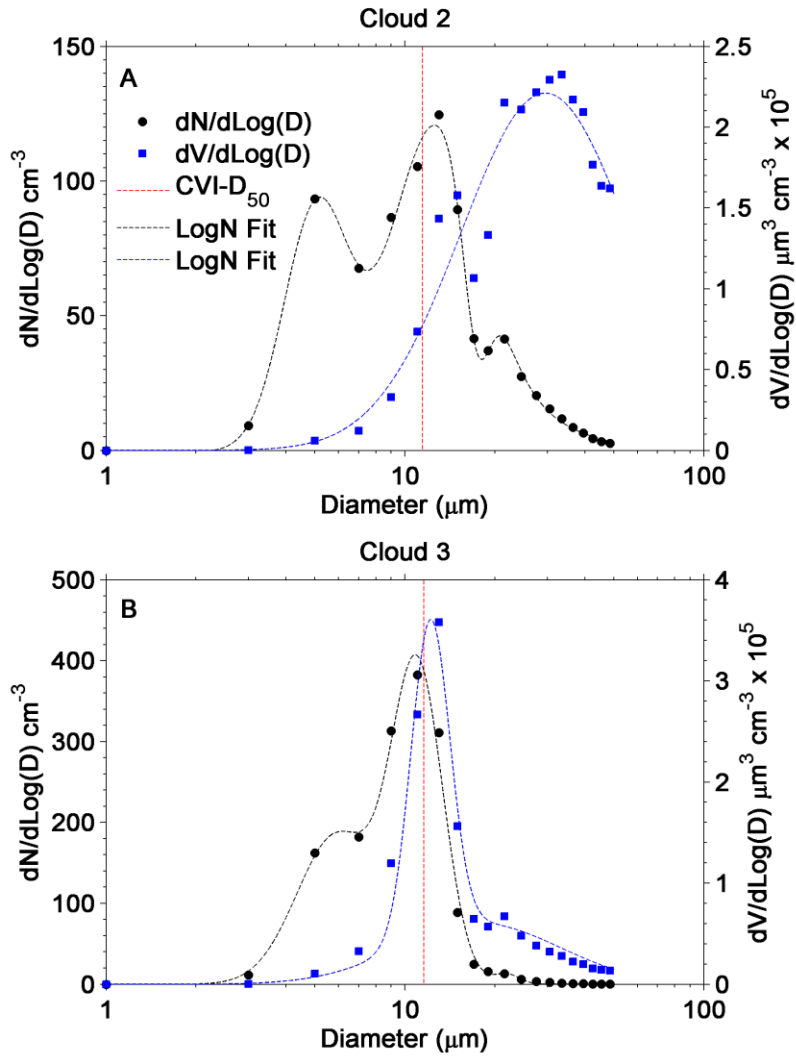


5
 6 **Fig. 2.** In-cloud HYSPLIT 96hr back trajectories ending at hourly intervals for Cloud 2 (12 June 21:00 13
 7 June 12:00 PDT) in panels A and C, and Cloud 3 (17 June 21:00 to 18 June 08:00 PDT) in panels B and D.
 8 All back trajectories started at 10 m a.g.l. Darker yellow regions on land in panels A and B indicate
 9 densely developed urban areas containing 50,000 or more people (United States Census Bureau). Panels
 10 C and D show the vertical profiles over the same hourly intervals shown in panels A and B.



1

2 **Fig. 3.** Time series data for both Cloud 2 (left side) and Cloud 3 (right side) showing; liquid water content
 3 (LWC, blue trace) and ambient temperature (red trace) in panel A; wind speed and direction in panel B;
 4 cloud droplet number size distributions with the CVI- D_{50} (black trace) overlaid in panel C; the number
 5 size distribution for the total aerosol in panel D, and the residual aerosol in panel E. All data shown are
 6 five minute averages and meet the criteria discussed in the text.

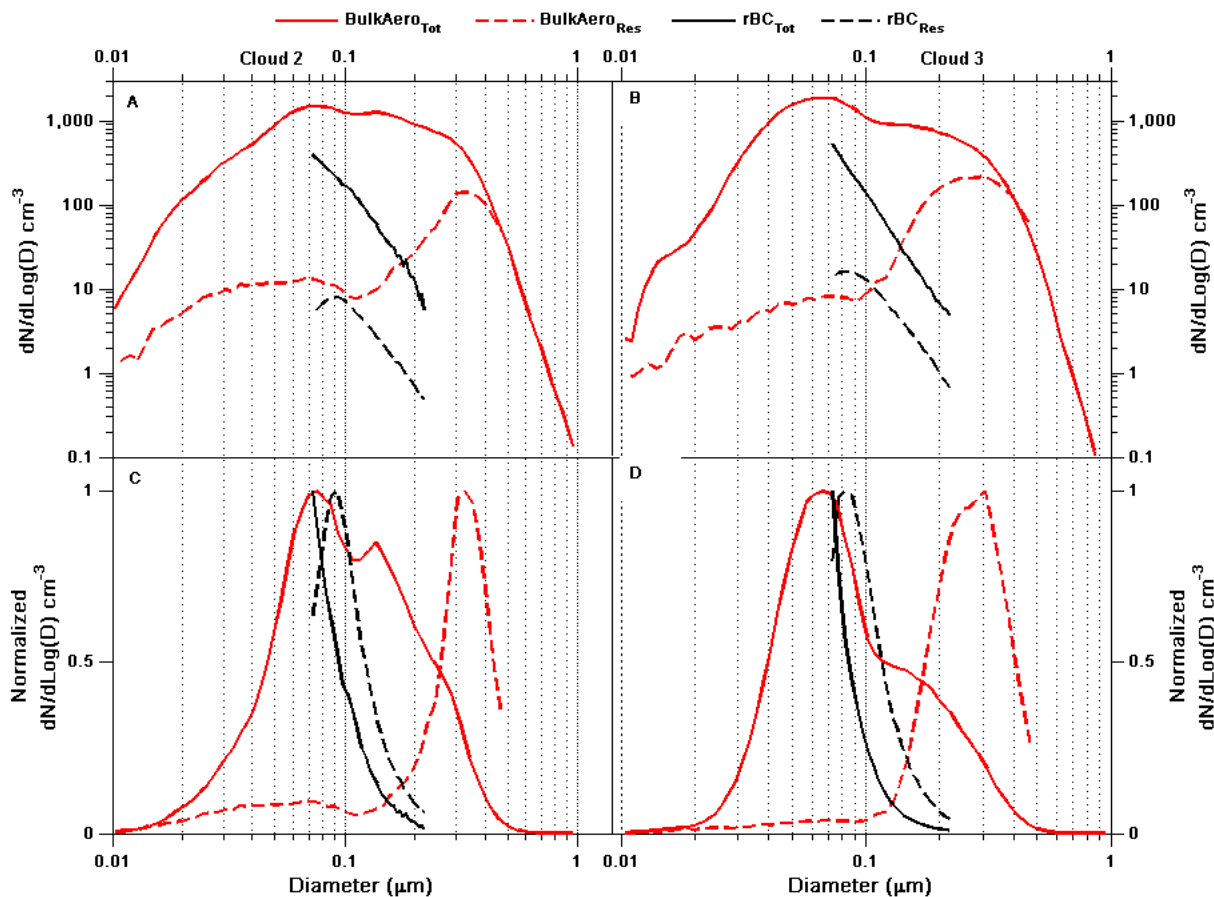


1

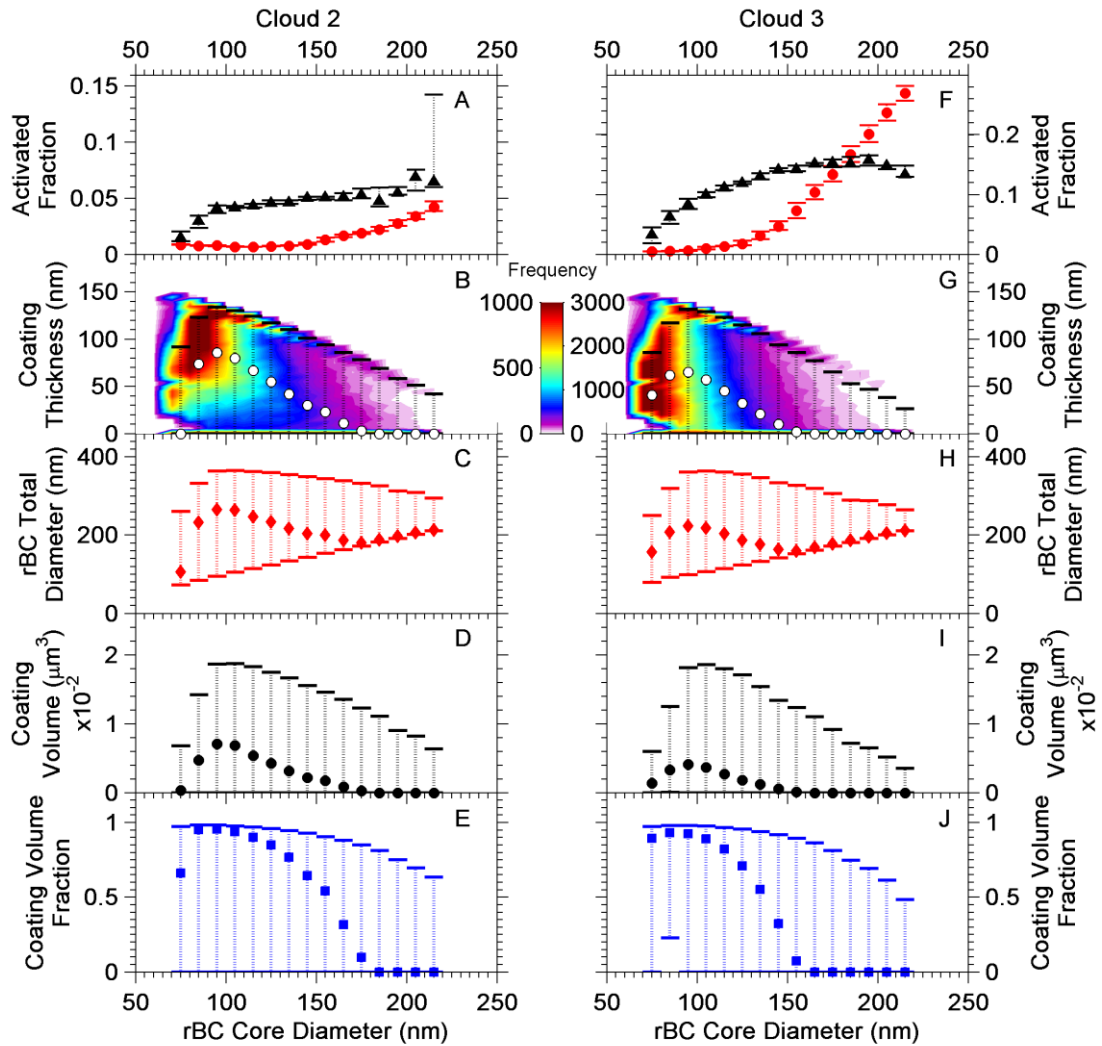
2 **Fig. 4.** Average cloud droplet number size distributions for Cloud 2 (panel A) and Cloud 3 (panel B)
 3 measured by the FM-100 (black circles) and fit to a lognormal distribution function (black dashed lines).
 4 The average cloud droplet volume distributions (blue squares) and lognormal fits (blue dashed lines) are
 5 also shown for each cloud event. The CVI-D₅₀ is indicated on each panel by a red dashed line.

6

7



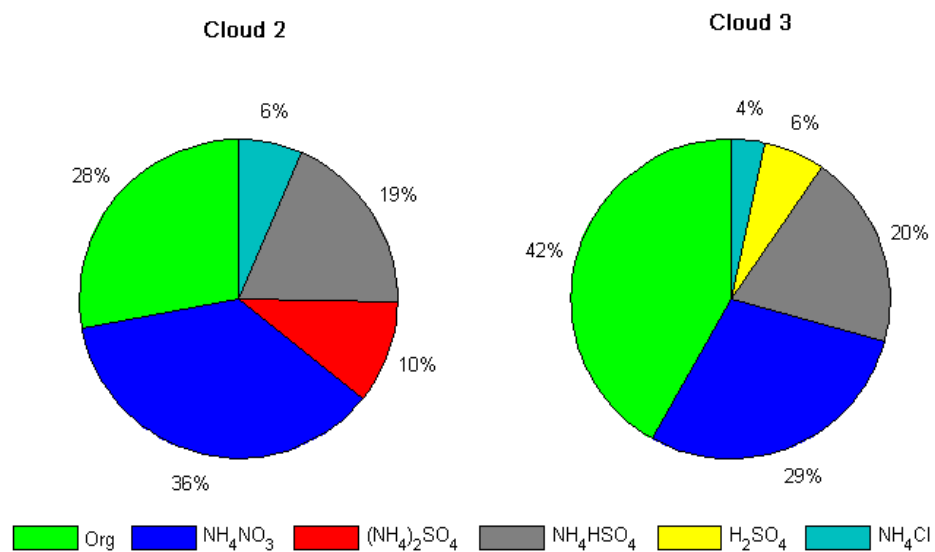
1
 2 **Fig. 5.** Summary of the averaged number size distributions for Cloud 2 (panels A and C) and Cloud 3
 3 (panels B and D) for the total aerosol (red solid lines); residual aerosol (red dashed lines); total rBC as a
 4 function of core diameter (black solid lines); residual rBC as a function of core diameter (black dashed
 5 lines). Both the aerosol and rBC for each cloud event are shown in two ways, a log scale (panels A and B)
 6 to highlight the relative differences between the aerosol and rBC as well as normalized to the respective
 7 maximum value (panels C and D) to highlight the shift in size distributions. All residual distributions have
 8 been corrected for instrument sensitivity (see Fig. 2), CVI enhancement (see A Supplementary Material
 9 Sect. S1), and droplet losses (see Supplementary Material Sect. S4).



1

2 **Fig. 6.** Shown in panels A and E are the median size dependent activated fraction (AF) for the aerosol
 3 (red circles), and rBC (black triangles) for Clouds 2 and 3, respectively, where the error bars represent
 4 the 10th and 90th percentiles. The bottom axes represent particle diameter for the aerosol and core
 5 diameter for rBC. Panels B and G show a 2D histogram of coating thickness with the median values
 6 (white circles) overlaid on top, where the error bars are the 10th and 90th percentiles. Panels C and H
 7 show rBC total diameter (i.e. the core + the coating), panels D and I the coating volume, and panels E
 8 and J the coating volume fraction, all as a function of rBC core diameter.

9

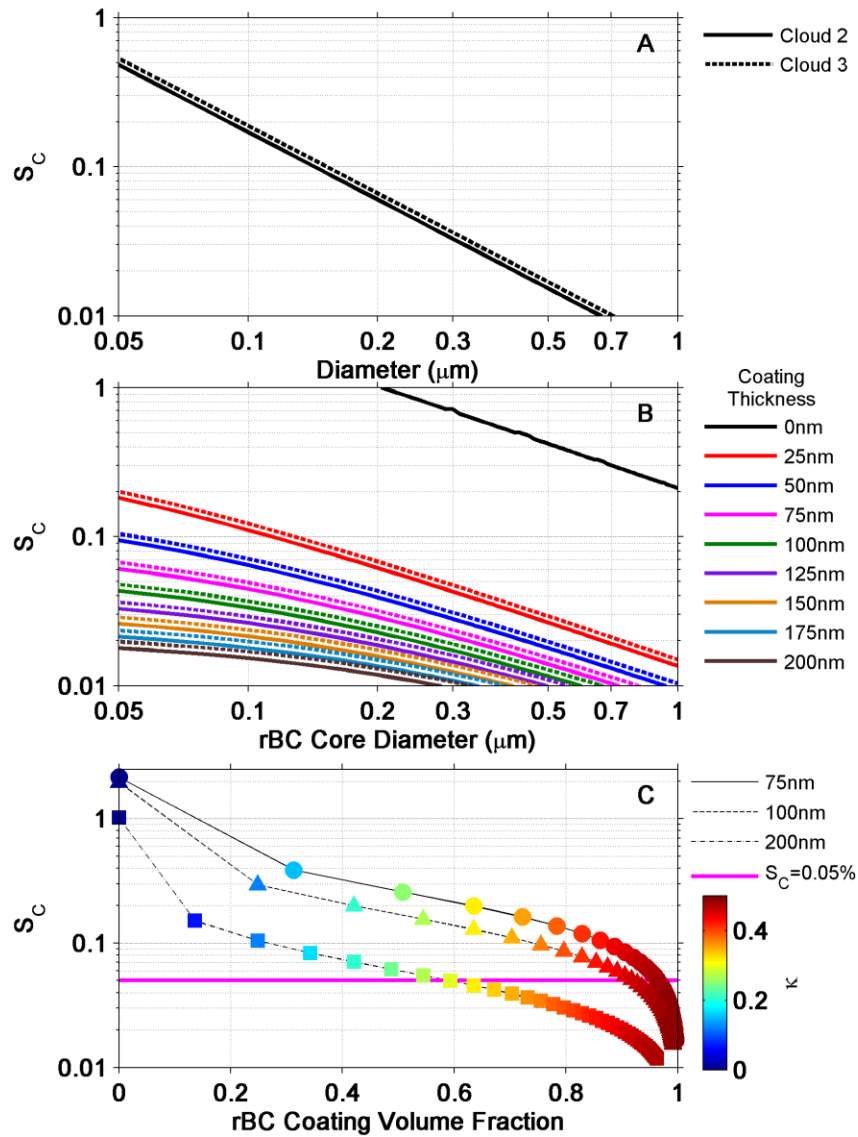


1

2 **Fig. 7.** Sub-micrometer non-refractory average aerosol mass fractions for Clouds 2 and 3 based on an

3 ion-pairing scheme (see text and Supplementary Material Sect. S5) and measured from a high resolution

4 time-of-flight aerosol mass spectrometer.



1

2 **Fig. 8.** Panel A shows the critical supersaturation (S_C , black lines) as a function of particle dry diameter
 3 based on measured AMS bulk compositions and an ion-pairing scheme. Panel B shows S_C as a function of
 4 rBC core diameters with coatings ranging from 0-200 nm. In panel B, the coatings are assumed to have
 5 the same composition as the bulk residual aerosol (Fig. 8). The solid lines are for Cloud 2 and the dashed
 6 lines are for Cloud 3. Panel C shows S_C as a function of rBC coating volume fraction at three different rBC
 7 core diameters (75, 100, and 200nm), where each data point is colored by its corresponding kappa. Also
 8 shown on panel C is the estimated S_C (pink line) determined for both clouds in this study.

9 Tables

10 **Table 1:** Summary of cloud microphysical properties showing the average CVI cut-size (CVI- D_{50}) where
 11 the uncertainty stems from the calculated cut-size (see text for details); average liquid water content
 12 (LWC) and 1 standard deviation; and the cloud droplet number ($CDNC_{Tot}$) and volume (Vol_{Tot})

- 1 concentration for droplets with diameters between 2-50 μm . Also shown is the number ($\frac{CDNC_{Samp}}{CDNC_{Tot}}$) and
- 2 volume ($\frac{Vol_{Samp}}{Vol_{Tot}}$) fractions of droplets sampled, where $CDNC_{Samp}$ and Vol_{Samp} are the number and
- 3 volume concentrations, respectively, for the fraction of droplets sampled.

Cloud #	Date Sampled	CVI-D ₅₀ (μm)	LWC (g m^{-3})	$CDNC_{Tot}$ (cm^{-3})	$\frac{CDNC_{Samp}}{CDNC_{Tot}}$	Vol_{Tot} ($\mu\text{m}^3 \text{m}^{-3}$)	$\frac{Vol_{Samp}}{Vol_{Tot}}$
2	June 12-13, 2012 20:43-11:35 PDT	11.5 ± 0.72	0.13 ± 0.07	67.67	0.38 ± 0.03	1.24E5	0.91 ± 0.02
3	June 17-18, 2012 20:36-07:52 PDT	11.6 ± 0.72	0.09 ± 0.02	145.8	0.24 ± 0.1	8.88E4	0.68 ± 0.10

Table 2: Averaged number (N) and mass (M) concentrations, modal parameters D_g and σ_g for aerosol and rBC particles during the two cloud events measured at Mt. Soledad. The subscripts Tot and Res represent measurements made from the total and residual inlets respectively.

	Cloud 2		Cloud 3	
	Aerosol	rBC	Aerosol	rBC
N_{Tot} (cm^{-3})	980.8	75.24	994.0	62.13
M_{Tot} ($ng\ m^{-3}$)	-	73.41	-	61.83
$D_{g,Tot}$ (nm)	107.7	<0.07	80.54	<0.07
$\sigma_{g,Tot}$	1.577	-	1.703	-
N_{Res} (cm^{-3})	43.46	2.000	83.15	3.86
M_{Res} ($ng\ m^{-3}$)	-	2.741	-	4.735
$D_{g,Res}$ (nm)	331.9	87.30	269.2	80.72
$\sigma_{g,Res}$	1.187	1.259	1.281	1.268

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