Analysis of ATOFMS Datasets from the 2009 CalWater Campaign

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EXECUTIVE SUMMARY

Background:

Atmospheric aerosols have been shown to play an important role in climate by acting as the nuclei for cloud droplet and ice crystal formation. Variations in particle concentration and chemistry can alter a wide range of climate related parameters including: absorbing and scattering solar radiation, changing cloud lifetimes, increasing cloud albedo, and altering precipitation locations and amounts. During this study measurements of both new particle formation (NPF) events as well as measuring particle residues in rainwater allow us to analyze aerosol impacts on climate from two separate, yet important directions. Studying aerosols has traditionally been accomplished through bulk filter measurements, which have provided a great deal of information about bulk particle chemistry and mass concentrations. However, bulk studies have been limited by time resolution, sampling artifacts, and a lack of understanding which species exist together in the same particles (i.e. mixing state). The primary method used in this report, aerosol time-of-flight mass spectrometry (ATOFMS), determines the size and chemical composition of single particles in real-time avoiding many of the limitations of bulk methods.

Methods:

A suite of aerosol instrumentation including both traditional bulk analysis (PM$_{2.5}$ concentration and black carbon mass concentration), size distribution measurements (SMPS and APS), as well as a cloud condensation nuclei counter (CCNc) were used during this study to measure ambient aerosol properties. These techniques were combined with an ATOFMS and an ultrafine-ATOFMS (UF-ATOFMS), which analyzes individual particle size and composition in real time. In addition to aerosol measurements gas-phase instruments operated at the site measured SO$_2$, NO$_x$, and O$_3$.

Results:

The two foci of this report are measurement of NPF events that can act as CCN and analysis of rainwater samples with the ATOFMS to look at particle residues. With respect to NPF ambient amine- and sulfate-containing particles were observed during new particle formation events on non-precipitating days with low temperatures and high relative humidity. Analysis of the rainwater showed the impact of long range transport on rainwater chemistry during an atmospheric river when compared to an atmospheric river that was not impacted by long range transport.
A. Introduction

1. Research Objectives and Studies Conducted

This project focused on gas- and particle-phase measurements to investigate size and temporal variation in the chemical composition of aerosols at the Sugar Pine Dam in the American River Basin during the 2009 CalWater campaign (February 20 – March 11, 2009). The major goals of the study were to monitor changes in ambient aerosols and particles in collected rainwater to provide insight into their potential effects on atmospheric rivers (ARs) common in this region. In addition, ambient aerosols were correlated to local meteorology, air mass transport mechanisms, and cloud condensation nuclei (CCN) measurements to determine how they are affected by local conditions, their source, and their role in regional cloud formation. Figure 1 shows a map of the sampling site and co-located UCSD-SIO and NOAA instrumentation.

Figure 1: Deployment of instrumentation as part of CalWater Early Start - Winter 2009
2. Summary of Sections

i. Introduction
   Section A introduces overall goals of the campaign.

ii. Materials and Methods
   The aerosol time-of-flight mass spectrometer is introduced in Section B. Previously developed as well as novel data analysis techniques are described.

iii. Results
   In Section C, results from two different observations are presented in addition to specific introductions for each of the observations. Section C.1 discusses aerosol chemistry observed during new particle formation events and section C.2 describes the impact of particles from long range transport on atmospheric rivers.

iv. Summary and Conclusions
   Section D includes concluding remarks with respect to the study and results.

v. Publications in Preparation
   Two papers are currently in preparation that will present the findings from this study and their references are included.

vi. Appendices
   Abbreviations used herein are listed.

vii. References
B. Materials and Methods

1. Instrumentation

The principal sampling technique for ambient particles used throughout this dissertation is aerosol time-of-flight mass spectrometry (ATOFMS). ATOFMS simultaneously acquires positive and negative ion spectra, as well as size information, for single particles in real-time. A detailed description of operation and performance of the transportable version of this instrument has been provided previously (1), though a brief explanation is included here. A schematic diagram of the standard inlet ATOFMS is given in Figure 1. The inlet region consists of a converging nozzle, followed by two skimmers. Similar to the APS, the particles undergo supersonic expansion upon introduction into vacuum and are accelerated to velocities dependent on their aerodynamic sizes. The different regions separated by skimmers fulfill two primary functions: to permit differential pumping from atmospheric pressures to the pressures necessary to operate the mass spectrometer and to collimate the particle beam by removing those particles which do not follow a straight trajectory. The particle beam next enters the light-scattering region, which includes two continuous-wave 532 nm diode pumped Nd:YAG lasers. These lasers are positioned orthogonally to the particle beam, so that when a particle passes through the laser beam, its scattered light is focused onto PMTs by means of ellipsoidal mirrors. The PMTs send pulses to an electronic timing circuit that measures the time the particle takes to travel the known distance (6 cm) between the two laser beams. The velocity of the particle is calculated with the particle time of flight and the distance and is converted to a physical aerodynamic diameter via an external size calibration with particles of known size. With the determined particle velocity, the timing circuit counts down to when the tracked particle will reach the center of the ion source region of the mass spectrometer and sends a signal to a pulsed Nd:YAG laser (frequency quadrupled to 266 nm) to fire. Through direct laser desorption/ionization (LDI), the laser pulse produces ions, which are then mass analyzed in a dual-ion reflectron time-of-flight mass spectrometer. The dual polarity permits simultaneous acquisition of positive and negative ion spectra for an individual particle, which is unique as most SPMS techniques can only obtain spectra of single polarity at a given time. The standard ATOFMS instrument can analyze single particles with aerodynamic diameters over a broad size range from approximately 200 to 3000 nm.
Ultrafine aerosol time-of-flight mass spectrometry (UF-ATOFMS) has improved detection efficiency for small particles (< 300 nm) over the standard ATOFMS by replacing the converging nozzle inlet with an aerodynamic lens inlet (2). Figure 1b shows the schematic diagram of the UF-ATOFMS instrument. The lens system tightly collimates the particle beam, so that smaller ultrafine particles will be more efficiently transmitted in the instrument (3,4). Upon exiting the aerodynamic lens, the gas molecules undergo supersonic expansion, accelerating the particles to terminal velocities based on their aerodynamic diameter – just as with standard inlet ATOFMS. UF-ATOFMS also has enhanced light-scattering detection by incorporating a focusing lens to tighten the continuous laser beams, increasing the laser beam power density, and by employing a fast amplifier to improve the signal-to-noise ratio. All of these
enhancements, in addition to the aerodynamic lens systems, are necessary to improve the minimum optical detection size of ~100 nm down to 50 nm. Together, standard ATOFMS and UF-ATOFMS cover an aerodynamic size range of ~50 to 3000 nm when sampling side-by-side.

2. Data Analysis Methods

ATOFMS generates large quantities of data; the instrumentation is capable of collecting size and chemical information on greater than 500 individual particles per minute, depending upon the atmospheric concentrations. While simple laboratory experiments may run for only a few hours, ambient monitoring studies with ATOFMS may operate for weeks. Therefore, continuous sampling during a single ambient study can yield tens of millions of individual spectra – far too many to analyze by hand. For efficient analysis of such a volume of data, an ideal data analysis technique must perform automatic sorting and classification of individual particles. There are a number of available mathematical algorithms that have been adapted to cluster mass spectral data, such as fuzzy c-means clustering, k-means clustering, hierarchical clustering, and artificial neural networks (5-9). The two main data analysis methods used in this dissertation are described in the next sections. Any adjustments to these methods or alternative approaches will be discussed in subsequent chapters. The adaptive resonance theory-based neural network algorithm, ART-2a, has been used to analyze ATOFMS data for several years. In a benchmark test against other clustering methods, ART-2a has been shown to yield comparable results (8). A modification of ART-2a analysis involves matching to predefined seeds, such as a source signature library described below.

Though more detailed descriptions of the ART-2a algorithm have been provided elsewhere (10-12), a brief description is included here. Using the mass spectral ion patterns and peak intensities, ART-2a separates particles into distinct classes (clusters) of chemically similar particles within large ATOFMS data sets and generates new clusters whenever a data point (mass spectrum) falls outside the proximity to all existing classes. Thereby, ART-2a provides the advantage of determining the contributions from previously detected particle classes while also introducing information on new particle types. For each particle, ART-2a combines all of the ion peak patterns and intensities in the positive and negative spectra to form an n-dimensional weight vector (normally 350 m/z units for each polarity, making 700 units total), in which the ion intensity at each m/z ratio is normalized with respect to the maximum peak intensity present in the vector. In the classification process, particles are selected randomly and their spectral information is compared to each particle cluster (weight vector) by calculating the dot product of the particle vector and cluster weight vector. The dot product value ranges from 0 to 1, where 1 represents identical vectors. If the dot product value between the particle vector and any of the existing weight vectors is above the user-defined threshold (vigilance factor - VF), that particle is added to the cluster with the highest dot product value. If a learning rate is defined, that cluster will slightly weight its vector toward the newly added particle. If the dot product value is below the VF, the particle defines a new cluster. Once all of the particles have been assigned, ART-2a then compares each particle against the entire set of created clusters to ensure proper placement. This final step is repeated for a number of set iterations (usually 20).
Upon completion of the ART-2a analysis, there may be hundreds to thousands of resulting clusters based on the complexity of the data and the VF used. For example, a low VF (≤ 0.5) will yield a low number of clusters with limited homogeneity, whereas a high VF (≥ 0.7) will yield a large number of clusters with high homogeneity. The user then visually inspects the ART-2a clusters to manually classify and label them based on their spectral characteristics. Some clusters may be combined by hand if they have similar spectral characteristics or key class features, in order to reduce the total number of clusters to a more manageable size.

One of the features of ART-2a is that it can compare the ambient particle vectors to a set of predefined weight vectors, known as seeds. In direct analogy to the procedure described in the previous section, the dot product of each particle vector is crossed with each seed weight vector. The particle is placed into the seed cluster that produces the highest dot product, assuming it is above the user-defined VF. The main difference between this matching method and the normal ART-2a procedure is that if no dot product value exceeds the VF, the particle is placed into an “unmatched” category, rather than initiating a new particle class. In addition, this method has no learning rate parameter, so the vectors of the seeds remain constant as particles are matched to them.

The matching function is ideal for apportioning individual ambient particles to specific sources using a source signature library. The recently developed source signature library is described in detail elsewhere (13), but a brief description is given here. The size-segregated library combines the carefully identified mass spectral source signatures from a series of source (such as vehicle dynamometer studies) and ambient characterization studies to serve as the predefined cluster seeds. Designed to expand as the ATOFMS signatures for particles from new sources are obtained, the library presently contains source fingerprints for dust, sea salt, and biomass. It also has non-source specific signatures acquired in ambient studies, including aged elemental carbon (EC), aged organic carbon (OC), amine-containing particles, ammonium-rich particles, vanadium-rich particles, EC, and polycyclic aromatic hydrocarbon (PAH)-containing particles. Mass spectral signatures of these particle types are shown in figure 2. The major advantages of using this data analysis technique are the elimination of user bias in labeling and the speed in which it can apportion particles.
Figure 3: Representative mass spectral signatures acquired from the ATOFMS.
C. Results

1. Measurements of Aerosol Chemistry during New Particle Formation Events at a Remote Rural Site

i. Introduction

Aerosols are ubiquitous in the troposphere and have important implications for climate through the direct and indirect effects (14). Aerosols can scatter and absorb incoming short wave and outgoing long wave radiation, but they can also act as cloud condensation nuclei (CCN) and affect cloud radiative and physical properties. If these CCN are exposed to supersaturated conditions they compete for available water vapor, increasing cloud droplet number concentration (CDNC) by creating large populations of small-sized cloud droplets (15). This increases the reflectivity (16), thickness, and lifetime of clouds (15). Smaller cloud droplets also take longer to grow into precipitation-sized droplets (typically ~2 mm in diameter), therefore preventing precipitation to occur (15).

The indirect effect has the largest uncertainty of any major contributor to the global radiative forcing estimate (17), therefore a better understanding of the aerosols that determine the magnitude of this effect is needed. One important source of tropospheric aerosol is in situ particle nucleation and subsequent growth. This occurs from anthropogenic or biogenic precursors (18) and these new particles have been directly linked to activate cloud droplets (19). Although anthropogenic aerosols are a large fraction of the global aerosol burden and affect solar radiative transfer and cloud processes (20), newly-formed biogenic aerosols can play a large role in regional cloud formation over remote locations, specifically in forests which cover about 30% of the earth’s land area (21,22). In order to assess anthropogenic influences on clouds, the biogenic processes for particle production must be understood (20). This will help improve regional and global climate models by decreasing the indirect effect uncertainty, specifically parameters involving the newly-formed biogenic species that activate as CCN.

New particle formation (NPF) is considered a 2-step process (23). The first step involves the nucleation of neutral or ion clusters and the second step is activation of clusters for growth into a particle (24-26). In most cases, clean ambient conditions and availability of gas-phase precursors are ideal conditions for NPF. This process can occur in remote/rural (27,28), urban (29,30), or coastal atmospheres (31). Also, NPF is likely to occur with higher relative humidity and lower temperature (26), which is usually during the evening or at night. It was previously thought that H$_2$SO$_4$, formed from oxidation of the gas-phase precursor SO$_2$, homogeneously nucleated into a particle, however, the growth rates of observed particle formation cannot be explained solely by H$_2$SO$_4$ (30,32,33). Therefore, other species in addition to H$_2$SO$_4$ must contribute to NPF, such as NH$_3$ or H$_2$O. Binary and ternary nucleation theories describe nucleation of clusters by means of a H$_2$SO$_4$–NH$_3$ or a H$_2$SO$_4$–NH$_3$–H$_2$O system, respectively (23). Additional growth after the nucleation step has been attributed to multiple species, including NH$_3$ and H$_2$SO$_4$ (34), or more recently organic vapors (26). More specifically,
(HNR₃)₂SO₄ has been modeled and detected in newly-formed particles, signifying the contribution of amines/nitrogen-containing organics and H₂SO₄ to NPF (35,36).

Particles formed after the cluster nucleation step are only a few nm in diameter. Because of instrumental difficulties measuring the chemistry of particles this small, it is very challenging to chemically identify them during their initial stage. Also, chemical composition is typically inferred for newly-formed particles by utilizing multiple instruments. Mäkelä et al. (2001) found a significant presence of dimethylammonium ((CH₃)₂NH₄⁺) using 2-stage cascade impactors and ion chromatography during NPF events, which they suggested could be present during nucleation and/or growth as ((CH₃)₂NH₄)SO₄ or (CH₃)₂NH₄HSO₄ (35). This study sized and chemically identified particles down to ~5 nm while sampling during NPF events, which lasted 13.6-35.8 hours. Although they were able to see down to 5 nm, this is still above the size of the freshly nucleated particles (~1-3 nm). Also, the time resolution is low and aminium sulfate ((HNR₃)₂SO₄) was inferred from the correlation of bulk particle measurements of (CH₃)NH₂⁺ and SO₄²⁻ or HSO₄⁻. Smith et al. (2008) measured nitrogen-containing organics and sulfate using a Thermal Desorption Chemical Ionization Mass Spectrometer (TDCIMS). They detected particles from 10-30 nm with a 5-10 minute time resolution (37) and found that nitrogen-containing organics played a large role in the growth of nanoparticles. Like Mäkelä et al., inferences were made about organics nucleating/growing with SO₄²⁻ during NPF events.

The issue with bulk-phase measurements is that particle chemistry is inferred from the bulk chemical composition of many particles. For instance, particles identified as (HNR₃)₂SO₄ on filters could actually be separate HNR₃ and sulfate-containing particles. Determining single particle mixing state can confirm that these two species are present within a single particle; therefore chemistry does not have to be inferred. In the current study, aerosol time-of-flight mass spectrometry (ATOFMS) was used to provide dual polarity, single-particle analysis during NPF events in real-time. This allows for the determination of single-particle mixing state, meaning organics and sulfate can be detected within the same particle. This work describes the detection of NPF events in a pristine, remote location in the Sierra Mountains using ATOFMS in conjunction with particle concentrations, particle size distributions, and CCN concentrations. We report observations of organics (specifically nitrogen-containing) and sulfate within single particles during NPF events that occurred almost daily during non-precipitating periods. To our knowledge, this is the first time (HNR₃)₂SO₄ has been detected in single particles during NPF events.

ii. Summary of Results

Particles formed in the atmosphere are a large source of cloud condensation nuclei (CCN) which can alter cloud physical and radiative properties. The single-particle mixing states of newly-formed particles have been determined in real-time during non-precipitation periods at a remote rural site in the Sierra Mountains. Key factors that influenced new particle formation (NPF) were high relative humidity, low temperature, and decreased solar radiation (see Figure 3). Also, NPF occurred after O₃ and SO₂ concentrations peaked, suggesting oxidation of gas-phase SO₂ and subsequent contribution to particle growth as shown in Figure 3c.
Growth rates calculated for each of the events averaged 10.0±2.3 nm/h and resulted in rapid growth from the smallest sizes to 100 nm in ≤9 hours. Increases in the fraction of amine-containing particles (200-600 nm) were observed during NPF, increasing from 29% before the events to 57% at the end of the events as shown in Figure 4. Correlation between the numbers of particles containing amine and sulfate ion markers existed during NPF periods, but not between the ammonium and sulfate markers, suggesting (HNR₃)₂SO₄ formation. The intensities for amine and sulfate markers also increased during the events; however the species of amine present depended on if precursors originated in the mountains or the Central Valley. Determining the chemistry of these newly-formed particles and their ability to act as CCN is necessary to accurately predict the impact of NPF events on the properties of orographic clouds formed during lifting along the front of the Sierra Nevada range near the sampling site. The possibility that higher CCN concentrations from NPF events are impacting clouds and potentially precipitation patterns needs to be considered broadly when evaluating the indirect impact of aerosols.
NPF events were observed after heavy precipitation periods at a remote rural site in the Northern Californian Sierra Mountains. These events occurred daily after the RH increases, T decreases, SR decreases, and during clean, non-precipitating periods, demonstrating their dependence on ambient meteorological conditions. The growth of these newly-formed particles was relatively fast compared to previous observations, with growth rates from 8.1-14.5 nm/h and 100-nm particles forming within 9 hrs versus 1-2 days. This could be attributed to the extremely clean conditions and availability of gas-phase species. The abundance of different gas-phase species available for particle growth leads to differences in particle chemistry during NPF events. By using UF-ATOMS, a single-particle, real-time technique, the size- and temporally-resolved chemical mixing states can be acquired to better understand the particles during NPF events. Over the course of the events, the major particle types were amines, ECOC, and biomass particle types, with amines having the highest fractions. As the NPF events evolved, UF-ATOFMS detected amine-containing particles from 100-600 nm increase in number fraction from 44% before the events to 52% during the beginning of events, then 46% during the end of events. By looking at the chemical mixing state using mass spectral markers, correlation of the normalized number of particles containing \( m/z \) 86 and \( m/z \) -97 falling close to the 1:1 line was observed, but only during time periods of high concentrations or NPF. This suggests internal mixing of amine-containing particles and sulfate that are contributing to particle growth during NPF events. NPF events can be formed from different precursors from different sources, with events 1-2 originating over less-populated areas of the mountains from higher altitudes (less local) and events 3-6
originating from and traveling closer to ground level (more local) in the Central Valley. This suggests that events 1-2 were possibly derived from more biogenic amine precursors while events 3-6 were from more anthropogenic precursors due to the proximity to major highways and Sacramento.
2. Impacts of Asian Dust on Cloud Microphysics and Precipitation during an Atmospheric River during the CalWater Early Start Campaign

i. Introduction

The link between aerosols, clouds, and precipitation has received considerable attention in recent years due to the potential for changes in the transfer of solar radiation and the alteration of precipitation patterns (38-41). Despite the importance of these processes the large uncertainties associated with the aerosol indirect effect and lack of reliable predictions for precipitation pattern changes necessitates a more detailed understanding of cloud droplet and rain drop properties on a chemical and microphysical level. The research discussed herein describes a collaborative effort between the University of California, San Diego, Scripps Institution of Oceanography, NOAA, and the California Energy Commission. This work is part of the CalWater experiment, which includes two major science elements focused on California precipitation in a changing climate, i.e., the role of aerosols in modulating orographic precipitation and the role of atmospheric rivers in creating extreme events and in providing a major portion of the region’s water supply. This poster focuses on the aerosol-precipitation topic.

ii. Summary of Results

The instrumentation involved in the CalWater Early Start –Winter 2009 campaign included the UCSD mobile laboratory at Sugar Pine Dam housing an ATOFMS, an UF-ATOFMS, a condensation particle counter (CPC), a cloud condensation nuclei counter (CCNc), an aerodynamic particle sizer (APS), a scanning mobility particle sizer (SMPS), and a beta-attenuation monitor (BAM). The mobile laboratory was co-located with the NOAA portable laboratory housing a 2875-MHz Vertical S-Profiling Radar, a meteorology station, and a Parsivel Disdrometer. Figure 4 shows a picture of the sampling site and mobile laboratory.

Figure 4: Pictures of the Sugar Pine sampling site including the ATOFMS mobile laboratory and NOAA portable laboratory
Atmospheric rivers that make landfall have been linked to flooding rains and are a significant contributor to precipitation on the western coast of the United States through the enhancement of orographic precipitation (42-45). Two atmospheric rivers were observed during the CalWater early start campaign: February 22-23, 2009 and March 1-3, 2009. As can be see for the integrated water vapor determined from special sensor microwave imaging (SSM/I) in Figure 5. Both atmospheric rivers can be seen reaching the California coast and qualify as atmospheric rivers using the criteria established in Neiman et al. 2008 (42). Each storm shows a connection to the tropics as is common for winter atmospheric rivers, but not summer ones (42).

Figure 5: Atmospheric rivers shown during Storm 1 and Storm 2.

Air mass back trajectories were calculated for each storm going back 120 hours at 7500 m and are shown in Figure 6. Additionally the height above sea level is shown for each trajectory in black. Storm 1 (a) shows back trajectories scattered over the Pacific Ocean without a consistent pattern and altitudes crashing out to the surface after 60
hours. Storm 2 (b) shows back trajectories that initially end over the ocean on March 1\textsuperscript{st}, but that transition to a consistent path starting on March 2\textsuperscript{nd} and 3\textsuperscript{rd}. The elevations (shown as color on each trajectory) indicate a slight dip in elevation over China. The conditions observed with these air mass back trajectories are supportive of long range transport of Asian aerosols, specifically dust.

Figure 6: HYSPLIT back trajectories at 7500m for 120 hours during a) storm 1 and b) storm 2

Over the course of the study rainwater samples were collected and aerosolized to determine the chemical composition of cloud water residues that may be related to the original droplet nucleus. Fractional chemical composition is shown for each sample collected in Figure 7. During Storm 1 a high fraction of organic carbon is observed, while during Storm 2 the originally high fraction of organic carbon decreases rapidly and dust becomes the dominate particle type. This is shown slightly differently in Figure 8, where chemical composition is shown as a function of time and rain water amounts are included. From this perspective it can be seen that the transition from greater than 90\% organic carbon to greater than 80\% dust occurs over roughly 1 day.
Figure 7: Relative fractions of different particle types by rainwater sampling period.

Figure 8: Relative fraction of particle types with each bin representing the time it was collected. Rain (mm) is shown in blue, while time periods are denoted by numbers and shades of gray.
D. Summary and Conclusions

Through ground based measurements at the rural/pristine site of Sugar Pine Dam in the Northern Sierra Nevada’s different impacts of aerosols were investigated using a suite of cutting edge instrumentation. The first set of findings discussed in this report dealt with new particle formation (NPF) events, which involve rapid increases in particle size and concentration over roughly a day. NPF events have primarily been studied using bulk techniques without regard for chemistry. These measurements provide greater information on the chemistry of these particles, which is an important, but relatively recent advancement. These particles have the potential to act as CCN, but further measurements are needed to fully characterize their composition and cloud impact.

The second set of findings in this report approach aerosols impacts clouds and subsequently precipitation in terms of how they alter already existing clouds. Two extra tropical cyclones causing atmospheric rivers of moisture from the tropics to California were observed during the study providing considerable precipitation to the Sierra Nevada’s. During the second storm transported Asian dust interacted with the storms causing a shift in the chemistry of the rainwater samples analyzed by ATOFMS. The shift from mostly organic carbon residues to dust residues during the second atmospheric river stands in stark contrast to the consistent organic carbon composition observed during the first storm. The potential for transported dust to interact with and potentially alter precipitation is an important finding that needs further investigation.

The work from the CalWater Early Start campaign in the winter of 2009 serves as a demonstration of the potential for aerosol chemistry measurements to combine with meteorology and climatology to investigate import issues with respect to California’s water supply. The momentum generated during this campaign is being carried on by the full scale CalWater campaign to take place in January – March, 2010.
E. Publications in Preparation

Ault, A.P.; Creamean, J.M.; Gaston, C.J.; Williams, C.R.; Ralph, F.M.; Prather, K.A.
Impact of Asian Dust on Cloud Microphysics and Precipitation during an
Atmospheric River In preparation.

Creamean, J. M.; Ault, A. P.; Gaston, C. J.; Zauscher, M.; Roberts, G. C.; Prather, K. A.,
Measurements of Aerosol Chemistry during New Particle Formation Events at a
F. Appendices

1. Abbreviations

APS- Aerodynamic particle sizer
AR- Atmospheric river
ATOFMS- Aerosol time-of-flight mass spectrometry
CCN- Cloud condensation nuclei
CPC- Condensation particle counter
EC- Elemental carbon
NPF- New particle formation
OC- Organic carbon
PAH- Polycyclic aromatic hydrocarbon
RH- Relative humidity
SMPS- Scanning mobility particle sizer
T- Temperature
WD- Wind direction
WS- Wind speed
G. References


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