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Wind-Driven Sea Spray Aerosol Properties and the Research Systems That Sustain
Environmental Science

By

ELISE SARA PALOMBELLA
DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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DAVIS

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ABSTRACT

Marine aerosols represent one of the largest natural aerosol sources in the Earth system, yet substantial uncertainty remains in how wind-driven sea spray aerosol (SSA) properties evolve under varying wind conditions and influence cloud-relevant behavior. This dissertation examines the chemical composition, size distributions, and cloud condensation nuclei (CCN) activity of nascent SSA using measurements collected during the 2022 Characterizing Atmosphere-Ocean parameters in SOARS (CHAOS) campaign at the Scripps Ocean-Atmosphere Research Simulator (SOARS), a large-scale wind-wave channel facility. Controlled laboratory experiments were used to evaluate wind-speed-dependent variability in SSA properties under well-constrained conditions. Results show that while SSA mass and number concentrations increase with wind speed, submicron SSA properties relevant to CCN activation exhibit limited sensitivity to wind forcing under the conditions studied, emphasizing the importance of particle composition and mixing state in governing cloud-relevant behavior. Because large collaborative campaigns such as CHAOS rely on training environments that support the development and retention of early-career researchers, this dissertation also examines the role of mentorship within scientific research systems. A complementary case study therefore investigates graduate-led near-peer mentorship through the E-SEARCH program, which evaluates mentorship as a component of research infrastructure supporting confidence, inclusivity, and persistence among undergraduate and graduate researchers in STEM environments. Together, this work integrates controlled laboratory aerosol measurements with an examination of the human systems that sustain collaborative environmental research.

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I struggled to figure out how to write this section because, in many ways, I wanted to acknowledge only myself for persevering through what were often the most difficult six years of my life. I still want to take a moment to honor that effort, and especially the space I worked hard to create for protecting my mental health and staying grounded throughout the PhD experience. I hope that along the way I made a meaningful impact in the lives of some of the people I met, whether by inspiring them to pursue a non-traditional dissertation chapter, encouraging them to prioritize their mental health, challenging unfair academic environments, or simply reminding them to put their lives and well-being first.

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and helping me reach the finish line. I hope that somewhere along the way I made you a little proud.

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MATERIAL PENDING PUBLICATION

Chapter 2, in part, is being prepared for submission in *ACS Earth and Space Chemistry*. The dissertation author was the primary researcher and author of this material.

Chapter 3, in part, is being prepared for submission in *ACS Earth and Space Chemistry*. The dissertation author was the primary researcher and author of this material.

Chapter 4 is not being prepared for submission for publication. The dissertation author was the primary researcher and author of this material.

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1 INTRODUCTION

1.1 MARINE AEROSOLS IN THE EARTH SYSTEM

Since oceans cover 70% of Earth's surface, marine aerosols are one of the largest sources of natural aerosols on the planet along with mineral and soil dust. Globally, marine aerosols form an extremely important natural aerosol system: with influences on Earth's radiative budget, ecosystems, biogeochemical cycling, as well as regional air quality (O'Dowd & Leeuw, 2007). Through their influence on radiative transfer and cloud formation, marine aerosols contribute to both direct and indirect climate effects, making them a key component of uncertainty in climate forcing estimates. Marine aerosols are produced in two forms: directly as sea spray aerosol (SSA) particles (primary) and indirectly as biogenic gases that can create particles (secondary marine aerosols or SMA). Primary SSA particles originate at the ocean-atmosphere interface during wave breaking processes (de Leeuw et al., 2011).

Over remote oceans, SSA and SMA together constitute the dominant natural aerosol background and exert a strong influence on baseline atmospheric conditions. In the absence of significant continental influence, SSA often represents the primary contributor to aerosol mass and contributes substantially to background radiative and cloud-relevant properties of the marine boundary layer (Fitzgerald, 1991; O'Dowd et al., 1997; Lewis & Schwartz, 2004). As a result, marine aerosols provide a natural reference state against which anthropogenic aerosol perturbations are assessed, both in observational studies and in global climate models (Bates et al., 2012). Accurately characterizing this background is therefore essential for reducing uncertainty in model representations of marine aerosol processes and their associated climate forcing (Bian et al., 2019). Increasingly, marine aerosol studies aim to distinguish the relative contributions of SSA and SMA in natural environments to better constrain their respective roles in atmospheric and climate processes.

1.2 SSA PRODUCTION AND CHARACTERISTICS

Attention turns to the physical production of sea spray aerosol, which represents the primary pathway by which the ocean directly injects particulate matter into the atmosphere. Understanding the mechanisms governing SSA production, as well as the resulting physical characteristics, provides a critical foundation for interpreting the properties and impacts of marine aerosols in the atmosphere. SSA is generated through physical interactions between the ocean surface and the atmosphere, primarily driven by wind and wave activity. During wave breaking, air bubbles are entrained beneath the sea surface and subsequently rise and burst, ejecting particles into the atmosphere (Blanchard, 1989). This bubble-bursting process produces distinct classes of droplets that differ in both size and composition, commonly described as film drops and jet drops. Film drops originate from the rupture of the thin liquid film covering an entrained bubble at the ocean surface and tend to reflect the chemical characteristics of the sea-surface microlayer (SSML), while jet drops are formed from the collapse of the bubble cavity and more closely resemble the composition of bulk seawater.

The physicochemical properties of nascent SSA are closely linked to both ocean surface chemistry and the mechanisms by which seawater is transferred into the atmosphere. Supermicron SSA is typically dominated by inorganic sea salt components, including sodium chloride and other salts, and is generally associated with jet drop production. In contrast, submicron SSA often exhibits enhanced organic content, arising from film drop production and, in some cases, subsequent chemical processing of marine biogenic emissions (O'Dowd et al., 2004). Simultaneously, SMA form through gas-to-particle conversion processes in the marine atmosphere and are commonly composed of non-sea-salt sulfate and organic species (O'Dowd & Leeuw, 2007). Historically, submicron marine aerosol populations were largely attributed to secondary

formation pathways linked to oceanic biological activity, with gas-to-particle conversion assumed to dominate this size regime (O'Dowd et al., 1997). However, subsequent observations have demonstrated that primary SSA production can also contribute substantially to submicron aerosol populations, motivating continued investigation into the relative roles of primary and secondary marine aerosol sources. For example, Ovadnevaite et al. (2011) reported sea spray plumes with primary organic matter mass loadings reaching $3\text{--}4\ \mu\text{g m}^{-3}$, exceeding secondary sulfate mass concentrations under clean marine conditions (Ovadnevaite, O'Dowd, et al., 2011). Despite such observations, quantifying the relative contributions of primary and secondary processes to freshly emitted submicron marine aerosol remains challenging, as field measurements, laboratory measurements, and model simulations have yet to converge on consistent representations of production, flux, and atmospheric transport (Hartery et al., 2020; Wohl et al., 2020; Russell et al., 2023). More recent studies indicate that submicron sea spray aerosol may consist of both internally and externally mixed populations of primary and secondary particles, with organic enrichment present across multiple formation pathways (Wang et al., 2015). Varying mixing states add further complexity to the climatic impacts of marine aerosols, as particle origin, composition and processing history can all influence the environment, especially through aerosol-cloud interactions. As a result, understanding how these properties govern cloud activation provides a more direct framework for assessing the climate relevance of submicron sea spray aerosol.

1.3 SSA IMPACTS ON CLOUDS

SSA plays a central role in shaping cloud properties over the oceans by modifying particle populations available for cloud droplet formation. Estimates of marine aerosol fluxes suggest that SSA can substantially perturb marine boundary layer cloud environments. For example, O'Dowd et al. (2004) reported fluxes on the order of $2 \times 10^6\ \text{m}^{-2}\text{s}^{-1}$ at moderate wind speeds ($\sim 10\ \text{m s}^{-1}$),

corresponding to the introduction of several hundred particles per cm^3 into low-level marine clouds. Such perturbations are climatically relevant, as changes in marine cloud cover can strongly influence Earth's radiation balance. For example, modeling studies suggest that changes in low-level marine cloud cover on the order of 20-35% could offset radiative forcing associated with a doubling of atmospheric CO_2 (Fossum et al., 2020; Mulcahy et al., 2018).

The influence of SSA on clouds depends strongly on particle size and composition. Submicron SSA primarily affects clouds through their number concentration and ability to activate as cloud condensation nuclei (CCN), whereas supermicron marine aerosols influence radiation mainly through enhanced scattering due to their larger size and mass (Li et al., 2022; Russell et al., 2023). Consequently, cloud droplet number, cloud albedo, and precipitation processes are sensitive not only to SSA abundance, but also to the size distribution and chemical characteristics of SSA present in the marine atmosphere (Fossum et al., 2020). While field observations have provided important insights into the cloud impacts of SSA, the coupled influence of wind forcing, ocean surface conditions, and aerosol mixing state makes it challenging to isolate individual drivers in natural environments. Laboratory wind-wave channel studies offer a controlled setting in which nascent SSA production and cloud-relevant properties can be examined systematically.

1.4 CONTROLLED LABORATORY AND WIND-WAVE CHANNEL STUDIES

Interpreting cloud-relevant properties of SSA in natural environments is inherently challenging due to the simultaneous influence of wind forcing, ocean physicochemical conditions, biological activity, and atmospheric transport. In field settings, freshly emitted SSA is difficult to distinguish from aged or externally influenced aerosol populations, even under conditions commonly described as pristine (Seinfeld et al., 2016). These constraints limit the ability of field measurements alone to isolate the processes governing nascent SSA formation and transformation.

Laboratory-based ocean-atmosphere simulators provide an alternative framework in which key drivers of SSA production can be examined under controlled conditions. Previous studies have demonstrated that SSA properties are sensitive not only to environmental factors such as water temperature and biological activity, but also to the methods by which particles are generated (Collins et al., 2014; Forestieri et al., 2018; Wang et al., 2015). Advances in laboratory systems, including the Marine Aerosol Reference Tank (MART) and large-scale wave flumes, have enabled more physically realistic representations of wave breaking and bubble-mediated aerosol production (Prather et al., 2013; Sauer et al., 2022). Aerosols generated in these systems have been shown to reproduce key size-resolved chemical characteristics of freshly emitted SSA observed in the field, supporting their use as proxies for nascent marine aerosol populations.

Despite these advances, important uncertainties remain regarding how specific production pathways and oceanic physicochemical conditions influence the size-resolved composition and cloud-relevant properties of SSA. Addressing these uncertainties requires coordinated laboratory studies that can systematically vary production conditions while retaining relevance to natural marine environments. When considered alongside field observations and remote sensing, such studies provide a pathway toward reconciling controlled experimental insights with the complexity of aerosol-cloud interactions in the real atmosphere.

1.5 CHAOS SUMMER 2022 AND SOARS

The CHaracterizing Atmosphere-Ocean Parameters in SOARS (CHAOS) was conducted during the Summer 2022 at the Hydraulics laboratory at Scripps Institution of Oceanography in La Jolla, CA. CHAOS was a highly collaborative research effort involving more than ten laboratory groups from all across the United States, unified by the goal of investigating SSA generation and properties using the Scripps Ocean-Atmosphere Research Simulator (SOARS).

SOARS is a large-scale, enclosed wind-wave channel designed to simulate coupled air-sea interactions under controlled conditions, enabling the generation of realistic waves and associated aerosol production. Its enclosed design allows for the study of nascent SSA with reduced influence from external atmospheric variability, providing a platform for the coordinated, multi-instrument observations of aerosol physical, chemical and cloud-relevant properties.

Within the CHAOS campaign, the Cappa laboratory focused on characterizing SSA chemical composition using a ToF-ACSM, alongside complementary particle size distribution measurements and CCN activity experiments. Additional measurements conducted by collaborating groups included ice-nucleating particle concentrations, particle bounce behavior, water uptake, viscosity, and phase state. Across all participating studies, the central objective of the CHAOS campaign was to assess how wind forcing influences the physical, chemical, and cloud-relevant properties of nascent SSA.

1.6 DISSERTATION SCOPE AND STRUCTURE

Together, Sections 1.1-1.5 establish the scientific framework for this dissertation, which investigates the production, composition and cloud-relevant properties of nascent SSA under controlled laboratory conditions. Chapters 2 and 3 present results from the CHAOS campaign conducted in the SOARS wind-wave channel, with a focus on wind-speed-dependent variations in SSA chemical composition, particle size distribution, hygroscopicity and CCN activity.

Large collaborative research campaigns such as CHAOS rely not only on specialized instrumentation and experimental infrastructure, but also on training environments that enable researchers to operate complex systems, coordinate across teams, and sustain experimental programs over time. As a result, the scientific knowledge generated through such campaigns is closely tied to the educational structures that support researcher development and participation.

In addition to the experimental aerosol investigations presented in Chapters 2 and 3, this dissertation therefore includes a complementary case study examining graduate-led near-peer mentorship through the E-SEARCH program. While methodologically distinct from the aerosol studies, this chapter examines mentorship as a component of research infrastructure that supports training, confidence, and persistence among researchers participating in complex scientific environments. Together, the chapters of this dissertation address both the physical processes governing marine aerosol behavior and the human systems that sustain collaborative environmental research.

1.7 MENTORSHIP IN GRADUATE EDUCATION

Large-scale, collaborative research efforts such as the CHAOS campaign rely not only on advanced experimental infrastructure and instrumentation, but also on training structures that enable researchers to operate complex systems, coordinate across teams, and sustain participation over extended campaigns. Undergraduate researchers are increasingly embedded within complex research environments, where access to hands-on experience, procedural knowledge, and sustained mentorship plays a critical role in shaping education pathways. Within these settings, graduate students frequently serve as primary mentors responsible for onboarding undergraduates, transferring technical skills, and supporting day-to-day research activities.

During the CHAOS campaign, mentorship was embedded directly within experimental operations, as graduate researchers—including the author—worked alongside undergraduate participants during experimental setup, data collection, and analysis. This near-peer structure reflects a common but often informal feature of collaborative scientific research, in which graduate-undergraduate mentorship supports both research continuity and trainee development. Recognizing mentorship as a form of research infrastructure, this dissertation includes a

complementary case study examining graduate-led near-peer mentorship through the E-SEARCH program. Distinct from the experimental aerosol studies presented in earlier chapters, this case study employs a program-level evaluation framework to examine how structured mentorship supports confidence, inclusivity, and persistence in STEM research contexts. Together, the chapters of this dissertation highlight both the technical systems used to generate environmental knowledge and the human systems that sustain those efforts.

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CHAPTER 2: Wind-Driven Shifts in Sea Spray Aerosol Composition

Observed in a Controlled Wind-Wave Channel Experiment

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KEYWORDS

Sea spray aerosol, marine particles, wind speed, composition, size distributions

ABSTRACT

Sea spray aerosol (SSA) plays a critical role in marine atmospheric chemistry and cloud formation, yet the extent to which wind speed governs its production and, especially, composition remains poorly constrained. In this study, we used a controlled wind-wave channel to isolate the effects of wind speed on the mass and composition of SSA (PM_{2.5}) produced from coastal seawater. SSA mass and number concentrations increased by more than a factor of ten, and occurred along with marked shifts in chemical composition, as wind speeds increased from 9.6 to 21.2 m s⁻¹. A clear

transition in behavior occurred at wind speeds around 16 m s^{-1} , with relatively constant SSA production and properties below this threshold and changes above. At higher wind speeds, both the organic mass fraction (f_{org}) and the sulfate-to-chloride ratio decreased. The concentration of higher-molecular-weight organic species also increased with wind speed. These SSA compositional changes likely reflect changes in properties of the sea surface microlayer (SSML) that impact bubble-mediated production, along with changes in the importance of film drop and jet drop production mechanisms. Our findings demonstrate that wind speed alone can induce threshold-like changes in SSA composition, which will inform the development of wind-dependent source functions for atmospheric models.

2.1 INTRODUCTION

Marine aerosols, including sea spray aerosol (SSA), form a crucial link between oceanic and atmospheric systems through their influence on atmospheric chemistry, cloud formation, and Earth's radiative balance, which depend on their composition and physicochemical properties (O'Dowd et al., 1997; Quinn et al., 2017; Wang et al., 2015). Primary sea spray aerosol, produced by wind-driven wave breaking and bubble bursting at the ocean surface, contributes substantial amounts of both inorganic and organic components to the global aerosol flux, shaping many key atmospheric processes (Lewis and Schwartz, 2004; O'Dowd and de Leeuw, 2007; de Leeuw et al., 2011; Cochran et al., 2017). The large global flux of SSA into the atmosphere, estimated at 1,400 to 6,800 Tg per year—over 50% of global natural aerosol emissions—underscores its pivotal role in modulating cloud formation, atmospheric particle size distributions, and aerosol optical depth (AOD) (Quinn et al., 2017; de Leeuw et al., 2011; Lewis and Schwartz, 2004, IPCC 5 Chapter 7). SSA is generated through distinct mechanisms that occur during the bursting of air bubbles at the

ocean surface (film and jet droplets) and during wind-wave interactions (spume droplets). Film droplets are formed from the rupture of the bubble cap, jet droplets arise from the collapse of the bubble cavity, and larger spume droplets are ejected directly by wind-driven shearing of wave crests (Blanchard, 1989; Cipriano and Blanchard, 1981; Lewis and Schwartz, 2004). These processes collectively produce particles across a range of sizes and with varying compositions, from organic-rich submicron film droplets to large salt-dominated spume droplets. Variability in both size and composition influence their atmospheric residence time and climate impacts (O'Dowd and de Leeuw, 2007; Wang et al., 2017). In addition to primary SSA, secondary marine aerosols (SMA) are formed from the oxidation of ocean-emitted gases and subsequent nucleation or condensation of the oxidation products, adding to the variability in particle composition and size distributions (Quinn et al., 2017; O'Dowd and de Leeuw, 2007). In the atmosphere, primary and secondary processes happen concurrently, which can complicate efforts to separate their impacts. Even in remote marine regions, aerosol populations may still reflect non-marine influences, as truly pristine atmospheric conditions are rarely encountered (Andreae, 2007). Laboratory experiments that use realistic particle generation methods, such as those discussed here, can help elucidate the coupling between ocean water composition and physical production mechanisms at play and how they impact the size and chemical composition of SSA (Wang et al., 2015; de Leeuw et al., 2011; Forestieri et al., 2018).

Wind speed has long been identified as a dominant driver of SSA flux, with early parameterizations linking whitecap coverage—an indicator of air-sea energy transfer and wave breaking—to surface wind speed using power-law relationships (Monahan et al., 1986; Monahan and Muircheartaigh, 1980; Gong, 2003; de Leeuw et al., 2011). These foundational parameterizations emphasize the role of wind speed in controlling particle number, mass flux, and

size distributions. Satellite observations of coarse-mode aerosol optical depth (AOD_c), often considered a proxy for SSA, correlate with wind speed on daily and interannual timescales, although the observations show little seasonal coherence indicating the influence of other environmental factors (Dror et al., 2018). *In situ* field observations generally support the idea of a relationship between SSA mass concentrations and wind speed, although the observed correlations may be weak because the local wind speed may not fully capture the upwind conditions ($R^2 < 0.2$ and < 0.15 , respectively) (Russell et al., 2023). Number concentration of SSA, which are dominated by submicron particles, during individual field campaigns exhibit a dependence on wind speed, but with high variability that cannot fully be explained by local wind speed alone (Saliba et al., 2019). Variability in observations of wind speed-SSA relationships have been partly attributed to seasonal biological activity: organic surfactants produced in biologically active regions can suppress or enhance SSA generation at given wind speeds, indicating that wind-driven SSA flux is modulated by biogeochemical conditions at the sea surface (Sellegrri et al., 2006; Forestieri et al., 2018). Changes in the seawater temperature likely also contribute to the variability in wind speed-SSA relationships (Liu et al., 2021). Challenges in separating SSA from other particles based on observed size distribution or water uptake behavior may also contribute.

In addition to its effect on aerosol flux, wind speed also influences the composition of SSA, particularly the organic fraction. It is well-established that submicron SSA can be enriched in biologically-derived organic material from the water column (O'Dowd et al., 2004, Quinn et al., 2014; Wang et al., 2015). Some ambient measurements indicate that the proportion of organic matter in submicron SSA decreases as wind speed increases (e.g., Gantt et al., 2011). This trend is commonly attributed to the disruption of the sea surface microlayer (SSML)—a biologically enriched interface layer—under higher wind conditions, which alters the incorporation of organic

material into aerosols. It may be that at lower wind speeds, where the SSML remains more intact, organic-rich gel particles and exudates, along with more surface-active species, are more readily incorporated into the submicron aerosol population (Gantt et al., 2011; Burrows et al., 2014). As wind speed increases and the SSML is disrupted, it may be that less surface-active species are incorporated into SSA, increasing the importance of biologically derived material from the water column, including both soluble exudates and gel-like particles (Aller et al., 2017). These changes may be further modulated by regional and seasonal variability in biological productivity (O'Dowd et al., 2004; Gantt et al., 2011), which alters the pool of available organic material at the ocean surface (Enders et al., 2023), or by variability in temperature (Bates et al., 2019), which affects bubble properties (Lewis and Schwartz, 2004). However, Quinn et al. (2014) found that the organic fraction of freshly generated SSA did not consistently correlate with chlorophyll-a or vary systematically between cruises, suggesting that bulk biological productivity alone is not a reliable predictor of aerosol organic enrichment. SSA composition ultimately reflects a dynamic interplay between wind-driven physical processes, temperature, and biological inputs in addition to diverse aerosol speciation from other sources. These compositional differences influence key aerosol properties such as hygroscopicity and particle size distribution, which in turn affect cloud condensation nuclei (CCN) and aerosol-cloud interactions (Farmer et al., 2015). These complex interactions demonstrate that SSA's atmospheric relevance hinges not only on its emission flux but also on its evolving chemical composition, emphasizing the importance of incorporating all relevant processes in emission models (e.g., O'Dowd and de Leeuw, 2007).

Laboratory experiments using wave channels and breaking wave analogs have effectively reproduced SSA production mechanisms, such as bubble bursting and jet and film droplet generation, establishing their value in exploring aerosol size distributions and composition under

controlled conditions (O'Dowd and de Leeuw, 2007; Collins et al., 2014; Wang et al., 2017; Forestieri et al., 2018). Compared to field data, wave flumes have produced SSA with size-resolved chemical composition generally resembling those of freshly emitted SSA particles (Prather et al., 2013), establishing them as reliable proxies for physically and chemically accurate representations of marine aerosols (Stokes et al., 2016; Quinn et al., 2015; Bertram et al., 2018). However, studies combining wind forcing with laboratory systems remain limited, highlighting a gap in understanding how wind-driven dynamics influence submicron SSA flux and composition. Bruch et al. (2021) have used a wind-wave channel to show how the SSA flux varies with wind speed, and consequently the properties of waves (e.g., height, slope), although they primarily focused on supermicron particles and did not consider particle composition. Various other wind-wave channel studies have also investigated production of supermicron or very large (up to 600 mm) droplets, primarily focusing on spume droplets (e.g., Liu et al., 2024; Troitskaya et al., 2017; Erinin et al., 2022). Sun et al. (2018) examined the effect of wind speed on the abundance and properties of exopolymer particles within the SSML but did not characterize their emission. Collectively, prior laboratory work highlights the values of wave channels in isolating SSA production mechanisms while also revealing a gap in understanding how wind forcing influences the composition of submicron particles—an issue we address here using SOARS.

Recently, Madawala et al. (2024) used a new wind-wave channel, the Scripps Ocean-Atmosphere Research Simulator (SOARS), to characterize how wind speed influences the morphology and composition of individual submicron SSA. As part of the same study, Moore et al. (2025) measured the wind speed dependence of SSA acting as ice nucleating particles (INP), finding that the INP concentration varied with wind speed while the INP activated fraction remained constant. Here, we present results from the same study, focusing on the influence of wind

speed on submicron SSA production and bulk composition. We characterize emitted SSA particles smaller than 2.5 microns in diameter in terms of their number concentrations, size distributions, and bulk chemical composition, providing an integrated view of both physical and chemical responses to varying wind speeds under controlled laboratory settings.

2.2 METHODS

2.2.1 SOARS WIND AND WAVE CHANNEL

The Scripps Ocean-Atmosphere Research Simulator (SOARS) is a recirculating, enclosed wind-wave channel that was used to create SSA during the Summer 2022 field campaign titled CHAOS (CHaracterizing Atmosphere-Ocean parameters in SOARS). SOARS is 36.5 m x 2.4 m x 2.4 m (L x W x H) and can hold ~138,000 L of sea water. Waves up to 0.9 m in height can be generated using a motor-driven paddle and can be made to break with or without wind. Zonally-averaged in-channel windspeeds up to $\sim 26 \text{ m s}^{-1}$ are achievable. SOARS can be programmed to create varying wave sizes and wind speeds in a sequence. The wave sequence used during CHAOS generated fixed-height waves (wave height $\sim 0.5 \text{ m}$ for a paddle amplitude of 1.3) with two breaking waves per every five wave crests at all wind speeds. Further information describing the specifications of SOARS and future directions is detailed in Leibensperger III et al., (2025).

SOARS operated under positive pressure to limit infiltration of ambient air during experiments and isolate sea spray. To further reduce the potential influence of ambient particles, an enclosed tent barrier was created around the external SOARS paddle, where leaks are most likely. Inside the tent were two Corsi-Rosenthal air filters with MERV 8 filters, which reduced the concentration of particles inside the tent, and the tent was allowed to “breathe” in response to the paddle motion via two HEPA filters installed in the tent walls.

A series of experiments were conducted over a period of 6 days. Each experiment followed a similar format. First, the SOARS fans were set to a low wind speed while the headspace air recirculated through a bank of gas and particle filters, removing residual and infiltrated contamination. This filtering period typically lasted about 30 mins and ended when the particle number concentration fell below at least $\sim 100 \text{ p cm}^{-3}$. At the end of this period, the filters were bypassed, creating a closed loop of recirculating air within the channel. Wave production then commenced, and the fans were ramped to a specified fan speed, during which particle concentrations increased and then stabilized at a relatively constant value. Particle concentrations across a typical experiment are shown in Figure 2.1.

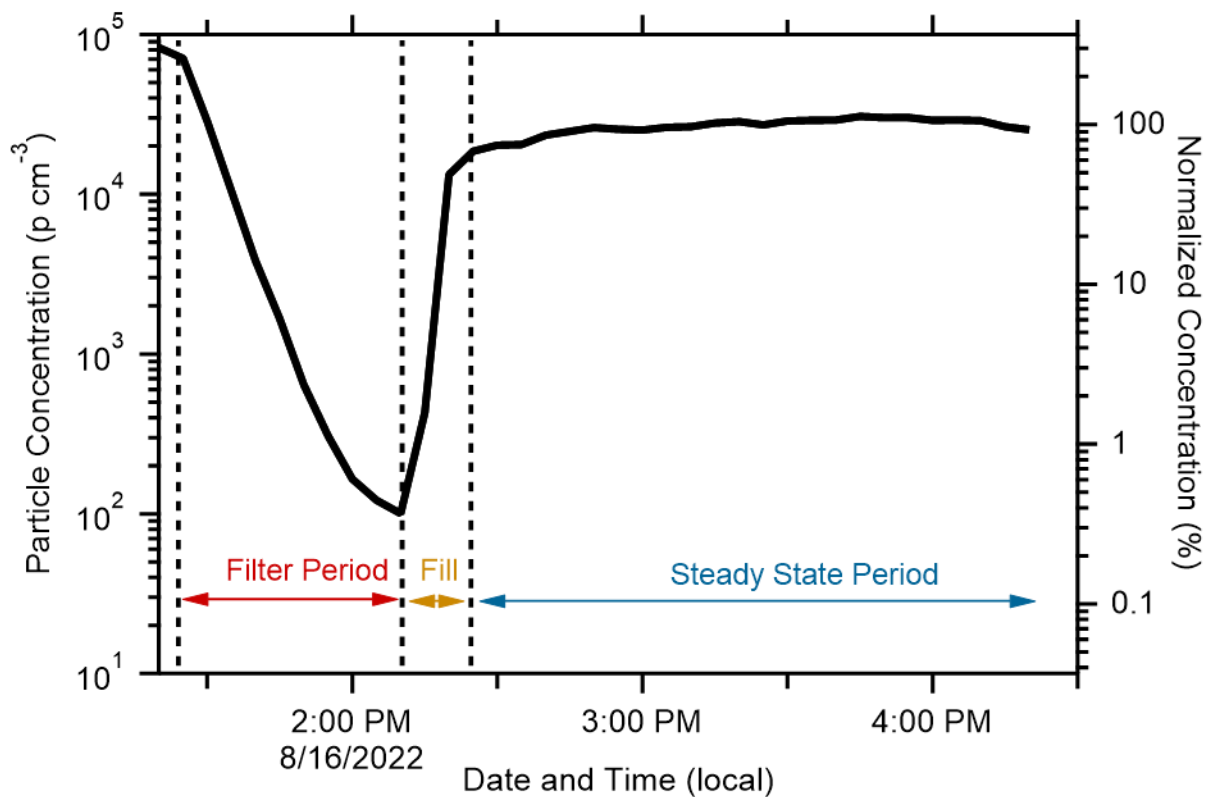


Figure 2.1: Particle number concentration on 8/16/22 across a wind speed experiment, illustrating the low-wind speed period during which particles were filtered out of SOARS to <

$\sim 100 \text{ p cm}^{-3}$ ($<1\%$ of steady state), followed by the fill period when the wind speed was increased, wave breaking began, and particle concentrations increased, and finally the steady-state period during which sampling took place. Absolute concentrations are shown on the left-axis and concentrations normalized to the steady state period on the right-axis.

The fan speeds (in revolutions per minute, RPM) were translated into wind speed based on in-channel anemometer-based air speed measurements (TSI Inc. model 9545-A) made at 0.6 m ($U_{0.6}$) without waves present, with a linear relationship between RPM and wind speed (Leibensperger III et al., 2025). The measured air speeds were converted to equivalent 10 m (U_{10}) wind speeds following Hsu et al. (1994). Wind speeds are reported as U_{10} because the 10 m reference height is the standard metric used in air-sea interaction studies and SSA parameterizations, allowing comparison with field observations. The applicability of the Hsu et al. (1994) relationship to the SOARS wind-wave channel during wave breaking has not been explicitly established and thus the resulting U_{10} values are best considered relative to each other, rather than in terms of their absolute values. The following fan RPM speeds were used during CHAOS sampling: 850, 1200, 1400, 1500, 1600, and 1800 RPM with equivalent U_{10} wind speeds of 9.6, 13.8, 16.3, 17.5, 18.7, and 21.2 m s^{-1} , respectively.

The CHAOS campaign wave sequence (or “wave packet”) was kept constant (~ 0.5 m wave height) for the entire study. In SOARS, whitecap coverage depends both on the wave packet amplitude, which controls the wave height, and on wind speed (Leibensperger III et al., 2025, Harb et al., *In prep.*). Field measurements over the open ocean indicate that while whitecap coverage generally scales with wind speed, substantial variability remains that cannot be explained by wind speed alone (Anguelova & Webster, 2006; Lewis & Schwartz, 2004). This behavior is commonly attributed to wind-driven energy and momentum transfer to the wave field, which promotes wave growth and breaking, although the specific mechanisms governing this relationship remain an

active area of investigation (Deike, 2026). Consistent with field observations, SOARS measurements show a monotonic increase in whitecap coverage with wind speed under fixed wave conditions (Harb et al., *In prep*).

SOARS was filled with Pacific Ocean water sourced from the nearby Scripps Pier. The pier has a water pump roughly 1-3 m above the ocean floor and supplies seawater to the local Birch Aquarium and various Scripps laboratories. From beginning to end of the pier, seawater is filtered using an aluminum screen and rotating drum with a variable mesh filter (18-120 μm) to remove debris and large biological species like phytoplankton (Jio, 2022). The seawater is then passed through additional coarse filters and is fed into a large settling tank for temporary storage. Once the seawater has settled, it is filtered additionally through high-capacity sand filters prior to longer-term storage in shared seawater holding tanks. For this study, the SOARS channel was gravity-filled with seawater from the holding tanks, and the water was not additionally filtered or UV sterilized before experimentation took place. During CHAOS, the SOARS channel was filled and washed four times from July 6-18th, July 19-21st, August 1-12th, and August 14-26th, 2022. The data presented in this study is from the fill period of August 15-20th, 2022 only. (A potential leak in the sampling line called into question the reliability of the data during the earlier experiments.) A table of the experimental times and wind speeds are presented in the Supplemental Information (Table S2.1). SOARS has the capability to adjust air and water temperatures, but temperatures were not controlled during this study and were allowed to fluctuate naturally. There are sensors throughout the wave-channel at various locations to measure CO_2 concentration, air and water temperature, and seawater salinity and turbidity. No nutrients were added to the seawater and the chlorophyll-*a* (chl-*a*) levels were low ($<0.5 \mu\text{g L}^{-1}$) and stable throughout the study period.

Particles were sampled from the SOARS headspace into a cylindrical manifold from which multiple instruments sub-sampled. Here, the SSA were sub-sampled from the manifold at 7.5 lpm through a 4 m long, 6.35 mm stainless steel tube. The sampled SSA passed through a 1 m long silica bead drier, which reduced the relative humidity to ~15-45%, and then through a PM_{2.5} cyclone. Particle losses between the manifold and instrumentation should be less than ~10% for all sizes comprising PM_{2.5} (Figure S2.1); results have not been adjusted for particle losses. The air stream was then split 3 ways between instruments for composition, size distribution, and CCN measurements. Only the composition and size distribution measurements are presented here; the CCN measurements will be considered as part of future work.

2.2.2 AEROSOL COMPOSITION WITH ToF-ACSM

The chemical composition of the SSA was measured using a Time-of-Flight Aerosol Chemical Speciation Monitor (Aerodyne, ToF-ACSM) with a PM_{2.5} inlet and a capture vaporizer, with an assumed unit collection efficiency for all species (Xu et al., 2017). A description of the instrument's operation is explained in detail by Fröhlich et al. (2013). The effective dry particle diameters measured by the ToF-ACSM were between 110 nm and 2.5 μ m with measured mass range from m/z 1 to 200 (Xu et al., 2017). The ToF-ACSM sampled for varying lengths during the steady state periods to account for the very different mass loadings encountered at different wind speeds. At high wind speeds, when SSA mass loadings were very large, sampling only occurred for a few minutes, while at lower wind speeds, when SSA mass loadings were smaller, sampling occurred up to the full period. This adjustment in sampling time was used to preserve the vaporizer lifetime, inlet flow, and measurement quality.

The ToF-ACSM often faces limitations when analyzing SSA with high inorganic salt content. Typically, the ToF-ACSM operates with the vaporizer at 600°C to characterize “non-refractory” particles, which are defined as aerosols that vaporize quickly and are subsequently detected. SSA contains both non-refractory organic species, along with various salts, including sodium chloride, sodium sulfate, and other inorganic salt species (Freney et al., 2021, O'Dowd et al., 2004). Due to the (semi-)refractory nature of these salts, quantifying SSA with the ACSM poses challenges, including inefficient salt vaporization and unit mass resolution (UMR) peak overlap. Documented issues include negative Cl^- peaks from the slow evaporation of material from the vaporizer and nonlinear contributions to the Na^+ signal due to surface ionization on the vaporizer (Tobler et al., 2020). To address these challenges, the response of the ToF-ACSM to dry NaCl particles as a function of vaporizer temperature, ranging from 400 to 650°C, was tested prior to the CHAOS campaign. The NaCl particles were generated from atomization (TSI, Model 3076) of an aqueous sodium chloride (NaCl , $\geq 99.5\%$; ThermoFisher) solution, followed by drying through a silica bead drier. Particles with mobility diameters of 300 nm were selected using a differential mobility analyzer and then split between the ToF-ACSM for composition and a condensation particle counter for counting.

The results of this vaporizer efficiency test can be seen in Figure S2.2. Tobler et al. (2020) previously found that the signal at $m/Q = 35$ (corresponding to Cl^+) and $m/Q = 36$ (corresponding to HCl^+), along with the $m/Q = 37$ and $m/Q = 38$ isotopomers, both responded slowly to changes in the ACSM filter state for pure NaCl particles when the vaporizer was at 600 °C, with prolonged signal decay (“tailing”) following filter switching, reflecting the slow evaporation of chloride-containing material from the vaporizer surface. The response time increased as the vaporizer temperature was increased but remained too slow to allow for proper determination of the chloride

mass. In contrast, we found that the signals at $m/Q = 58$ (corresponding to NaCl^+) and the isotopomer at $m/Q = 60$ exhibited rapid transitions when the filter state was changed, especially as the temperature was increased to 650 °C. We observed that the signals at $m/Q = 58$ and 60 reached an approximate plateau at 650 °C and therefore concluded that the optimal operation temperature for these experiments is 650 °C. From the laboratory experiments, after accounting for the long signal decay observed at $m/Q = 35$ and 37, we established that the ratio between signals at $m/Q = 35$ and $m/Q = 58$ was 8 at 650 °C. The ACSM fragmentation table (Allan et al., 2004) was therefore modified to use $\text{frag_Chl}[35] = 8 \times \text{Chl}[58]$ and $\text{frag_Chl}[37] = 8 \times \text{frag_Chl}[60]$.

A standard ToF-ACSM ionization efficiency (IE) and relative IE (RIE) calibration was conducted using atomized solutions of pure NH_4NO_3 and $(\text{NH}_4)_2\text{SO}_4$ to obtain IE_{NO_3} , RIE_{NH_4} and RIE_{SO_4} (Fröhlich et al., 2013). Experimental RIE values for each species are presented in Table 1S. Default RIE values were used for all species (Org, NO_3 , SO_4 , NH_4 , Cl, H_2O and K) during initial data analysis using the Tofwerk “IgorDAQ” package (Wavemetrics Inc.). To account for potential organic contributions to m/Q 58, which overlaps with NaCl, the ACSM was periodically operated at a vaporizer temperature of 525 °C. These tests demonstrated that any organic signal at this m/Q was negligible compared to that from NaCl when the vaporizer operated at 650 °C. The NaCl concentration calculated using the default chloride RIE was compared with concurrent filter measurements of submicron and supermicron particles reported by Madawala et al. (2024). This comparison indicated that use of the default ACSM RIE value led to an underestimation of the NaCl concentration, and thus the RIE_{Chl} was adjusted from 1.4 (default) to 0.82 to better match the filter measurements. A graph displaying sub- and supermicron filter measurements for Cl^- compared to the ACSM chloride mass at both RIE values is provided in Figure S2.3. The ToF-ACSM used here lacks the resolution to allow for robust distinguishing between inorganic and

organic sulfate (Chen et al., 2019); we assume here that all sulfate is inorganic. We assume that sodium is the dominant cation counterion for the measured anionic species and calculate its concentration assuming ion balance. The overall sea salt concentration is taken as the sum of the measured inorganic species, plus sodium. In our analysis we focus primarily on changes in the relative composition (e.g., the organic fraction of total $PM_{2.5}$) rather than absolute concentrations. This approach allows us to focus on relative proportions, avoiding the use of absolute mass values that are less relevant for modeling or comparison with previous studies.

2.2.3 AEROSOL SIZE DISTRIBUTIONS

Particle size distribution measurements were made behind the $PM_{2.5}$ cyclone. SSA size distributions were measured with a Scanning Mobility Particle Sizer (TSI, SMPS 3936) from mobility diameter ($D_{p,m}$) 14-736 nm, a Scanning Electrical Mobility Analyzer (Brechtel, SEMS) from $D_{p,m}$ 10 to 1339 nm, and an Aerodynamic Particle Sizer from aerodynamic diameter 0.54 to 19.8 μm (TSI, APS 3321) ($D_{p,a}$). The APS data were converted from $D_{p,a}$ to $D_{p,m}$ assuming a particle density (ρ_p) of 1.8 g cm⁻³ and then merged with the SEMS at 650 nm and with the SMPS at 630 nm. The merged size distributions were integrated (assuming spherical particles) to yield particle number and volume concentration. The volume concentrations were converted to mass concentrations assuming $\rho_p = 1.8$ g cm⁻³. Both the SEMS and the SMPS were used for all runs from August 15 to August 19th, 2022. The SEMS mixing condensation particle counter malfunctioned on August 20th and thus size distribution data is only available from the SMPS (and not the SEMS) for the three runs on this day. The size distributions shown used the merged SEMS+APS results and thus exclude the measurements on August 20th.

2.3. RESULTS AND DISCUSSION

2.3.1 STEADY STATE SSA CONCENTRATION RELATIONSHIP WITH WIND SPEED

The steady state SSA concentrations were characterized within SOARS at six U_{10} wind speeds (9.6, 13.8, 16.3, 17.5, 18.7 and 21.2 m s^{-1}). The corresponding SSA mass concentrations (in $\mu\text{g m}^{-3}$) are shown in Figure 2.2. Particle mass concentrations increased as wind speed increased, culminating in a nearly forty-fold increase once wind speed exceeded $\sim 19 \text{ m s}^{-1}$. SSA number concentrations exhibited similar behavior to mass concentrations. While there were some run-to-run differences at a given wind speed, most notably 9.6 m s^{-1} and 18.7 m s^{-1} , the overall behavior is clear, with a sharp increase in concentration as the wind speed goes from 16.3 m s^{-1} to 17.5 m s^{-1} .

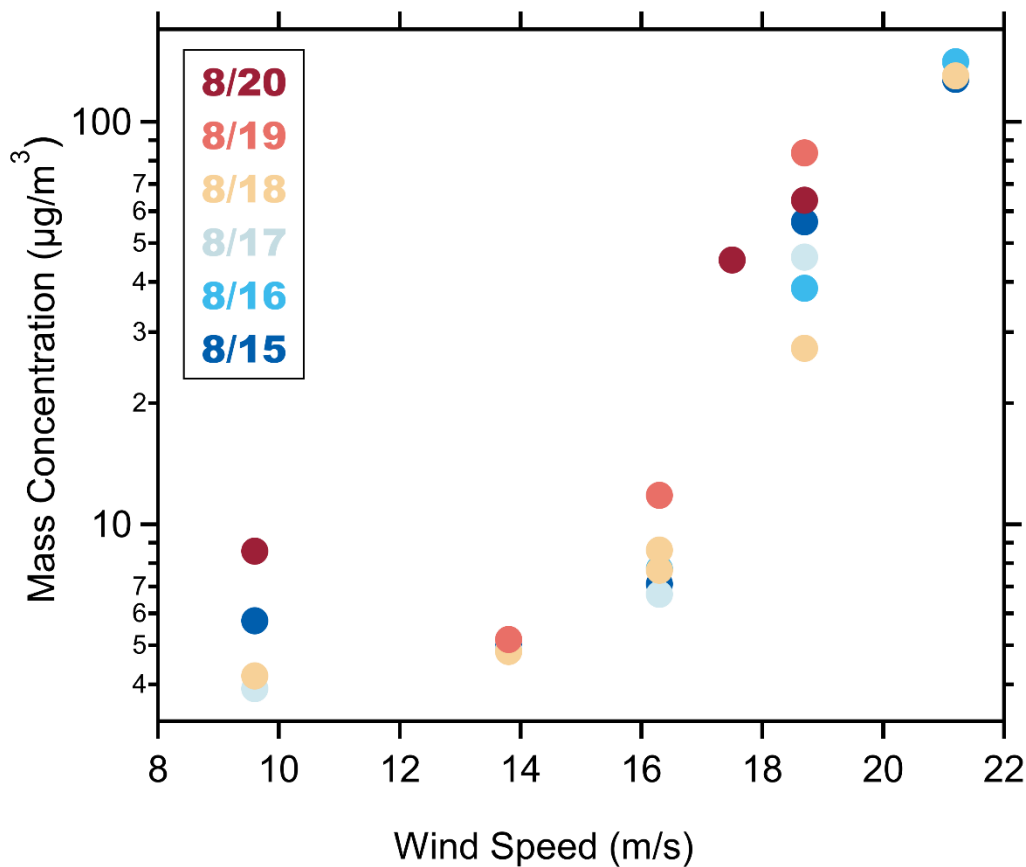


Figure 2.2: SSA mass concentration from the ToF-ACSM at each individual wind speed measured during CHAOS. The color of each point represents the date the sample was taken.

The observation that SSA concentrations increase with windspeed is generally consistent with previous field findings and with subsequent measurements from SOARS (Leibensperger III et al., *Submitted*). For example, Modini et al. (2015) observed a 6-fold increase in SSA number concentrations and a 4-fold increase in sea salt mass as the average wind speed changed from 12 m s⁻¹ to 16 m s⁻¹. Saliba et al. (2019) hypothesized the onset of mechanistic changes in SSA production above 16 m s⁻¹ but reported a somewhat weak relationship between SSA number concentrations and local wind speed, with their overall fit indicating a factor of 7 increase going from our lowest to highest wind speed. Ovadnevaite et al. (2011) observed a clear dependence of SSA PM_{2.5} concentrations on local wind speed, with low and relatively constant SSA concentrations below ~12 m s⁻¹ and then rapidly increasing concentrations with higher wind speed such that the SSA concentration was ~8 times larger at 21 m s⁻¹ compared to low wind speeds; their data were reasonably well-fit with a power-law function of the form $SSA = y_0 + a_1 \cdot (U_{10})^{b_1}$. The exponent, b_1 , varied between conditions when the wind speed was increasing versus when it was decreasing (2.8 versus 2.1, respectively), which the authors suggested reflected differences in the whitecap coverage.

Various parameterizations of the SSA flux dependence on windspeed also exist (see Grythe et al., 2014). While we measured SSA concentrations rather than SSA fluxes, de Leeuw et al. (2011) note that for submicron particles the effective flux (that is, the flux at some height) is similar to the interfacial flux (that is, the flux of particles leaving the surface). As such, the concentration relationship with wind speed should be similar to that for fluxes, although we note this limitation in making comparisons. Many SSA flux parameterizations assume a power law relationship with wind speed of the form $Flux = a_1 \cdot U^{b_1}$ where the exponent b_1 typically ranges from 3.41 to

3.74, although some suggest smaller values (e.g., de Leeuw et al., 2011; Grythe et al., 2014). This relationship derives from the non-linear dependence of whitecap coverage on wind speed, going back to the work of Monahan (1969), and an assumption that SSA production scales linearly with whitecap coverage. More recent assessments indicate a somewhat more complex relationship between whitecap coverage and wind speed, potentially with some threshold behavior (e.g., Schwendeman and Thompson, 2015). Some other parameterizations assume an exponential relationship of the general form $Flux = a_1 \cdot \exp(b_1 \cdot U)$ where b_1 is assumed either size-independent or size-dependent (e.g., Norris et al., 2008). The whitecap-based parameterizations are more commonly used in models.

Given this relationship, we attempted to fit the wind-wave channel observations with a power law function and found that the data can be well fit, but that the derived exponent ($b_1 = 13.7 \pm 3.7$) is much larger than those found in whitecap-based parameterizations and compared to Ovadnevaite et al. (2011), and also that a substantial y-offset is required. Similar results are obtained here whether considering particle mass concentrations or number concentrations. The Ovadnevaite et al. (2011) fit also exhibits a small y-offset whereas many of the whitecap-based parameterizations assume zero offset. The difference between our results and the field observations and whitecap-based parameterizations could result from the experimental constraints of the wind-wave channel experiments. Within SOARS the whitecap coverage increases with windspeed, similar to open ocean observations (Harb et al., *In prep.*), while the wave height was held constant. For equilibrium open ocean conditions both the wave height and whitecap coverage generally increase with wind speed, although also depend on wave age and other factors (Bourassa et al., 2001; Brumer et al., 2017). It may be that the use of a fixed wave height in our experiments resulted in a shift in the SSA-wind speed relationship relative to the open ocean, perhaps by altering the

mixing of particles from the near-surface interstitial layer to the mixed layer above. Compared to open ocean results, the wind-wave channel experiments yield a larger and more pronounced threshold wind speed and a somewhat stronger dependence of SSA production on wind speed above the threshold. While such differences complicate translation of the wind-wave channel results to parameterizations that can be used in models, general insights into the impacts of wind speed on particle production and properties can still be obtained.

2.3.2 SSA SIZE DISTRIBUTIONS AND WIND SPEED

Particle size distributions were highly consistent across replicate runs at each wind speed, suggesting stable SSA production dynamics. Figure 2.3 shows the normalized number-weighted size, surface area, and volume distributions averaged at each wind speed, highlighting systematic changes with increasing wind. At wind speeds exceeding $\sim 16 \text{ m s}^{-1}$, the number-weighted size distributions exhibit a distinct shift towards smaller diameters, with an increased relative contribution of particles smaller than 100 nm. This shift suggests enhanced production of ultrafine particles under stronger wind forcing. This increase could be driven by changes in film drop formation resulting from SSML disruption or increased bubble fragmentation. Alternatively, there is some suggestion that large ($>20 \text{ }\mu\text{m}$) particles can fragment in the SOARS fans to produce smaller particles (Leibensperger III et al., 2025). However, it seems likely that production of particles via a distinct mechanism (fan-induced fragmentation) would generate particles with a distinct size distribution, rather than leading to a continuous shift in the distribution, as was observed here, or an increase in concentration with little change in the size distribution (Leibensperger III et al., 2025). As such, we interpret the changes in size distributions, as well as in particle composition, with wind speed as being related to changes in relevant physical processes, rather than an artifact.

In contrast to the number-weighted distributions, surface area-weighted distributions shift slightly toward larger peak diameters and show a more apparent bimodal shape at the highest wind speeds, while volume-weighted distributions exhibit less clear trends. Focusing on the surface area-weighted size distributions, we find that both the lower wind speed and higher wind speed observations are well fit with a two-mode log normal distribution with fixed mode diameters and widths (Figure S2.4). Interestingly, the mode diameters and widths are very similar for both the lower and higher wind speeds, with the observed changes driven primarily by variations in the amplitudes.

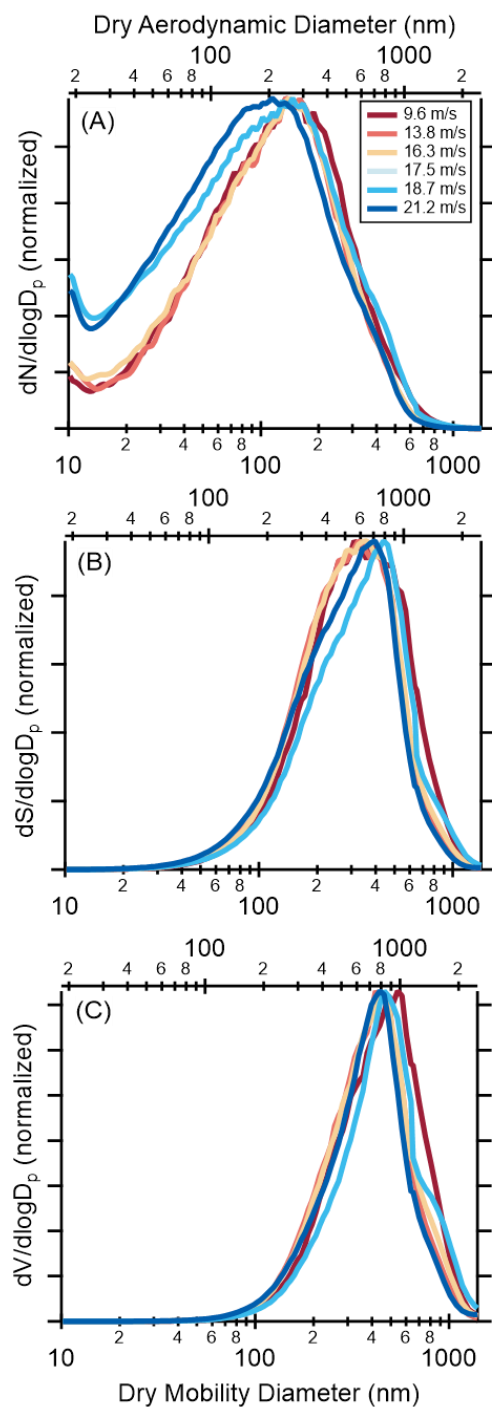


Figure 2.3: Average (a) number-weighted, (b) surface-area-weighted, and (c) volume-weighted size distributions for each wind speed, normalized to the maximum concentration. The bottom axis shows the mobility diameter and the top axis the aerodynamic diameter, assuming a particle density of 1.8 g cm^{-3} .

At the same wind speed threshold ($\sim 16 \text{ m s}^{-1}$) where SSA mass concentrations begin to increase more sharply (Figure 2.2), we also observe a notable enhancement of particles in the ultrafine size range ($<100 \text{ nm}$) at higher wind speeds (Figure 2.3a). These ultrafine particles contribute minimally to total mass (Figure 2.3c) and fall largely outside the ToF-ACSM detection range ($\sim 110 \text{ nm}$ cutoff), limiting their influence on the observed composition. However, changes in the surface area-weighted distributions (Figure 2.3b), including the emergence of a more pronounced larger mode at the highest wind speeds, suggest that distinct modes of particle formation may dominate under stronger wind forcing. Deike et al. (2022), building on the observations of Jiang et al. (2022), note that there are two modes of film droplet production (film bursting and film flapping) that give rise to SSA of different size, along with even larger jet drops. Changes in the SSML, and thus the bubble film, could promote one mechanism over the other; if we assume that the two modes in the surface area-weighted distributions come from film droplet production, the shift towards larger sizes suggests that the film flapping mechanism increases in relative importance (Deike et al., 2022). Comparison of the integrated area under the two modes fit to the size distributions (Figure S2.4) indicates that the film bursting mechanism contribution to the SSA surface area decreases from 88% at lower wind speed to 80% at higher wind speeds. This shift in the predominant mechanism has the potential to alter SSA composition, particularly if the different modes preferentially enrich or exclude specific organic or inorganic constituents.

2.3.3 SSA COMPOSITION AND WIND SPEED

Across all experiments, the organic aerosol (OA) mass fraction averaged $12.6 \pm 5.7\%$, while sea salt accounted for the remaining $87.4 \pm 5.7\%$, comprising 6.2% sulfate, 48.7% chloride, 32.5% sodium, $<1\%$ potassium (calculated assuming ion balance) and negligible contributions

from nitrate and ammonium. Figure 2.4a illustrates the relationship between wind speed and the PM_{2.5} SSA composition. Below 16 m s⁻¹ the OA mass fraction (f_{org}) is relatively insensitive to changes in wind speed, averaging $18.4 \pm 3.6\%$. Above 16 m s⁻¹ the f_{org} exhibits a clear decrease with increasing wind speed, falling to $5.0 \pm 0.7\%$ at the highest wind speed (21.2 m s⁻¹). In other words, as wind speed increases above the same threshold at which SSA PM_{2.5} production rapidly increases and the size distributions shift, the composition becomes increasingly sea-salt dominated. The observed dependence of f_{org} on wind speed is well fit using a sigmoid function with an inflection point at $U = 17.1 \text{ m s}^{-1}$. We note that the f_{org} at a given wind speed is reasonably constant across the six days of the experiment (Figure S2.5), indicating that the changes are driven by wind speed changes rather than co-variation between experiment day and wind speed or changes in the seawater composition (Figure S2.6-S2.7). Even at wind speeds with the most repeat measurements (16.3 and 18.7 m s⁻¹), f_{org} remained consistent over time, indicating no time-dependent enrichment of the organic fraction. This also suggests that accumulation of organic material or changes to the chemical composition of seawater organic material over time did not significantly alter the f_{org} -wind speed relationship.

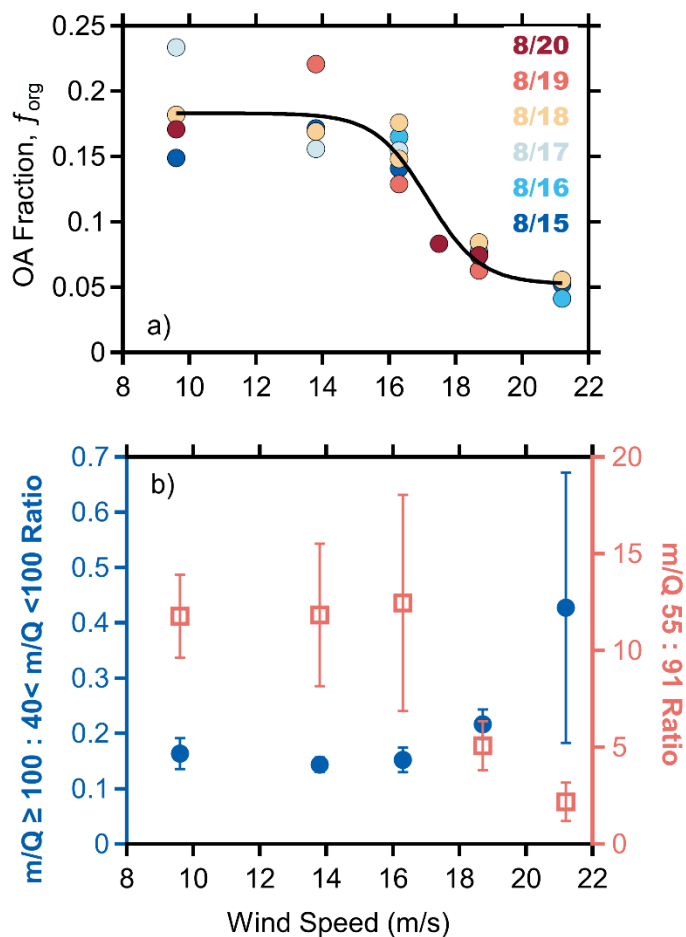


Figure 2.4: (A) The dependence of the organic aerosol mass fraction on wind speed. Points are colored by sample date. (B) The ratio of organic species with $m/Q \geq 100$ to those with $40 < m/Q < 100$ (blue circles) and the ratio of m/Q 55 (C_4H_7^+) to m/Q 91 (C_7H_7^+) (orange squares) as a function of wind speed.

The literature on particle composition-wind speed relationships from open ocean studies is mixed. For example, Gantt et al. (2011), based on measurements at coastal sites, found that the OA fraction of SSA $\text{PM}_{2.5}$ decreases with increasing wind speed, from about 80% to near zero and with a nominally sigmoidal relationship and a transition point around 7 m s^{-1} . Rinaldi et al. (2013) extended the dataset used by Gantt et al. (2011) and similarly determined that f_{org} decreases with wind speed, although they proposed a linear relationship rather than sigmoidal. Perhaps of note,

Gantt et al. (2011) show the data underpinning the (sigmoidal) relationship between f_{org} and wind speed while Rinaldi et al. (2013) simply state that a (linear) relationship exists without showing the data; it may be that the confounding influence of water composition (e.g., chlorophyll-a) is more prominent in Rinaldi et al. (2013) and thus the relationship between composition and wind speed less visually apparent or amenable to use of a sigmoid fit. Madawala et al. (2024), as part of the same CHAOS study as here, observed a similar decline in the organic carbon (OC) fraction with increasing wind speed based on analysis of samples collected on filters. They considered only two wind speeds, 10 m s^{-1} and 19 m s^{-1} , and found that the OC fraction of particles between $0.25 - 1 \text{ }\mu\text{m}$ diameter decreased from 7% OC to 2%, which is quantitatively consistent with our results assuming an OA/OC ratio of ~ 2 . The actual OA/OC ratio for submicron SSA is likely somewhat lower, around 1.6 (Bates et al., 2012). Concurrently, they found that the proportion of particles with a given morphology changed between low and high wind speeds, in particular with “core-shell” particles increasing in frequency while “rounded” particles declined. In contrast to these studies, van Pinxteren et al. (2017) concluded that the relationship between f_{org} and wind speed was essentially nonexistent, proposing that the f_{org} percent increase with wind speed exhibited a rate of 0.11% per unit change in wind speed (in m s^{-1}), meaning that a change from 10 m s^{-1} to 20 m s^{-1} leads to a 1.1% increase in f_{org} . They instead conclude that variations in ocean biological activity dominate changes in particle composition (van Pinxteren et al., 2017).

The f_{org} -wind speed relationship observed in our wind-wave channel experiment is qualitatively most similar to the Gantt et al. (2011) observations, with both indicating a sigmoidal relationship going from higher f_{org} at low wind speeds to lower f_{org} at high wind speeds. Gantt et al. (2011) proposed that the sigmoidal behavior reflects a disruption of the SSML as bulk water mixing intensifies at higher wind speeds, with a relatively sharp transition from a regime of

widespread SSML coverage to a low coverage regime. Such disruption reduces both the surface concentration and the surface-selective enrichment of organic material, which affects the SSA composition. Although both our results and Gantt et al. (2011) indicate sigmoidal behavior, the transition wind speed is much higher in our experiments ($\sim 7 \text{ m s}^{-1}$ versus 17 m s^{-1}). The higher transition wind speed observed here could reflect differences that resulted from the use of a constant wave height in our experiments, as discussed above. Also, the difference in transition wind speed may reflect the fact that our system isolates wind effects from biological variability, whereas field observations are sensitive to both wind speed and ocean composition, which may co-vary. Field observations also have the challenge that local conditions at the point of measurement may not reflect the conditions where SSA emission occurred. Such issues may also help explain differences between our results and the studies in which no sigmoidal relationship was observed (Rinaldi et al., 2013; van Pinxteren et al., 2017). Regardless, our results provide support for a general sigmoidal relationship between wind speed and SSA $\text{PM}_{2.5}$ organic content.

2.3.4 ORGANIC SSA COMPOSITION AND WIND SPEED

The average SSA mass spectra of the organic components for the five windspeeds with replicate measurements are shown in Fig. 5. The mass spectra at each wind speed were normalized to the $m/Q = 44$ peak. Complementary zoomed in spectra (m/Q 40 to 100 and m/Q 100 to 200) are included in the Supplementary information (See SI Figures S2.8-2.9). A notable feature is that there is an increase in the relative abundance of organic ions having m/Q above 100 at the two highest windspeeds, i.e., above the threshold wind speed identified above. This behavior is evident when the ratio of organic species with $m/Q \geq 100$ (high MW) to those with $40 < m/Q < 100$ (low MW) is considered as a function of wind speed (Figure 2.4b). The ratio grows from ~ 0.16 for $U_{10} < 17 \text{ m s}^{-1}$ to 0.42 at the highest windspeed (21.2 m s^{-1}). Dall'Osto et al. (2017), in a coastal

environment, observed high MW organic species internally mixed with sea salt in single particle spectra measured using an aerosol time-of-flight mass spectrometer. However, they were unable to observe similar high MW species with a high-resolution aerosol mass spectrometer, which operates similarly to the ACSM used here. It could be that the higher concentrations in the wind-wave channel here enabled the detection of these species. Alternatively, detection of these species may be a result of using the capture vaporizer or the higher vaporizer temperature. Regardless, consideration of the cosine similarity, S_c , of the mass spectra for the range $m/Q > 100$ indicates that the OA mass spectrum at the highest wind speed differs substantially from the spectra at wind speeds below the threshold ($0.66 \leq S_c \leq 0.74$) and shares greater similarity with the spectrum at the second highest wind speed ($S_c = 0.89$). This similarity suggests that there is a change in both the amount of high MW organic components and their chemical nature. The S_c values for the range $m/Q < 100$ are all ≥ 0.95 , indicating overall less sensitivity to wind speed.

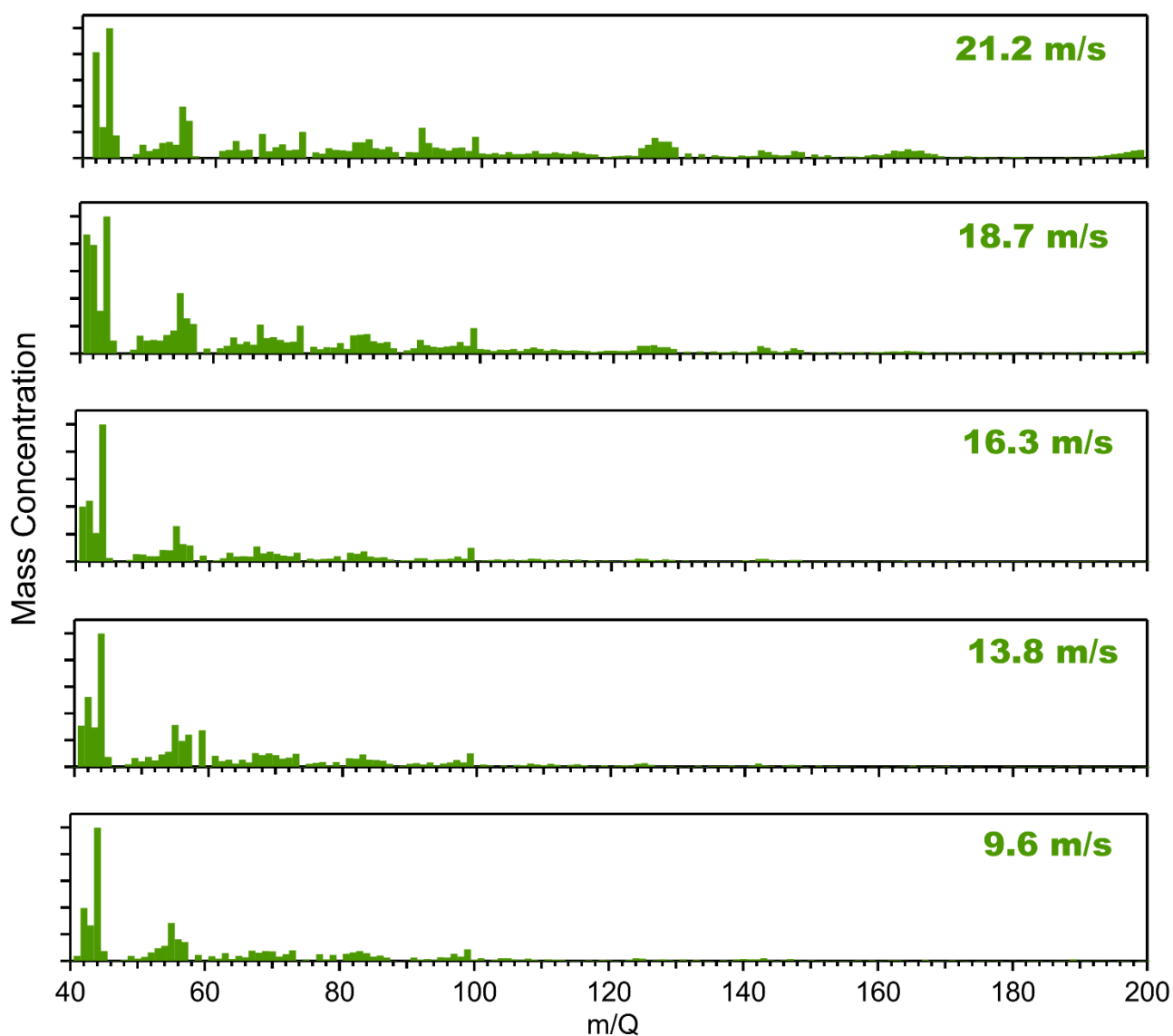


Figure 2.5: Normalized average OA mass spectra at each wind speed.

A few individual ions at $m/Q < 100$ exhibit notable variability in their relative intensity with windspeed, especially the ions at $m/Q = 67$, 73 , and 91 . The ions at $m/Q = 57$ ($C_4H_9^+$) and 55 ($C_4H_7^+$) are considered tracers for reduced, hydrocarbon-like organic aerosols (HOA) (Zhang et al., 2005; Presto et al., 2014), and we consider changes in the abundance of these ions relative to the $m/Q = 55$ ion. (The HOA tracer ion at $m/Q = 55$ can suffer from interference by isobaric

oxygenated organic fragments ($\text{C}_3\text{H}_3\text{O}^+$) (Zhang et al., 2005; McLafferty and Turecek 1993). However, we use this ion rather than $m/Q = 57$ because tailing from the large NaCl^+ ion signal at $m/Q = 58$ interferes with the $m/Q = 57$ ion signal. The 55/91 ion ratio exhibits a slight increase with wind speed below the transition point, with a sharp decrease observed above the transition point (Figure 2.4b), and the $m/Q = 67$ and 73 ions exhibit a similar wind speed dependence (Figure S2.10). The $m/Q = 91$ ion (C_7H_7^+) is commonly attributed to aromatic species, alongside ions at $m/Q = 77$ and 105 (Zhang et al., 2005). The ToF-ACSM used here lacks the resolution to allow for unambiguous identification of C_7H_7^+ . We note that previous studies that characterized primary SSA using aerosol mass spectrometers with higher resolution have observed a peak at $m/Q = 91$ that they identify as C_7H_7^+ , although they do not identify it as an important tracer ion (Frossard et al., 2014; Wang et al., 2015). The ion at $m/Q = 73$ is commonly attributed to biomass burning, alongside $m/Q = 60$ (Alfarra et al., 2007); overlap with the large signal from $\text{Na}^{37}\text{Cl}^+$ at $m/Q = 60$ here prevents clear identification of an organic signature. The ion at $m/Q = 67$ could correspond to an organic nitrate species (Graeffe et al., 2022). The same ion has also been linked to cooking (Zhu et al., 2021); while there is no reason to think that cooking-related organics should have a major presence here, it is possible that cooking-related organics are present in the coastal water used.

Madawala et al. (2024) characterized particle functional groups via AFM-IR spectroscopy for individual SSA in the size range of 0.18 - 0.56 μm during CHAOS. At 10 m s^{-1} they observed a modest contribution from compounds containing oxygenated functional groups, but with the spectra dominated by aliphatic compounds. At 19 m s^{-1} , the signatures from oxygenated functional groups, including those from carboxylic acids and esters, were much stronger. The fact that they observed clear differences in the OA composition between low and high wind speeds aligns with

our results and suggests that the high-MW organic components may be more oxygenated than the low-MW components.

The shift in OA composition—in addition to the change in the relative OA abundance—could result from changes in the SSML composition with wind speed. For example, Rahlff et al. (2017) observed that SSML bacterial community composition of a wind-wave channel shifted with increasing wind speed, with some taxa favored under calm conditions and others that appeared in the SSML only when wind speeds exceeded 8 m s^{-1} . While Rahlff et al. (2017) emphasizes bacteria as direct contributors to SSA, other studies have demonstrated that soluble microbial exudates—such as surfactants and extracellular polymeric substances (EPS)—are primary drivers of organic transfer across the air-sea interface (Patterson et al., 2016, Santander et al., 2022). Thus, the presence or absence of different taxa could reflect changes in these other species within the SSML, and in turn in SSA. A caveat is that their experiments lacked active, paddle-driven wave generation and so mixing likely differed from our experiments. This difference may explain why their observed SSML transition occurred at a lower wind speed than here. Surfactant enrichment in the SSML, a key feature of microbial exudates, persists at wind speeds up to $\sim 9.5 \text{ m s}^{-1}$ in open ocean studies (Wurl et al., 2011), suggesting that bubble-mediated transport continues under even moderately high wind speeds. While Wurl et al. (2011) state that oligotrophic waters often maintain greater surfactant enrichment than more productive regions and speculate that surfactant coverage is reduced above ambient wind speeds of $\sim 12 \text{ m s}^{-1}$, they show no data in this higher wind speed range to support their contention. Regardless, these ideas align with the decrease in f_{org} we observed at high wind speeds, potentially indicating a threshold above which SSML structure is consistently disrupted. Although the absolute wind speed at which disruption occurs is difficult to translate directly between laboratory and open-ocean systems—especially since wave

height and turbulence were decoupled in our experiment—our highest tested wind speed (21.2 m s⁻¹) may correspond dynamically to thresholds for SSML suppression observed in the field. Moreover, persistent wave breaking compresses and dilates the SSML surface and can also enhance particle aggregation and facilitate the condensation of high-MW surfactants (Carlson, 1993). This suggests that increased turbulence may favor the air-sea transfer of oxygenated and/or HMW organic species, consistent with our observed increase in the relative abundance of high m/Q ions in SSA with wind speed. High molecular weight organic species ($m/Q > 100$) were consistently more abundant at the two highest wind speeds but not observed at similar levels during low wind speed runs, suggesting their presence was tied to wind speed rather than cumulative changes in seawater composition. While concentrations varied across high-wind runs, they remained elevated relative to the lowest wind speed case. At these higher wind speeds, the organic spectra exhibited recurring groupings of ions above m/Q 100 (e.g., near ~125, ~145, ~165, and ~199) with approximate ~20 amu spacing for then a larger gap. This quasi-periodic structure is most consistent with homologous oxygenated series (OH/CHO-type fragments), reflecting incremental oxygenation or hydration steps rather than isolated ions. However, because absolute signals in this region are relatively low and the measurements are limited to unit-mass resolution, we emphasize this observation at the pattern level only and do not assign specific molecular formulas.

Biological and chemical characteristics of the bulk seawater, including total organic carbon (TOC), chl-*a*, and cell counts of bacteria, phytoplankton, and protozoa, were monitored throughout the experiment (Figure S2.6-S2.7). Chlorophyll-*a* concentrations in water collected from the bottom of the flume declined over time from 0.37 to 0.05 mg m⁻³, while TOC remained relatively constant. Surface water samples on 8/15/22 showed slightly lower chlorophyll-*a* (0.13 to 0.3 mg

m^{-3}) than bottom water, with TOC ranging from 92 to 98 μM in both. Bacterial and small phytoplankton counts also decrease over time. Despite these changes in bulk water composition, we observed consistent f_{org} and overall SSA mass spectra across sampling days for a given wind speed. However, specific mass spectral features—such as the relative abundance of ions at m/Q 91 or the high molecular weight signal—exhibited some variability, suggesting that while f_{org} is largely determined by wind speed, the detailed composition of the organic aerosol may be modulated by temporal changes in seawater composition. This distinction aligns with prior observations by Wang et al. (2015), who showed that the relative contribution of different classes of organic species in SSA, particularly aliphatic-rich versus oxygen-rich components, varied significantly over time in a wave channel mesocosm. While they did not report a direct f_{org} , their results demonstrate that detailed SSA composition is sensitive to changes in seawater biochemistry. The difference likely results from the much lower chlorophyll-a concentrations in our system, as well as the fact that Wang et al. (2015) intentionally induced a bloom through nutrient addition. Overall, our results suggest that wind speed can exert a stronger influence on SSA organic aerosol composition than biological variability, at least under the low-activity conditions of these experiments. This conclusion aligns with previous observations by Quinn et al. (2014) and Bates et al. (2019), who reported limited dependence of fresh SSA composition on sampling locations in field studies using *in situ* seawater.

2.3.5 A CHANGING SULFATE TO CHLORIDE RATIO

We observed that the sulfate-to-chloride ratio in SSA decreased with increasing wind speed (Figure 2.7), dropping below the seawater reference value of 0.14 (Morris and Riley, 1966) and remaining near ~ 0.07 for the highest wind speeds. (We note that the accuracy of the absolute

sulfate-to-chloride ratio from the ACSM is insufficient to quantitatively compare the values to the expected seawater value. However, the precision is sufficient to assess changes in the ratio.)

In general, we might expect that the relative abundance of dissolved ion species is preserved between sea water and SSA, and as such the large change in the relative abundance of sulfate and chloride ions is surprising; this is certainly the case for SSA produced via the jet droplet pathway. However, SSA produced via the film drop pathway may have an ion composition that deviates from the sea water value owing to selective binding of ions to organic species present in the SSML. Notable enrichment of many ions relative to Na^+ in submicron SSA is now well-established, with Ca^{2+} most commonly considered (e.g., Oppo et al., 1999; Sievering et al., 2004; Salter et al., 2016). The magnitude of the enrichment for these ions also tends to vary with the biological state of the source water (Jayarathne et al., 2016) and depends on particle size (Salter et al., 2016; Cochran et al., 2016). For the sulfate ion, both enrichment and depletion have been found (Jayarathne et al., 2016; Cochran et al., 2016), and similarly so for the chloride ion (Salter et al., 2016; Jayarathne et al., 2016; Cochran et al., 2016). Consequently, there may be reasons for the sulfate-chloride ratio to deviate from the sea water value for fresh SSA.

Chemical processing in the atmosphere can change the sulfate-to-chloride ratio, typically with both sulfate formation (Bonsang et al., 1980) and chloride displacement (Gard et al., 1998) increasing the ratio. The short residence time of a few seconds (based on the wind speeds and dimensions) in the wind-wave channel between particle production and sampling is insufficient for either of these mechanisms to notably alter the SSA composition. As noted above, the sulfate-to-chloride ratio in SSA decreased with increasing wind speed (Figure 2.7), and like other properties, exhibited a threshold behavior. These observations indicate that sulfate and chloride enhancements or depletions respond differently to changes in wind speed. It is possible that this

observation results from a shift in the particle production mechanism with wind speed, i.e., a change in how much the mechanism of film drops of a given type or jet drops contribute. This change could also be connected to the change in the organic composition and f_{org} and differences in the binding between sulfate versus chloride with different organic compounds. Our observations are supported by single-particle elemental composition analysis by Madawala et al. (2024) during CHAOS, who observed variability in the relative abundances of Na, Cl, S, Ca, and Mg within and between individual particles.

Our findings have implications for the determination of non-sea salt sulfate (nss-SO_4^{2-}) in marine aerosol samples. The concentration of nss-SO_4^{2-} is typically calculated as

$$[\text{nss} - \text{SO}_4^{2-}] = [\text{SO}_4^{2-}] - [\text{Na}^+] \cdot \left(\frac{[\text{SO}_4^{2-}]}{[\text{Na}^+]} \right)_{\text{seawater}}$$

where $[\text{SO}_4^{2-}]$ and $[\text{Na}^+]$ are the observed ion concentrations and the ratio is the sulfate-to-sodium ratio in seawater (e.g., Bates et al., 2008). The implicit assumption is that the $\text{SO}_4^{2-}:\text{Na}^+$ ratio in SSA is the same as that of seawater. If the actual ratio in SSA is smaller than that in seawater, but the seawater value is still used to calculate nss-SO_4^{2-} , then the nss-SO_4^{2-} would be underestimated, and negative values could result. We are unable to establish whether the shift in the $\text{SO}_4^{2-}:\text{Cl}^-$ ratio is due to changes in the transfer of sulfate or chloride (or both) from seawater to SSA. However, if it is driven by changes in SO_4^{2-} then our results suggest that there may be a wind speed influence on the determination of nss-SO_4^{2-} . If we assume that the $\text{Cl}^-:\text{Na}^+$ ratio is wind-speed independent, then the $\text{SO}_4^{2-}:\text{Na}^+$ ratio would exhibit similar behavior to the observed $\text{SO}_4^{2-}:\text{Cl}^-$ ratio, and potential for underestimation of nss-SO_4^{2-} would increase with wind speed.

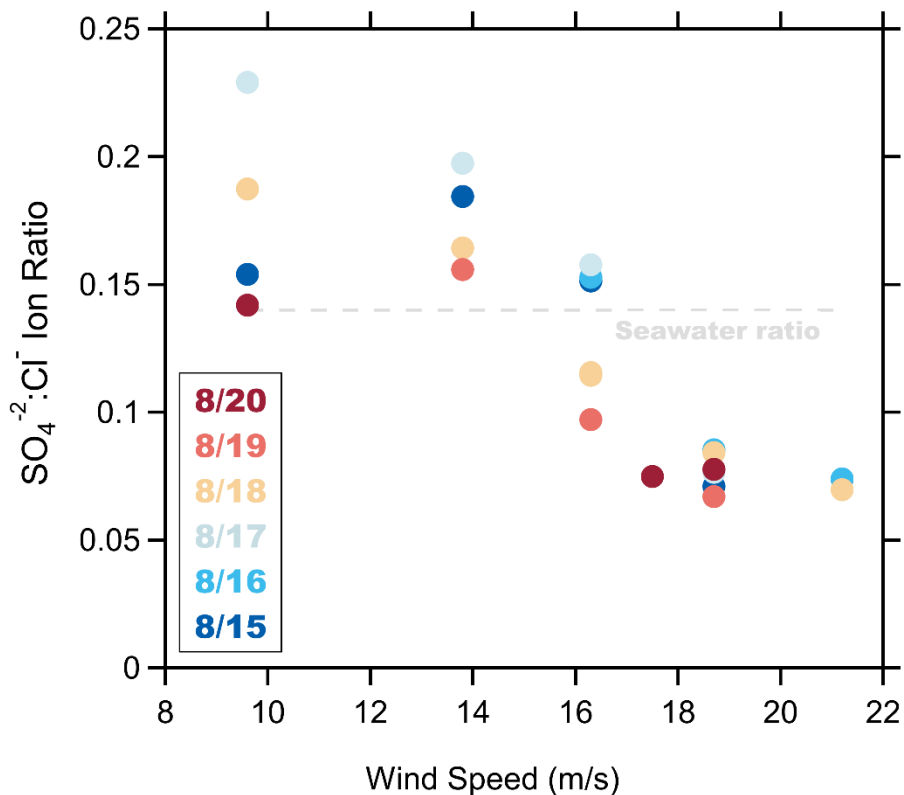


Figure 2.7: Sulfate-to-chloride ratio in SSA as a function of wind speed in SOARS. Each marker is colored by the date of the sample, and the reference sea water sulfate to chloride ratio (= 0.14) is shown as the grey dashed line.

2.4 SUMMARY AND CONCLUSION

This study used a controlled wind-wave channel (SOARS) to investigate how wind speed influences SSA production and composition, focusing on PM_{2.5}. Across 10 m wind speeds ranging from 9.6 to 21.2 m s⁻¹, we observed a near tenfold increase in SSA mass concentration, with concentrations relatively constant below ~16 m s⁻¹ and a rapid increase above this threshold. The shape of the SSA size distributions also exhibited a distinct change across this threshold; the number-weighted distributions exhibited a shift towards smaller particles at higher wind speeds

while the surface area-weighted distributions shifted slightly towards larger sizes. At the same wind speed threshold, we observed a shift in SSA composition: the organic mass fraction (f_{org}) decreased alongside a change in the organic composition, highlighted by an increase in high-molecular weight organic components ($m/Q > 100$). Notably, the sulfate-to-chloride ($\text{SO}_4^{2-}:\text{Cl}$) ratio also varied with wind speed, decreasing above the $\sim 16 \text{ m s}^{-1}$ threshold.

The observed transitions in SSA composition, particularly the suppression of f_{org} at high wind speeds, likely reflects disruption of the sea surface microlayer and corresponding changes in the amount and type of organic species transferred to SSA. This, coupled with the shift in the particle size distributions with wind speed, also suggests a change in the relative contributions from different SSA production mechanisms, film drop (bursting or flapping) versus jet drop. One limitation of our study is that wave height was decoupled from wind speed, whereas in the open ocean these are often related. This difference could influence, for example, the wind speed at which we observe the transition in SSA production and composition. Nonetheless, these results demonstrate that wind speed alone, independent of any changes in seawater composition, can induce significant shifts in SSA composition. Laboratory systems like SOARS provide a useful tool to disentangle physical drivers from biogeochemical variability and offer new insights into thresholds for SSA generation that may inform future SSA parameterization in climate models.

ASSOCIATED CONTENT

Supporting Information

The following files are available free of charge.

Supporting figures S2.1-S2.10

(PDF)

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. Author Contributions: Conceptualization: THB, CDC, KAP; Investigation: ESP, RJL III, RAB, JD, FR, MDS, GBD, CL, KAP, THB, CDC; Data analysis: ESP, CDC; Project Administration: CL; Supervision: THB, CDC; Writing: ESP, CDC

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Notes

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Abbreviations

SSA, sea spray aerosol; SSML, sea surface micro-layer; PM_{2.5}, particulate matter <2.5 μm; f_{org} , organic mass fraction; SMA, secondary marine aerosol, AOD_c, coarse-mode aerosol optical depth; SOARS, Scripps Ocean-Atmosphere Research Simulator; INP, ice-nucleating particles; CHAOS, Characterizing Atmosphere-Ocean properties in SOARS; RPM, revolutions per minute; ToF-ACSM, time-of-flight aerosol chemical speciation monitor; UMR, unit mass resolution; IE, ionization efficiency; RIE, relative IE; SEMS, scanning electrical mobility analyzer; SMPS, scanning mobility particle sizer; APS, aerodynamic particle sizer; OA, organic aerosol; OC, organic carbon; MW, molecular weight; HOA, hydrocarbon-like organic aerosol; EPS, extracellular polymeric substances; TOC, total organic carbon, nss-SO₄, non-sea-salt sulfate

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2.8 Supplemental information

Supplemental information for:

Wind-Driven Shifts in Sea Spray Aerosol Composition Observed in a Controlled Wind-Wave Channel Experiment

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Table S2.1. SOARS Run schedule

Date	Time	RPM	m s ⁻¹	Notes
8/15/2022	9:45-10:45	1600	18.7	
8/15/2022	11:45-12:45	850	9.6	
8/15/2022	13:45-14:45	1200	13.8	
8/15/2022	15:45-16:45	1400	16.3	
8/15/2022	17:45-18:45	1800	21.2	
8/16/2022	9:20-10:20	1400	16.3	
8/16/2022	11:10-13:10	1600	18.7	
8/16/2022	14:20-16:20	1800	21.2	
8/17/2022	10:05-12:15	850	9.6	
8/17/2022	13:15-15:15	1200	13.8	
8/17/2022	16:15-17:15	1400	16.3	
8/17/2022	18:15-19:15	1600	18.7	
8/18/2022	8:40-9:40	850	9.6	
8/18/2022	10:46-11:40	1200	13.8	
8/18/2022	14:30-16:30	1400	16.3	
8/18/2022	17:35-18:35	1800	21.2	
8/18/2022	19:30-20:30	1600	18.7	
8/19/2022	8:30-9:31	850	9.6	
8/19/2022	10:40-12:45	1200	13.8	
8/19/2022	13:45-14:45	1400	16.3	
8/19/2022	15:45-17:50	1600	18.7	
8/20/2022	8:43-9:43	850	9.6	
8/20/2022	11:00-12:00	1500	17.5	

8/20/2022	13:05-15:05	1600	18.7	
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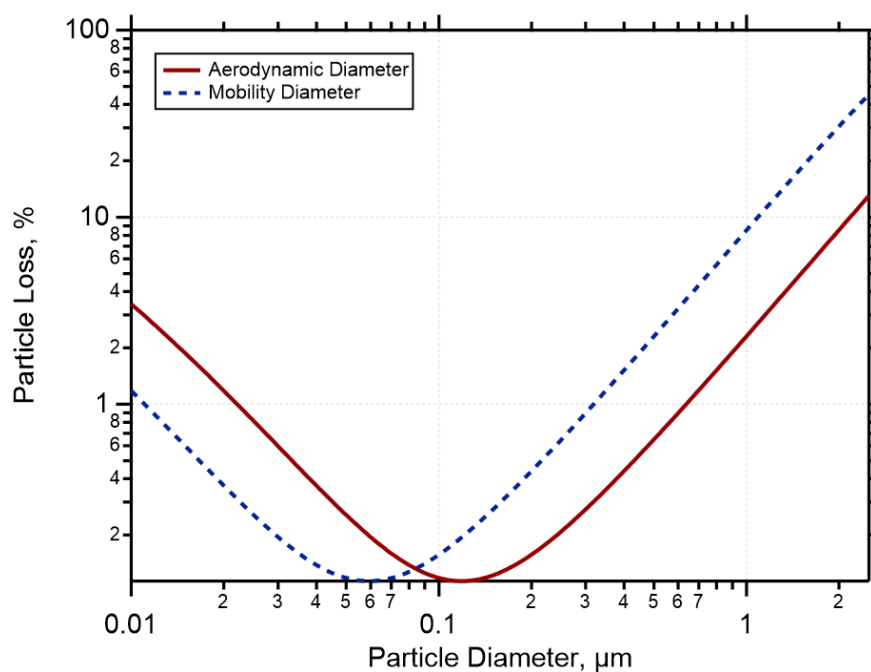


Figure S2.1. Calculated particle losses from sampling between the manifold and instruments. Results were obtained using the Particle Loss Calculator (von der Weiden et al., 2009) assuming a particle density of 2.0 g cm^3 and tubing diameter of 5.5 mm at a flow rate of 7.5 lpm. The losses are shown as a function of both the aerodynamic diameter and the mobility diameter.

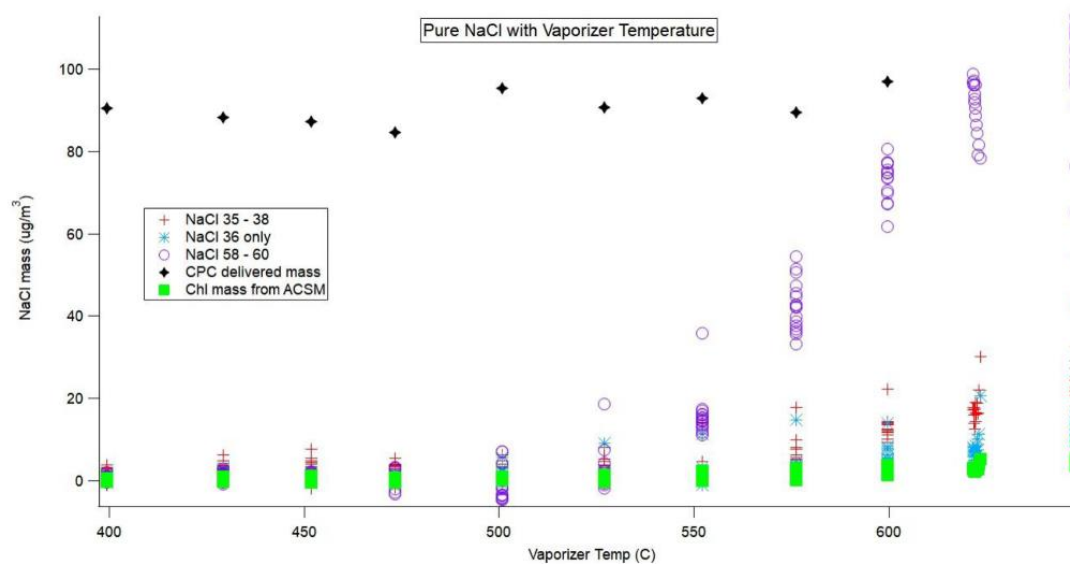


Figure S2.2: Preliminary comparison test of nebulized NaCl CPC delivered mass (black diamond), Chl mass from the ACSM, and 3 m/Q ion sets that represent NaCl (35-38, 36, 58-60) as a function of ACSM vaporizer temperature.

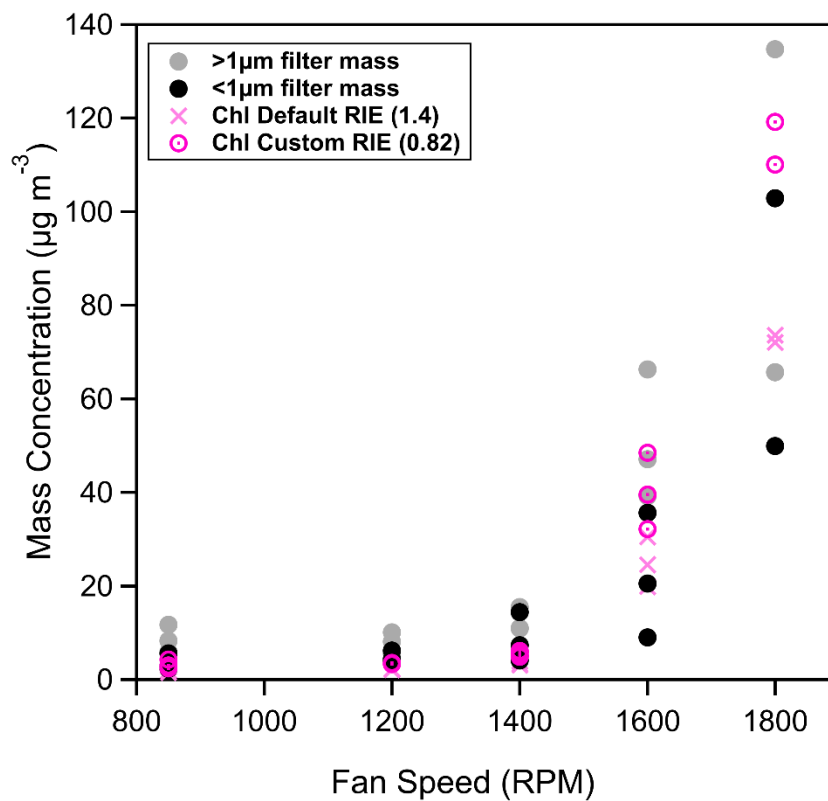


Figure S2.3: Sub and supermicron filter measurements (from Madawala et al., 2024) for Cl^- (black and grey dots) and the ACSM Chl mass at the default and custom RIE values (pink markers).

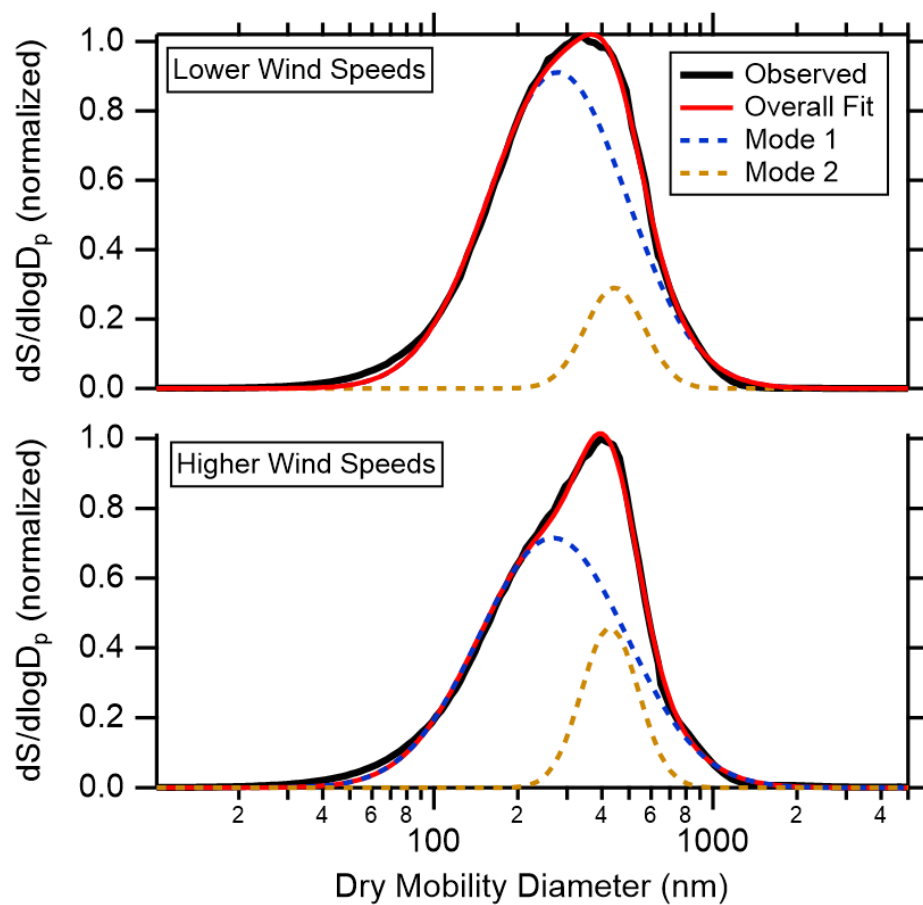


Figure S2.4. Bimodal log-normal fits to the average surface area-weighted size distributions observed at (top) lower wind speeds and (bottom) higher wind speeds. The best-fit diameters and widths for the two modes are Mode 1:[277 nm; 1.77] and Mode 2:[444 nm; 1.28] for the lower wind speeds and Mode 1:[267 nm; 1.84] and Mode 2:[427 nm; 1.26] for the higher wind speeds.

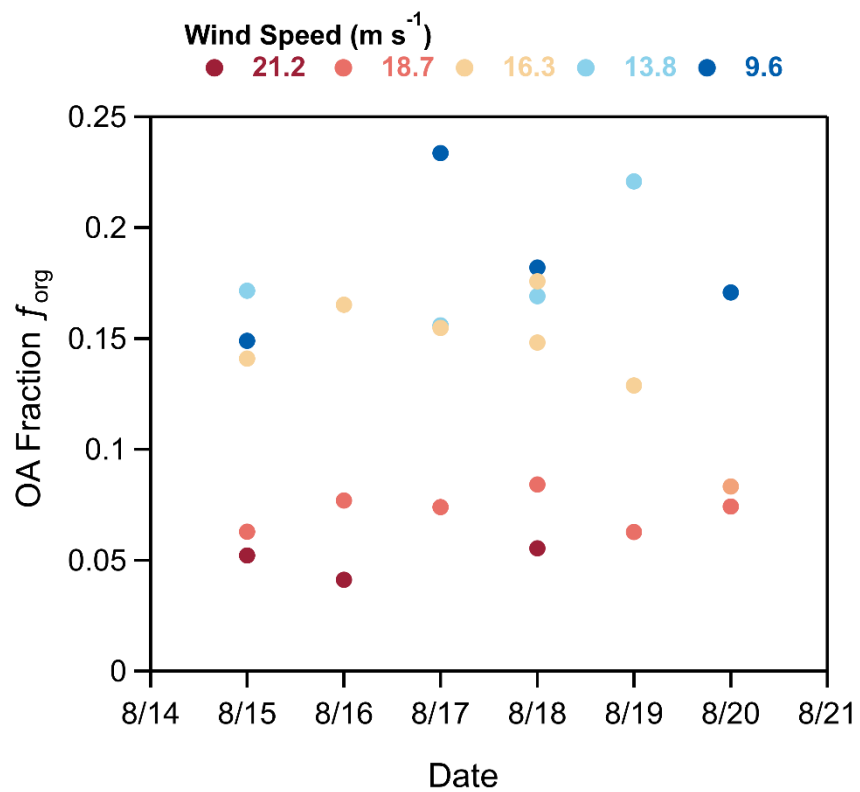


Figure S2.5: OA fraction f_{org} as a function of sample date.

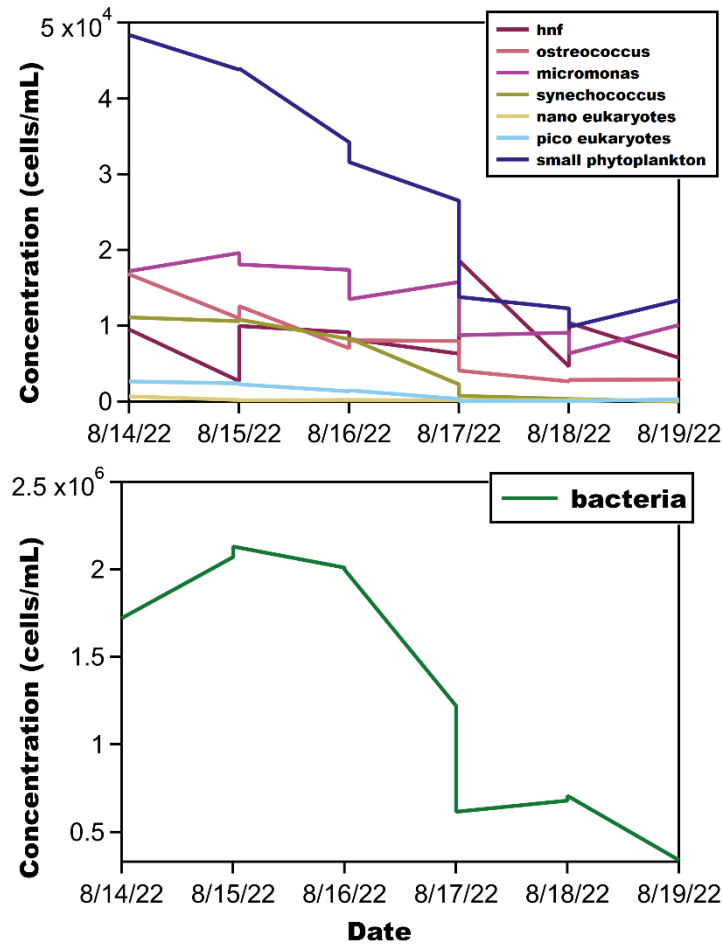


Figure S2.6: Biological counts (in cells/mL) of various phytoplankton species (ostreococcus, micromonas, synechococcus, nano-eukaryotes, pico-eukaryotes, small phytoplankton) and protzoa (hnf) are shown in the top graph. Biological counts of bacterial in SOARS is shown in the bottom graph. All biological counts show a slight downward trend from the beginning of experimental dates (8/15) to (8/20). Data from Julie Dinasquet of Prather group.

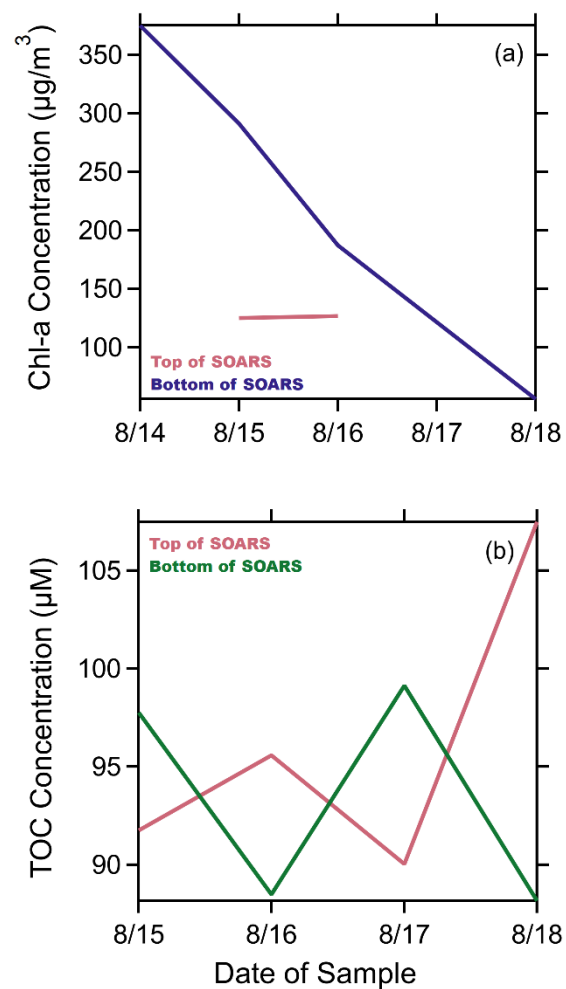


Figure S2.7 (a) Concentration of Chlorophyll-a as a function of sample date, measured at the top and bottom of SOARS. (b) Concentration of TOC as a function of sample date at the top and bottom of SOARS. Data from Julie Dinasquet of Prather group.

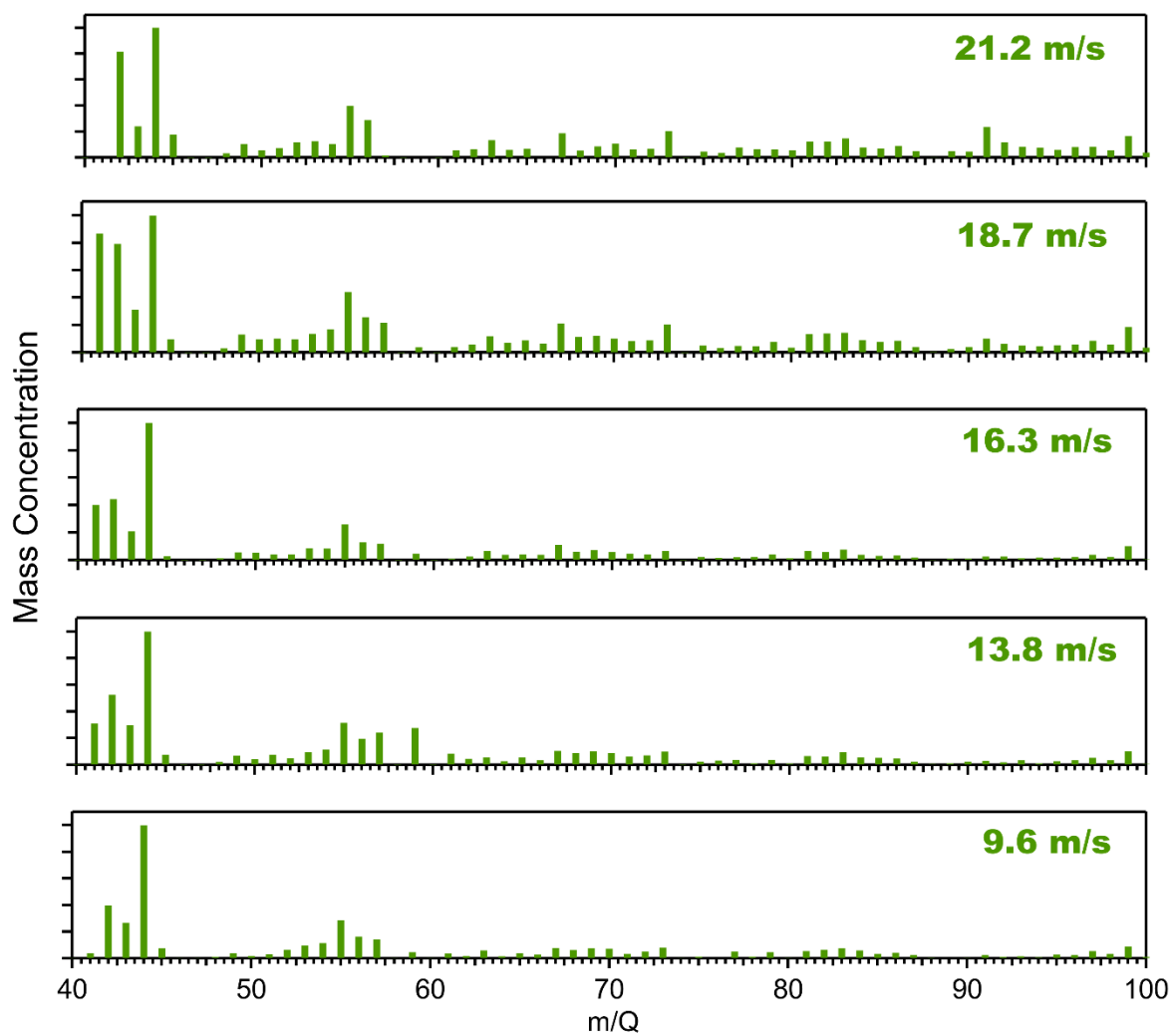


Figure S2.8: Zoomed in normalized average OA mass spectra at each wind speed from Figure 5 in the text. Showing only m/Q 40 to 100. Y-axis maximum is 1.1.

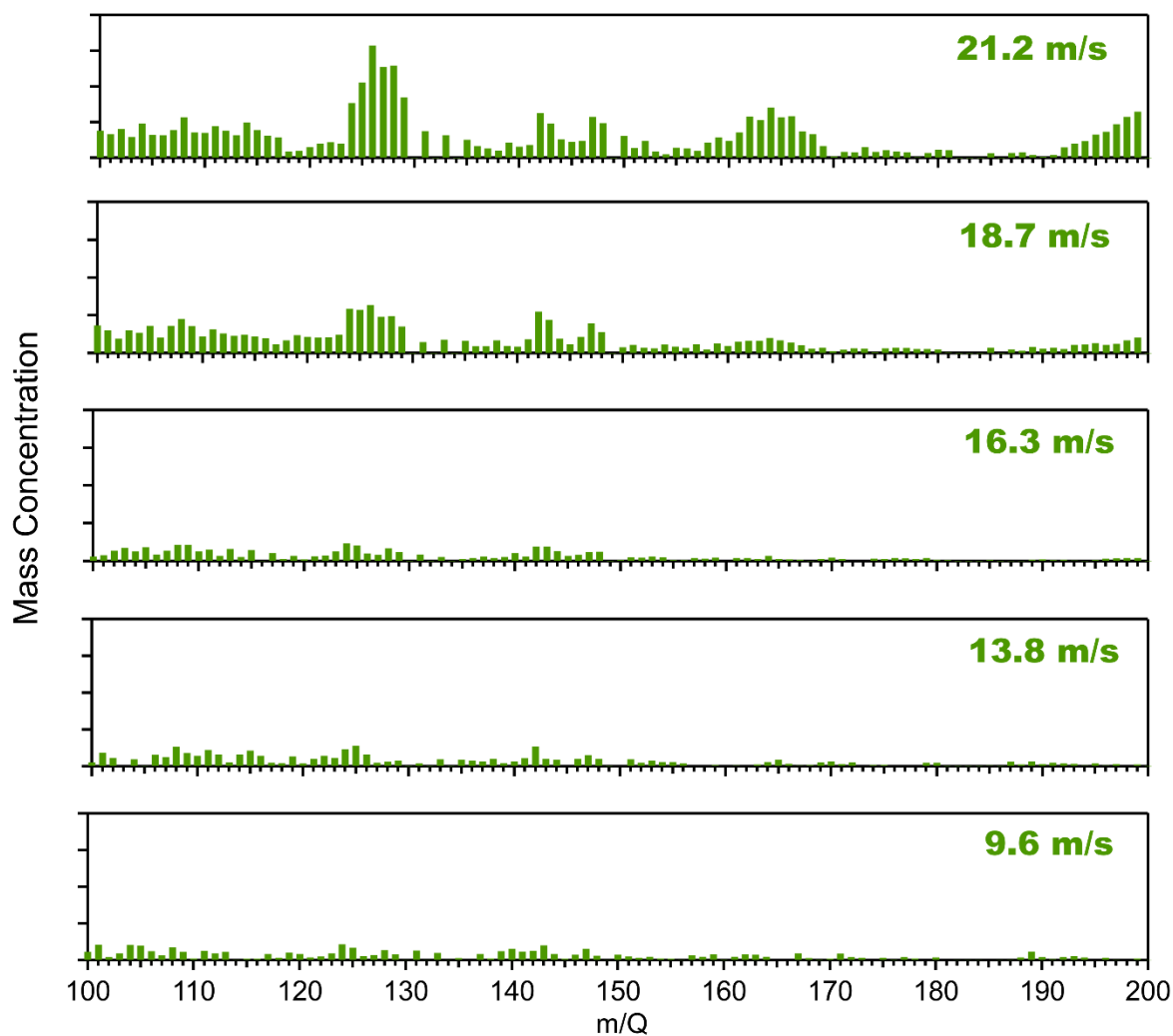


Figure S2.9: Zoomed in normalized average OA mass spectra at each wind speed from Figure 5 in the text. Showing only m/Q 100 to 200. Y-axis maximum is 0.2.

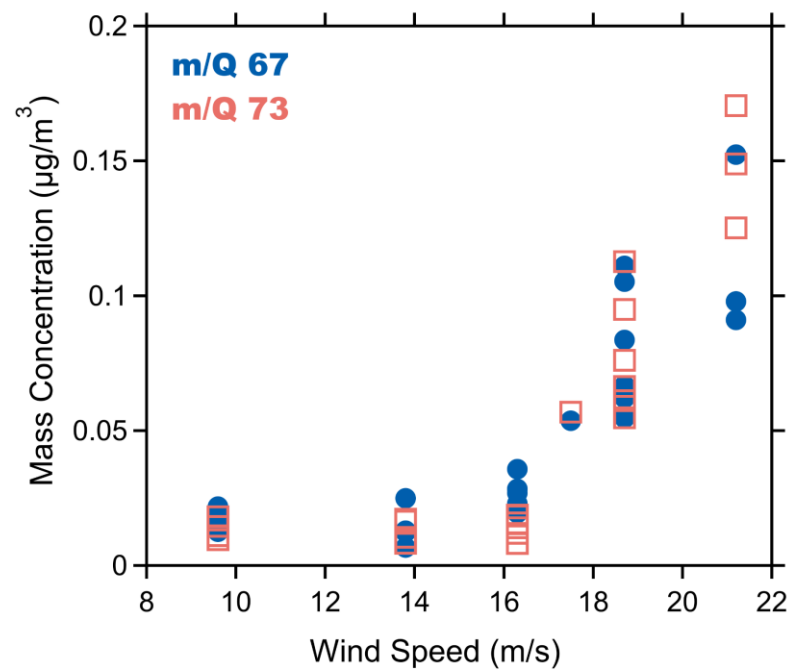


Figure S2.10: Mass concentration of individual ions m/Q 67 and 73 as a function of wind speed.

CHAPTER 3: Submicron Sea Spray Aerosol CCN Activity in a Wind-Wave Channel: Limited Sensitivity to Wind Speed

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ABSTRACT

Marine aerosol particles emitted from the ocean surface play a critical role in regulating cloud properties and climate through their ability to act as cloud condensation nuclei (CCN). Wind-driven sea spray aerosol (SSA) production is a major source of natural CCN in remote marine environments, yet the influence of wind speed on the CCN-relevant properties of nascent submicron SSA remains poorly constrained due to the complexity of ambient measurements and co-varying environmental factors. Here, we investigate the impact of wind speed on the CCN activity of freshly emitted submicron SSA using the Scripps Ocean–Atmosphere Research Simulator (SOARS), a controlled wind–wave channel operated during the CHAOS campaign in summer 2022. Under a range of wind speeds ($U_{10} \approx 9.6\text{--}21.2 \text{ m s}^{-1}$), we measured neutralized and

non-neutralized submicron mobility size distributions and CCN activation of size-selected 55 nm particles. CCN activity was quantified using critical supersaturation and hygroscopicity (κ) derived from CCN activation spectra. While submicron neutralized size distributions varied systematically with wind speed, κ exhibited substantial variability that was not explained by wind speed alone. These results show that wind speed alone does not fully determine CCN activation behavior of nascent submicron SSA and emphasize the need for more controlled measurements to disentangle physical drivers of marine aerosol–cloud interactions.

3.1 INTRODUCTION

Understanding how aerosol particles influence clouds remains one of the most persistent challenges in climate science. Aerosol-cloud interactions continue to contribute substantial uncertainty to modeled radiative forcing and climate sensitivity (Boucher et al., 2013; Seinfeld et al., 2016). Progress depends on characterizing the particles that can activate as cloud condensation nuclei (CCN), including their origins, number distribution, and chemical characteristics, all of which affect their cloud forming potential (Farmer et al., 2015). Marine environments are central to this effort: the global ocean is a dominant source of atmospheric aerosol through wind-driven sea spray production. In addition, marine biogenic activity emits gas-phase compounds that undergo atmospheric oxidation, leading to secondary marine aerosol (SMA) formation and condensational growth of existing particles, making the ocean a major contributor to the atmospheric CCN pool (O’Dowd et al., 2004; Quinn et al., 2017).

Sea spray aerosol (SSA) arises from wind-enhanced wave breaking, where mechanical disruption of wave crests produces spume droplets and air entrainment generates bubbles that release film and jet drops upon bursting, collectively yielding a diverse population of particles with

variable sizes, compositions and properties (Deike et al., 2022; Lewis & Schwartz, 2004; O'Dowd & Leeuw, 2007). These particles influence climate through two primary pathways: direct radiative interactions with incoming solar radiation and indirect effects mediated by their activation as CCN, which alter cloud droplet number, reflectivity, precipitation efficiency, and cloud lifetime (Boucher et al., 2013; Fossum et al., 2020). Because cloud albedo, persistence, and precipitation efficiency all depend sensitively on CCN abundance and composition, accurate characterization of CCN populations is essential for constraining indirect aerosol effects in climate models (Boucher et al., 2013). This need is further reinforced by environmental controls on SSA production and composition, such as temperature-dependent bubble film stability and biological activity (Forestieri et al., 2018), which introduce additional variability in the properties of nascent SSA.

SSA spans a broad size range, from submicron particles that dominate CCN number to larger sea-salt particles, often referred to as giant CCN, that can influence cloud evolution by accelerating condensational growth and warm rain formation (Jensen & Nugent, 2017). While giant CCN are relatively fewer in number, they can disproportionately affect precipitation efficiency and cloud lifetime. Among this size spectrum, submicron SSA ($<1\ \mu\text{m}$) are especially critical for understanding aerosol-cloud interactions because CCN number and cloud droplet number are primarily controlled by particles in this size range (Boucher et al., 2013; Farmer et al., 2015). Submicron sea-spray particles constitute the majority of sea-spray number and, particularly for diameters below $\sim 0.2\ \mu\text{m}$, can provide a major source of CCN in remote marine environments, even though they contribute relatively little to total SSA mass (Quinn et al., 2017; Russell et al., 2023).

Their ability to activate as CCN is influenced by particle size, hygroscopicity and organic-inorganic mixing state (Farmer et al., 2015; O'Dowd et al., 2004). Submicron SSA also exhibit substantial compositional variability, including enrichment in primary organics, surface-active material, and other biogenically derived components, which can strongly modulate CCN activity yet remain poorly constrained in global models (Boucher et al., 2013; Clarke et al., 2006; Facchini et al., 2008; Russell et al., 2023). Despite their importance, direct measurements of freshly emitted submicron SSA over the open ocean remain sparse because chemically specific, high-time resolution measurements of sea salt are challenging, and because ambient marine aerosol populations are typically mixtures of primary SSA, secondary marine aerosol, and continental influence (Quinn et al., 2017; Russell et al., 2023). As a result, much of our current understanding relies on a combination of laboratory simulations and targeted field campaigns whose results are incorporated into parameterizations of SSA emissions and CCN-relevant properties in large-scale models (Brumer et al., 2017; Gettelman et al., 2020; McFarquhar et al., 2020). Many laboratory systems have provided foundational insight into SSA formation, including glass-frit bubblers (Mårtensson et al., 2003), plunging-jet systems (Christiansen et al., 2019; Salter et al., 2014), and breaking-wave analogues such as MART (Stokes et al., 2013) which have been instrumental in elucidating bubble entrainment, film-drop production, and biologically driven variability in SSA composition (Cochran et al., 2017; Collins et al., 2016). However, because these platforms generally lack wind forcing, they cannot fully reproduce the coupled wind-wave dynamics, whitecap formation, and air-sea exchange that govern open-ocean SSA production (Callaghan et al., 2008; Veron, 2015). Still, aerosol-cloud interactions involving natural marine aerosol continue to contribute substantially to uncertainty in climate projections, underscoring the need for

controlled experimental systems that can isolate key controlling processes under well constrained conditions (Boucher et al., 2013; Carslaw et al., 2013; Mallet et al., 2023; Sellegri et al., 2024).

Freshly emitted SSA has often been reported to exhibit a sub-100 nm mode associated with film-droplet production during bubble bursting, although both the prominence and interpretation of this mode vary substantially across experimental and observational contexts. Laboratory studies, coastal observations, and bubble-bursting experiments have reported enhanced particle number concentrations within the ~30-100 nm size range, including coastal breaking-wave measurements (Clarke et al., 2006) and controlled bubble experiments (Bates et al., 2012; Jiang et al., 2022). However, some approaches may exaggerate the contribution of small particles or conflate freshly emitted SSA with background aerosol populations, particularly in nearshore environments (Zhou et al., 2025). Recent work demonstrates that shoreline wave breaking can strongly enhance sub-100 nm particle concentrations and CCN due to fundamentally different wave-breaking mechanisms and source regions (Zhou et al., 2025). Where present, particles in this size range frequently contain elevated fractions of organic material and surface-active compounds, which influence hygroscopicity and CCN activation behavior (Facchini et al., 2008; Farmer et al., 2015). Despite their relevance, sub-100 nm SSA remains poorly constrained in the open ocean because isolating nascent particles from background aerosol mixtures is challenging, particularly given the lack of chemically specific, high-time-resolution measurements for particles smaller than ~0.1 μm (Quinn et al., 2017; Russell et al., 2023). In addition to these observational challenges, environmental forcing plays a central role in controlling SSA production and properties.

Relationships between wind speed, SSA production and cloud-relevant particle properties also remain inconsistent across studies. Field observations integrate multiple environmental factors that co-vary with wind, including changes in water temperature, salinity, biological

activity, and surfactant abundance, all of which can influence bubble lifetimes, film drainage, and the efficiency of film-drop and jet-drop production(Christiansen et al., 2019; Forestieri et al., 2018; Schwier et al., 2017; Zinke et al., 2022). Even laboratory wave-channel studies show variability because airflow structures, wave geometry, and the onset of wave breaking differ across tank designs; secondary circulations and distorted boundary layers can modify air-sea momentum exchange and bubble entrainment, complicating the interpretation of wind-speed dependent SSA production (Villefer et al., 2021; Vollestad & Jensen, 2021; Zavadsky & Shemer, 2012). As a result, relationships between wind forcing and the CCN-relevant properties of SSA—such as size distributions, hygroscopicity, and activation behavior—remain difficult to constrain from ambient observations alone. This motivates the use of controlled experimental systems that isolate wind forcing while minimizing confounding environmental variability, enabling targeted investigation of submicron SSA production and CCN activity under well-defined conditions.

A convenient framework for describing the hygroscopic properties of aerosol particles is the κ -Köhler parameterization introduced by Petters and Kreidenweis (2007). In this formulation, the hygroscopicity parameter κ represents the effective ability of a particle to take up water and activate as a cloud condensation nucleus. Because κ integrates the influence of particle composition, solubility, and water affinity into a single parameter, it provides a useful metric for comparing CCN activity across different aerosol populations. Variability in κ reflects differences in particle chemical composition and mixing state, which can substantially influence the supersaturation required for CCN activation. SSA is often assumed to exhibit high hygroscopicity due to its dominant inorganic sea salt composition. Pure sea salt particles typically exhibit κ values of approximately 1.1-1.3, reflecting the strong water uptake of sodium chloride and other soluble salts(Petters & Kreidenweis, 2007). Other common inorganic aerosol species exhibit somewhat

lower hygroscopicity, such as ammonium sulfate ($\kappa \approx 0.6$), while many organic compounds display substantially lower κ values, often ranging from ~ 0.01 - 0.3 depending on solubility and molecular composition. However, numerous laboratory and field studies have shown that nascent SSA frequently contains substantial fractions of organic material derived from the sea surface microlayer (SSML), including surface-active compounds and biogenic exudates (Cochran et al., 2017; Facchini et al., 2008; Quinn et al., 2014; Russell et al., 2023). Enrichment in organic material can reduce particle hygroscopicity relative to pure salt and introduce significant variability in observed κ values. Reported κ values for marine aerosol therefore span a broad range, often between ~ 0.3 and ~ 1 depending on particle size, biological conditions, and particle mixing state (Quinn et al., 2017; Russell et al., 2023; Schill et al., 2015).

Wind forcing may influence the effective hygroscopicity of SSA through its influence on particle composition and mixing state. Increased wind speeds enhance wave breaking and whitecap formation, which alters bubble entrainment and the production of aerosol droplets originating from different regions of the bubble. Because organic material and surface-active compounds are often enriched in the SSML relative to bulk seawater, changes in aerosol production mechanisms with wind forcing may influence the degree of organic enrichment in nascent SSA and thereby modify particle hygroscopicity. In addition, environmental factors such as biological productivity, surfactant abundance, and variability in surface microlayer composition may further influence the effective κ of marine aerosol populations, introducing variability that is not directly controlled by wind speed alone (Facchini et al., 2008; Pinxteren et al., 2017; Russell et al., 2023).

Although particle hygroscopicity plays an important role in determining CCN activation, its influence must be considered alongside particle size and number concentration. In κ -Köhler

theory, the critical supersaturation required for activation depends on both particle dry diameter and hygroscopicity, with particle size exerting a particularly strong influence on activation behavior relative to comparable changes in κ (Petters & Kreidenweis, 2007). Rearranging the κ -Köhler formula indicates that the critical supersaturation (S_c) scales approximately with dry particle diameter (D_{dry}) and hygroscopicity as $S_c \propto D_{dry}^{-3/2} \kappa^{-1/2}$, illustrating that relatively small changes in particle size can produce larger shifts in activation behavior than comparable changes in κ . As a result, variations in aerosol size distributions and emission fluxes often exert the dominant control on CCN abundance in the marine boundary layer, while particle hygroscopicity primarily modulates activation efficiency within a given size class (Farmer et al., 2015; Quinn et al., 2017). Nevertheless, characterizing variability in κ remains important because it reflects changes in particle composition and mixing state that may signal shifts in the processes governing SSA production. Controlled laboratory systems therefore provide an opportunity to isolate the influence of wind forcing on SSA hygroscopicity while minimizing the environmental variability present in ambient marine environments. Most previous laboratory and field investigations of SSA CCN activity have relied on bulk aerosol populations in which particle size distributions and composition vary simultaneously. Because particle size exerts a strong control on CCN activation, variability in size distributions can obscure the role of particle composition and hygroscopicity when interpreting CCN measurements. Size-resolved CCN measurements provide a more direct assessment of compositional influences on activation behavior by isolating particles of a fixed diameter. Despite the importance of this approach, relatively few studies have reported size-resolved CCN activation for freshly generated SSA, particularly under controlled wind-wave conditions.

The Scripps Ocean-Atmosphere Research Simulator (SOARS) was developed to address these limitations by integrating a recirculating wind tunnel with an enclosed 36-m wave channel, enabling controlled SSA production under coupled wind-wave conditions while allowing water temperature and biological activity to vary naturally with ambient room conditions (Leibensperger et al., 2025). SOARS incorporates a large water volume along with extensive aerosol and gas filtration, along with environmental controls that minimize contamination and allow systematic manipulation of air-sea exchange conditions. Recent work has shown that SOARS produces SSA number size distributions with reproducible size-dependent features consistent with field and laboratory observations, including enhanced concentrations at sub-100 nm sizes, accumulation-mode scale particles near $\sim 0.15\text{-}0.20\text{ }\mu\text{m}$, and coarse particles attributable to jet-drop production (Leibensperger et al., 2025). These characteristics enable SSA production to be examined under controlled environmental conditions and provide a platform for investigating how wind speed influences submicron SSA abundance and properties.

Here, we use the SOARS wind-wave channel to examine how wind speed influences the CCN-relevant properties of submicron SSA produced during wave breaking, with a focus on characterizing particle hygroscopicity (κ). We focus on particles with mobility diameters near $\sim 55\text{ nm}$, which lie within the Aitken-mode size range and are near the critical activation threshold for typical marine supersaturations, making CCN activation at this size highly sensitive to particle hygroscopicity (Petters & Kreidenweis, 2007; Quinn et al., 2017). Specifically, we characterized the CCN activity of size-selected SSA produced at five different wind speeds ranging from $9.6\text{ to }21.2\text{ m s}^{-1}$. Measurements of SSA number concentrations and both neutralized and non-neutralized mobility size distributions were used to provide context for interpreting wind-speed-dependent changes in particle activation behavior. Neutralized distributions were used to characterize the

particle population under a defined Boltzmann charge distribution, while non-neutralized distributions allowed evaluation of how the native charging state of freshly emitted varied with wind speed or sampling day. Together, these measurements constrain how wind speed influences the hygroscopicity parameter (κ) of nascent submicron SSA under controlled laboratory conditions.

3.2 METHODS

3.2.1 SOARS WIND-WAVE CHANNEL

A full description of SOARS operation, wave dynamics, and seawater preparation protocols can be found in Leibensperger et al. (2025). A concise summary is provided here for context. SOARS is a closed-loop wind-wave facility designed to generate and isolate sea spray aerosol under controlled laboratory conditions. The results here were obtained during a one-week period (August 15-20) of the CHAOS (Characterizing Atmosphere-Ocean particles in SOARS) campaign conducted in Summer 2022. Waves were generated using a motorized paddle programmed to produce a repeating sequence with a fixed wave amplitude of 1.3. For every five wave crests, two breaking waves occurred consistently across all wind speeds tested. The wind system is fully recirculating, and the channel was maintained under slight positive pressure to minimize the intrusion of outside air and prevent contamination.

Each of the experimental days followed a standardized procedure. The system began at a low wind setting while HEPA filters were placed in line to purge the wave channel headspace of residual particles. This flushing process continued for approximately 30 mins until background concentrations stabilized below $\sim 100 \text{ p cm}^{-3}$, at which point the filters were withdrawn (See SI Figure S3.1). Wind speed and wave production were then initiated, leading to a steady rise in

particle concentrations that eventually plateaued under stable operating conditions. The aerosol concentrations during wave breaking were at least 10 times, and up to 10^4 times, larger than this minimum value after filtering, and with the size distributions measured at the end of purging having shapes distinct from those observed during wave breaking. As such, the particle properties measured during wave breaking reflect those of primary SSA with minimal contributions from residual particles. During sampling, fan speeds were set to 850, 1200, 1400, 1500, 1600 and 1800 rpm, corresponding to equivalent U_{10} wind speeds of 9.6, 13.8, 16.3, 17.5, 18.7, and 21.2 m s^{-1} , respectively. We refer to the measurements made during the steady state period at a given wind speed and on a particular day as a Run. The wave packet amplitude was held fixed at 1.3 and was selected to produce whitecap coverage within SOARS that is comparable in magnitude to open-ocean conditions across the range of wind speed studied, based on established parameterizations (Monahan & Muircheartaigh, 1980). Within SOARS, whitecap coverage increases with wind speed (Harb et al., *in Prep*), consistent with qualitative trends observed in the open ocean, while wave height remains fixed. Under equilibrium open-ocean conditions, both wave height and whitecap coverage generally increase with wind speed and depend on wave age and other environmental factors (Bourassa et al., 2001; Brumer et al., 2017). As a result, the use of a fixed wave height may lead to differences in the relationship between wind speed and SSA production relative to the open ocean. While this complicates direct translation of wind-wave channel results to open-ocean parameterizations, the controlled SOARS framework enables systematic investigation of wind-speed-dependent changes in SSA production and CCN-relevant particle properties.

The SOARS channel was filled with seawater collected at Scripps Pier, which was transported through the SIO seawater supply system, filtered, stored in campus holding tanks, and

gravity fed to the SOARS facility. For a detailed overview of the Scripps Pier seawater treatment system, refer to Jio (2022). No additional filtration or UV sterilization was performed prior to the start of sampling. No nutrients were added to the seawater and the chlorophyll-a (chl-a) concentrations remained relatively low and stable, averaging at $\sim 123 \mu\text{g L}^{-1}$.

SSA generated during wave breaking were drawn into a cylindrical manifold chamber that was connected to the SOARS headspace ~ 25 m downwind from the point where the waves broke. The manifold provided a common sampling point from which multiple instruments drew subsamples. Here, particles were sampled from the manifold at 7.5 L min^{-1} through a 4 m long $\frac{1}{4}$ " (6.35 mm OD) stainless-steel tube. The SSA were dried to a relative humidity of $\sim 15\text{-}45\%$ by passing them through a 1 m silica gel diffusion drier after which the flow passed through a $\text{PM}_{2.5}$ cyclone. Particle losses between the manifold and instrument inlets were estimated to be below $\sim 10\%$ for all $\text{PM}_{2.5}$ -relevant sizes. The dried aerosol stream was divided into three branches to supply instruments measuring bulk particle composition, particle size distributions, and cloud condensation nuclei activity (CCN). This study presents CCN data and a subset of size distribution results, while results from the composition measurements are reported in Palombella et al., (In prep).

3.2.2 CLOUD CONDENSATION NUCLEI COUNTER

3.2.2.1 CCN OPERATING PRINCIPLES

The CCN counter has been described in detail previously and is summarized briefly here (Lance et al., 2006; Roberts & Nenes, 2005). Aerosol particles are introduced into a cylindrical vertical flow tube and exposed to a controlled water vapor supersaturation (SS%), generated by continuously wetting the column walls and maintaining a near-linear axial temperature gradient

under laminar flow conditions. This temperature gradient established coupled heat and water vapor diffusion, producing a well-defined supersaturation profile within the column. The amount of water a particle takes up at a given relative humidity depends on both its size and composition, as described by Köhler theory (equation 1).

$$RH = \frac{p_w}{p_o} = a_w \exp \left(\frac{4\sigma_w \bar{V}_w}{RTD_{wet}} \right) \quad (1)$$

where RH is relative humidity, p_w is the vapor pressure of water, p_o is the saturation vapor pressure of water above a flat surface, a_w is the water activity, σ_w is the surface tension of water, $\bar{V}_w$ is the molar volume of water, T is temperature, R is the gas constant, and D_{wet} is the wet diameter of the cloud droplet. At relative humidities below a particle's critical supersaturation, water uptake is reversible, and particles grow or shrink in equilibrium with changes in ambient humidity. When the imposed supersaturation exceeds the critical values, particles rapidly activate, undergoing irreversible water uptake and growing into cloud droplets.

At the bottom of the column, particles that activate at grow to diameters greater than $\sim 1 \mu\text{m}$ and are detected and counted by an Optical Particle Counter (OPC). Under the conditions used here, particularly for size-selected 55 nm particles, detected droplets correspond to particles that have activated at the imposed supersaturation. The CCN instrument therefore quantifies the concentration of particles that act as CCN at a given supersaturation.

By measuring both the activated particle concentration (CCN) and the total particle number concentration (CN), the activated fraction (CCN/CN) can be determined. Measurements of CCN/CN as a function of supersaturation allow the critical supersaturation to be inferred, typically defined as the supersaturation at which 50% of particles activate. The shape of the activation curve

reflects the distribution of particle hygroscopicities within the sampled population; internally mixed particles typically produce steep activation curves, whereas externally mixed or compositionally heterogeneous populations can produce broader transitions or multi-step activation behavior (Roberts & Nenes 2005; Schill et al., 2017). Particle composition influences this behavior through presence of soluble material and surface-active compounds modify water activity and droplet surface tension, providing a mechanistic basis for interpreting variability in particle hygroscopicity (κ).

3.2.2.2 CCN OPERATION

Particles were sampled from the SOARS channel through the aerosol manifold, dried and size selected to a mobility diameter of 55 nm using a DMA (TSI, DMA). The resulting monodisperse (10:1 sheath: sample air flow ratio) particle stream was split between a cloud condensation nuclei counter (DMT-CCN) and a CPC (TSI, CPC), both operating at a 1 s time resolution. The CCN instrument was operated in scanning supersaturation mode, with supersaturation ramped stepwise from 0.1 to 0.7% over a one-hour period. Each scan included an initial 13 minute stabilization period to ensure equilibrium following previous measurements. Supersaturation steps were unevenly spaced to provide higher resolution near the critical supersaturation. CCN and total particle concentrations at each supersaturation were calculated as 1-minute averages. Instrument supersaturation was calibrated prior to the experiment using size-selected ammonium sulfate particles to ensure supersaturation accuracy. Hygroscopicity parameters (κ) derived from sequential CCN scans at a given wind speed were averaged to obtain representative values for each experimental condition.

3.2.2.3 CCN ACTIVITY AND ACTIVATION CURVES

We determine the critical supersaturation (S_{crit}) of CCN, that characterizes the activation of the sampled particle population into cloud droplets, a property commonly used to describe CCN activity. This can be parameterized by the hygroscopicity factor κ , which describes the composition-dependent water uptake of particles, independent of particle size. More hygroscopic particles, reflecting greater solubility or water affinity of their composition, activate at lower supersaturations, while particle size independently influences the supersaturation required for activation. The critical supersaturation marks the point at which a particle activates and undergoes spontaneous growth as a cloud droplet.

CCN measurements were made using a CCN counter operated downstream of a differential mobility analyzer (DMA) and condensation particle counter (CPC). The DMA selects monodisperse particles of a defined electrical mobility from a polydisperse population. The relationship between electrical mobility and mobility diameter depends on the number of charges on a particle; for a given electrical mobility, particles with one charge have the smallest diameter and are usually of greatest abundance. Here, we select particles with 55 nm mobility diameters, for singly charged particles. The monodisperse aerosol flow is split between the CCN and the CPC. The activated fraction ($f_{\text{CCN/CN}}$) is calculated at a specified dry diameter and supersaturation as the ratio of CCN-active particles to the total particle count. CCN activity spectra are plotted as activated fraction versus supersaturation. Each activation curve is fitted with a sigmoid function, including a y-offset to account for the potential influence of larger, multiply charged particles that will activate at lower supersaturations than the smaller singly charged particles. The steepness of the activation transition is quantified using the rate parameter returned by the sigmoid fit, which provides a measure of the slope of the activation curve. The midpoint of the sigmoid corresponds to the critical supersaturation (S_{crit}), defined as the supersaturation at which 50% of the particles

active. The critical supersaturation is coupled with the diameter of the activating particle, which is the activation diameter (D_{act}). The slope of the sigmoid provides information about particle population heterogeneity: a steep slope indicates a more chemically homogenous (internally mixed) population, while a broader slope implies greater heterogeneity or external mixing. As heterogeneity in particle size and composition within an aerosol population increases, CCN activation occurs over a broader range of supersaturations, resulting in a more gradual CCN activation curve rather than discrete activation steps (Schill et al., 2015)). CCN parameterizations commonly assume that particles within a given size class are internally mixed compositionally uniform. However, several studies have shown that neglecting particle-to-particle variability in composition can lead to substantial biases in CCN predictions, with errors approaching order-unity under certain conditions (Cubison et al., 2008; Schill et al., 2015). Accounting for external mixing state has been shown to significantly improve CCN model closure, reducing discrepancies between predicted and observed CCN concentrations to approximately 10-20% (Schill et al., 2015).

The instrument supersaturation was calibrated using size-selected, monodisperse ammonium sulfate particles by measuring CCN activation spectra across a range of particle diameters and comparing the observed activation behavior to expected values based on the known hygroscopicity of ammonium sulfate. A representative example of a CCN activation curve is shown in Figure 3.1, based on two replicate runs using 55 nm particles sampled in SOARS on August 16th, 2022.

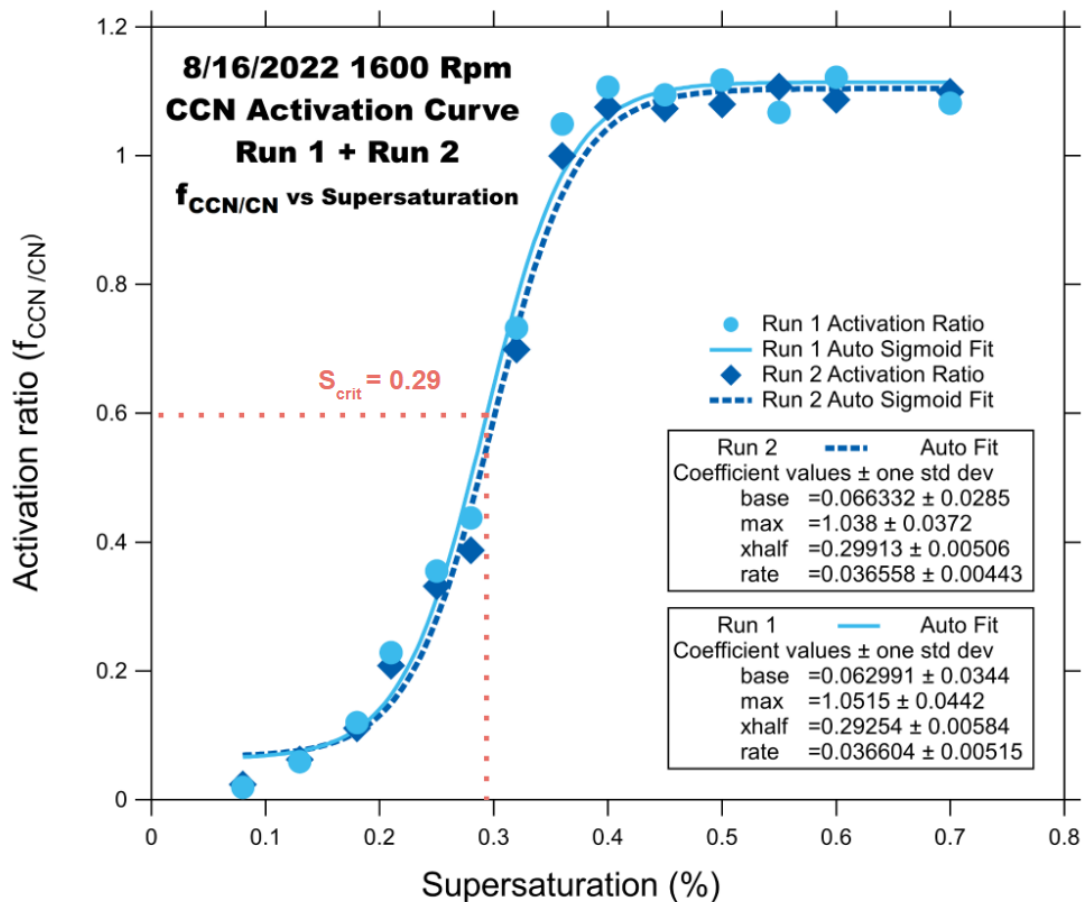


Figure 3.1: An example of a CCN efficiency spectrum or activation curve, showing how critical supersaturation is extrapolated from size-resolved experimental CCN data. This data is from 2 identical runs using 55 nm particles in SOARS on 8/16/22. The critical supersaturation of a pure NaCl particle at 55 nm is 0.25%. Activation fractions slightly exceeding unity arise from small differences in counting efficiency and particle transmission between CCN counter and CPC used to measure total particle number concentration. CCN tends to overcount at high activation fractions, but this does not affect determination of critical supersaturation.

The hygroscopicity parameter κ is calculated from the observed S_{crit} using the following equation

(2):

$$\kappa = \frac{4A^3\sigma_{lv}^3}{27T^3D_{act}^3\ln^2(S_{crit})} \quad (2)$$

Where $A = 8.69251 \times 10^{-6} \text{ K m}^3 \text{ J}^{-1}$, σ_{lv} is the surface tension of the droplet interface, T is temperature, D_{act} is activation diameter (in this case 55 nm), and S_{crit} is critical supersaturation (Petters & Kreidenweis, 2007). The derived κ values were compared to reference values from literature where $\kappa \sim 1.1$ for inorganic sea salt, ~ 0.67 for ammonium sulfate and ~ 0.1 - 0.2 for typical organic species (Petters & Kreidenweis, 2007; Shen et al., 2018). While NaCl particles typically activate at lower supersaturations than sulfate or organic particles of the same size due to their high hygroscopicity, some studies have reported primary organic SSA exhibiting κ values higher than expected based on inorganic salt composition alone, leading to enhanced CCN activation (Ovadnevaite, Ceburnis, et al., 2011).

Measurement accuracy for CCN concentration depends on minimizing particle losses between the CPC and CCN instruments and accounting for differences in counting efficiency. These effects influence absolute CCN and CN concentrations but do not affect the determination of the critical supersaturation (S_{crit}), which is derived from the relative activation fraction (CCN/CN) as a function of supersaturation. The influence of multiply charged particles selected by the DMA was accounted for during data analysis following standard charge-correction procedures (Roberts & Nenes, 2005). Most experimental runs were sufficiently long to allow two sequential CCN activation scans to be collected at a given wind speed. Comparison of S_{crit} values derived from these replicate scans demonstrates strong reproducibility, as shown in the supplemental information (Figure S3.2).

3.2.3 AEROSOL SIZE DISTRIBUTIONS

Sea spray aerosol size distributions were characterized using four instruments. Submicron particle number size distributions were measured using two scanning mobility particle sizers (TSI, SMPS 3936 and TSI, SMPS 3938) covering mobility diameters from 14 to 736 nm ($D_{p,m}$). One SMPS was operated with a radioactive neutralizer to establish a Boltzmann charge distribution, providing neutralized size distributions, while the second was operated without a neutralizer to characterize the native charge state of freshly emitted SSA. No polarity selection was imposed in the non-neutralized measurements; particles were classified according to their electrical mobility under the instrument's standard operating conditions.

A scanning electrical mobility analyzer (Brechtel, SEMS) measured mobility diameters from 10 to 1339 nm ($D_{p,m}$) and was operated with a radioactive neutralizer to provide size distributions over an extended range. Supermicron particle sizes were measured using an aerodynamic particle sizer (TSI, APS 3321) covering aerodynamic diameters from 0.5 – 2.5 μm ($D_{p,a}$). To create continuous size distributions spanning the submicron to supermicron range, APS measurements were converted from aerodynamic to mobility diameter assuming a particle density of 1.8 g cm^{-3} and merged with SEMS data at 650 nm and SMPS data at 630 nm. The resulting merged distributions were used to characterize the overall shape and continuity of the SSA size distributions across instruments. Both the SEMS and the SMPS were operational for all sampling runs from August 15th to 19th, 2022. On August 20th, however, the SEMS mixing condensation particle counter failed, so only SMPS data are available for the three runs conducted on that day.

3.3 RESULTS AND DISCUSSION

3.3.1 HYGROSCOPICITY (κ)

Hygroscopicity (κ) values derived from CCN activation spectra are shown as a function of wind speed in Figure 3.2. Each point represents κ determined for a single run at a given wind speed; when multiple scans were available for a run, κ values were averaged across replicates.

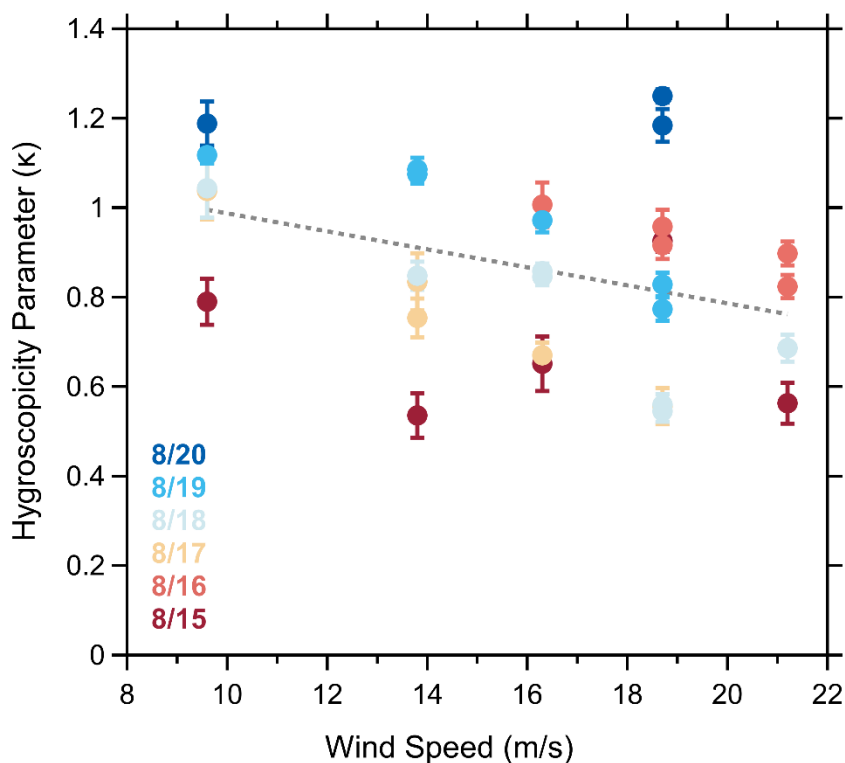


Figure 3.2: The hygroscopicity parameter as a function of wind speed. The markers are colored by the date of measurement. A linear trendline (grey dashed line) is added with $R^2 = 0.133$. Vertical error bars are added representing $\pm \sigma_\kappa$. For reference, pure sea salt particles exhibit $\kappa \approx 1.1$ -1.3, while enrichment in organic material can reduce κ to values below ~ 0.5 depending on composition and mixing state (Petters and Kreidenweis, 2007; Schill et al., 2015)

Observed hygroscopicity values exhibit a weak inverse dependence on wind speed, with κ tending to decrease slightly as wind speed increases (Figure 3.2). Linear regression yields a low coefficient of determination ($R^2 = 0.133$), indicating that only a small fraction of the variability in κ can be explained by wind speed and that the relationship is poorly described by a linear model. A Spearman rank correlation analysis ($n=31$) similarly reveals a weak, non-significant negative

association between κ and wind speed ($\rho = -0.33$), below the threshold for statistical significance ($|\rho| \geq 0.36$ at $\alpha = 0.05$). While the data hint at a downward trend in κ with increasing wind speed, no statistically significant dependence is observed across the full dataset.

This weak inverse tendency contrasts with expectation based on bulk particle composition measurements from Palombella et al., (*In Prep*), which indicate that the fractional contribution of inorganic sea salt (f_{ss}) increases with wind speed, accompanied by a decrease in the organic fraction (f_{org}). Given the high hygroscopicity of sea salt ($\kappa = 1.1$) relative to typical organic material ($\kappa = 0.1$ - 0.2), such a compositional shift would be expected to increase particle hygroscopicity with wind speed in SOARS. However, no direct composition measurements were available for the size-selected 55 nm particle population analyzed here. The bulk composition measurements referenced above are mass-weighted and therefore dominated by larger particles, while particles smaller than 100 nm contribute only a minor fraction of total aerosol mass. As a result, wind-speed-dependent changes observed in bulk composition are not necessarily representative of compositional variability in the sub-100 nm particles most relevant for CCN activation in this study. Submicron SSA—particularly near 55 nm—are often enriched in organic material, which may offset increases in inorganic sea salt fraction inferred from bulk measurements. Accordingly, chemical influences on hygroscopicity in this study are inferred from CCN-derived κ values interpreted as an effective bulk hygroscopicity, implicitly assuming volume-averaged mixing and constant surface tension, consistent with prior marine aerosol studies (Quinn et al., 2017). If surface-active organic components substantially reduce droplet surface tension, CCN activation may be enhanced without a corresponding increase in κ , further complicating attribution of observed activation behavior to bulk compositional changes alone.

Field measurements have also attempted to assess whether wind speed influences the hygroscopicity of marine aerosol under ambient conditions. For example, Ou et al. (2025) reported slightly higher average κ values for submicron aerosol during a higher-wind period in the South China Sea (0.49 at 7.26 m s^{-1}) compared to a lower-wind period (0.44 at 3.18 m s^{-1})(Ou et al., 2025). However, these measurements represent the bulk submicron aerosol population rather than isolated primary nascent SSA and were conducted in a region influenced by continental and anthropogenic sources, limiting attribution to wind-driven SSA production. Additionally, no variability, replicate uncertainty, or statistical significance was reported for this comparison, making it difficult to assess whether the reported difference is meaningful.

More broadly, both observations and modeling indicate that wind speed alone is unlikely to explain variability in CCN-relevant properties of small marine aerosols, because competing processes (e.g. new particle formation, scavenging, and size-dependent compositional variability) influence the particles that dominate CCN activation at low supersaturations. In Dunne et al. (2014), particles with dry diameters below $\sim 70\text{-}100 \text{ nm}$ exhibited substantial variability that was not uniquely linked to wind speed (Dunne et al., 2014). Consistent with this, our size-selected 55 nm SSA shows no statistically significant dependence of κ on wind speed, suggesting that factors beyond wind-driven production likely govern CCN activity in this size regime. Direct observational constraints on how wind speed affects the hygroscopicity of nascent sub- 100 nm SSA remain limited, because ambient measurements typically sample mixed aerosol populations and size-resolved composition at Aitken-mode diameters is rarely available.

Taken together, the absence of a clear κ -wind speed relationship motivates examination of variability along other dimensions. In particular, κ values varied considerably between sampling days even at fixed wind speeds, suggesting that factors such as seawater composition or biological

activity may have exerted a stronger influence on CCN properties than physical forcing alone. The temporal changes in κ are shown in Figure 3.3.

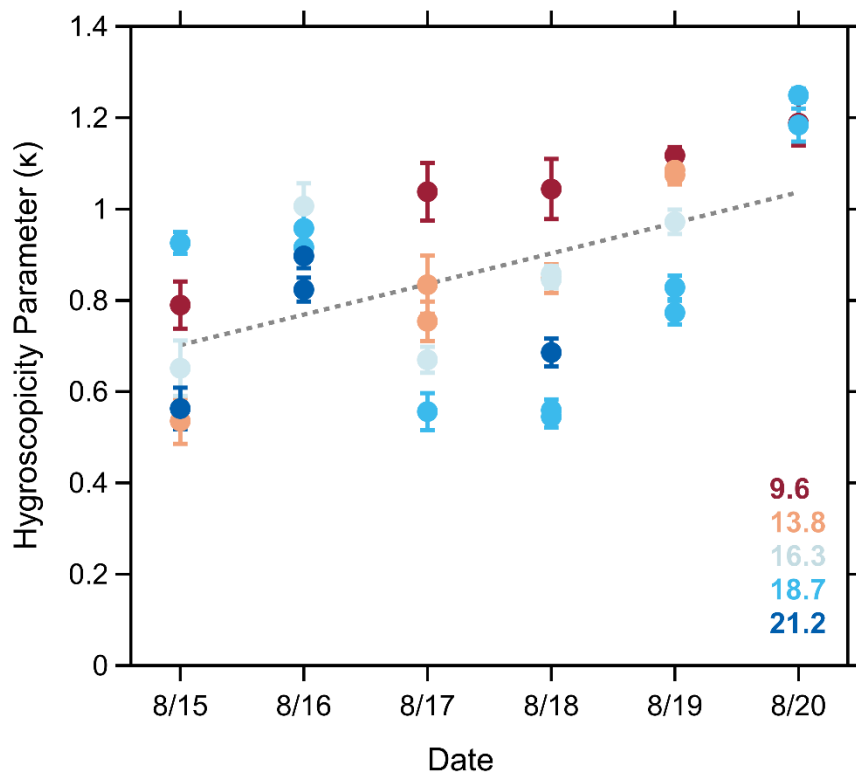


Figure 3.3: Hygroscopicity (κ) as a function of sample date. The markers are colored by wind speed in m s^{-1} . A linear trendline (grey dashed line) is added with the $R^2 = 0.277$. Vertical error bars are added representing $\pm \sigma_{\kappa}$.

A linear regression of κ against experimental time across all wind speeds reveals a modest positive trend ($R^2 = 0.277$), indicating that progression of the experiment accounts for a non-negligible portion of the observed variability in κ . To evaluate the robustness of this trend, a Spearman rank correlation analysis was performed ($n=30$), which revealed a statistically significant positive association between κ and date ($\rho = 0.51$, critical value = 0.36, $\alpha = 0.05$). Together, these results indicate that κ increased over the course of the experiment and suggest that temporal evolution in seawater conditions contributed to changes in the hygroscopicity of 55 nm

particles in SOARS. The magnitude of the temporal variability in κ observed here is broadly consistent with previous laboratory studies of SSA hygroscopicity. For example, Collins et al. (2016) reported CCN-derived hygroscopicity values spanning $\kappa_{\text{app}} \approx 0.7\text{-}1.4$ during induced phytoplankton bloom experiments. However, those measurements were not size-resolved, whereas the present study derives κ from size-selected particles (55 nm mobility diameter). The ability to constrain CCN activation for a fixed particle size provides a more direct assessment of compositional influences on hygroscopicity by reducing the confounding influence of size-distribution variability. Despite these methodological differences, both studies indicate that substantial changes in seawater chemistry do not necessarily translate into systemic changes in κ for nascent SSA. Accordingly, the day-to-day variation in κ observed at fixed wind speeds likely reflects gradual changes in seawater chemistry or particle production processes—such as shifts in dissolved organic matter composition, surfactant availability or bubble-film processing—rather than large-scale microbial perturbations (e.g., bloom-driven regime shifts).

Large-scale biological perturbations are unlikely to explain the observed κ variability, biological activity can nonetheless influence seawater chemistry through the production of dissolved organic matter and surface-active compounds that affect particle formation and CCN activation. To evaluate whether temporal changes in biological activity could plausibly contribute to the observed variability in κ , we examined microbial abundance throughout the campaign (Figure 3.4a and b). Total bacterial abundance declined over the course of the campaign, accompanied by decreases in several phytoplankton groups. However, the temporal evolution differed across taxa. *Synechococcus* and *Micromonas* exhibited overall declining trends, whereas *nano*- and *pico*-*Eukaryotes* showed comparatively smaller changes and no consistent monotonic trend over time. These patterns suggest that while biological activity evolved over the course of

the campaign, it did not follow a coherent bloom or decay trajectory that would directly explain the observed increase in κ . This is consistent with the SOARS experimental design, in which no bloom was induced and biological conditions were allowed to vary naturally over time. Previous laboratory studies have similarly shown that even strong biological perturbations do not necessarily produce systemic changes in SSA hygroscopicity. For example, Collins et al. (2016) found that κ derived from CCN activation did not exhibit a consistent, directional shift across phytoplankton blooms (Collins et al., 2016). At the same time, field and laboratory observations demonstrate that marine biological activity can substantially influence SSA chemical composition and mixing state (Mayer et al., 2020; Prather et al., 2013), often in episodic or process-dependent ways that do not translate directly into predictable changes in CCN activation behavior. Together, these observations suggest that while seawater biology influences SSA composition, it may not be the dominant control on the hygroscopicity of nascent submicron SSA under the conditions studied here.

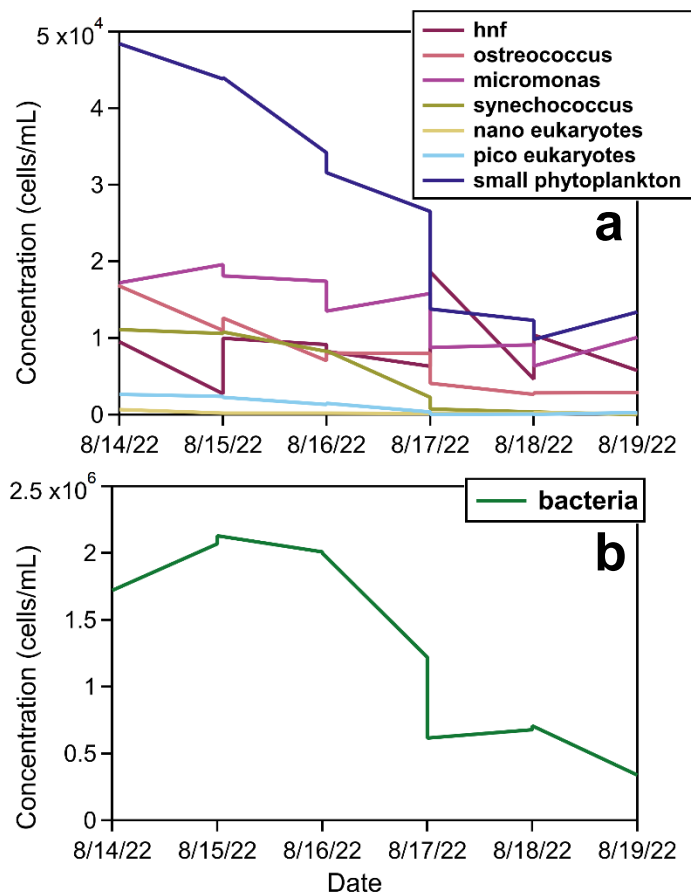


Figure 3.4: Average counts for a) various phytoplankton taxa and b) bacteria as a function of sample date.

3.3.2 CCN ACTIVATION CURVES AND SLOPE

While bulk hygroscopicity (κ) provides a useful means of characterizing CCN activity, it offers limited insight into the underlying chemical complexity of the aerosol population. This is especially relevant for freshly emitted SSA, which is often characterized as externally rather than internally mixed (Hawkins & Russell, 2010; Prather et al., 2013). A single κ value implicitly assumes a uniform composition across all particles of the same size, yet this assumption may oversimplify the true CCN activation behavior. Schill et al. (2015) demonstrated that when particles of differing hygroscopicity exist as an externally mixed population, activation efficiency

curves broaden and deviate from the idealized sigmoidal shape, with the slope of the curve serving as a diagnostic for mixing state (Schill et al., 2015). In their laboratory experiments, particle populations consisting of multiple particle types exhibited shallower activation curves compared to a homogeneous population. While the observed curves could still be fit with a single sigmoid curve, yielding a single value for κ , Schill et al. (2015) demonstrate that a more appropriate approach treats the activation curves as a linear combination of individual, sharp activation curves corresponding to particles of varying hygroscopicity (Schill et al., 2015). These findings suggest that careful inspection of the activation curve shape—and in particular, the slope near the midpoint of activation—can offer additional information about the mixing state of SSA.

Given the unexplained day-to-day differences in κ observed at similar wind seeds that are not explained by wind forcing alone, we next examine the CCN activation curves for individual days to assess whether changes in activation slope may indicate shifts in chemical mixing state or population heterogeneity. CCN activation curves for each of 5 days of experiments at different wind speeds are presented in Figure 3.5. These curves illustrate day-to-day differences in activation behavior and curve shape across the range of wind speeds sampled. For example, some days (e.g., 8/16 and 8/19) exhibit steeper activation transitions across all wind speeds, whereas others (e.g., 8/17 and 8/18) show more gradual transitions. Representative examples of steep and broad activation curves derived from the experimental data are shown in Figure 3.6. Activation curve slopes were quantified using the rate parameter obtained from the sigmoid fits applied to each CCN activation spectrum (see Figure 3.1 sigmoid fit results). Notably, days characterized by lower κ values tend to exhibit broader activation curves, whereas higher κ values are associated with steeper transitions. This correspondence indicates that κ and activation slope vary together

over time and motivates a quantitative analysis of activation slope as an additional descriptor of CCN activation behavior.

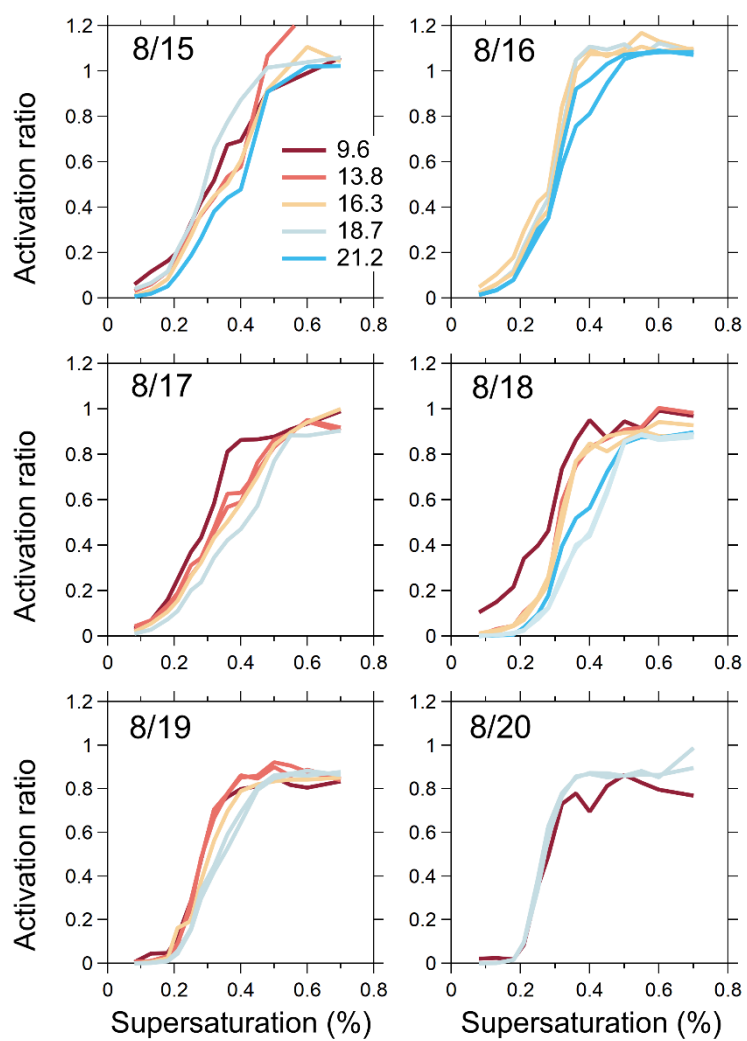


Figure 3.5: CCN activation efficiency curves for each sampling day, colored by wind speed in m s^{-1} .

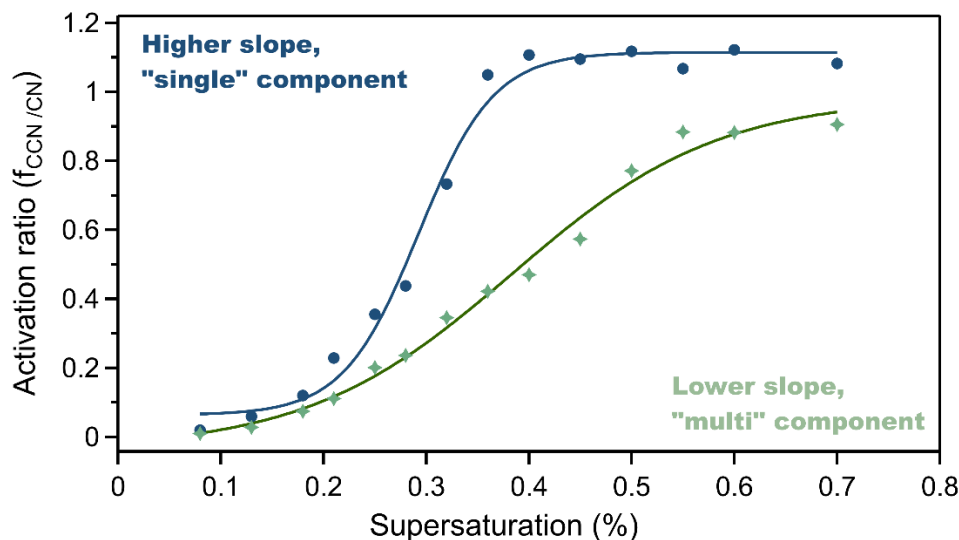


Figure 3.6: Representative examples of “steep” (blue) and “broad” (green) activation curves from the experimental data. Higher slope activation curves are assumed to be more “single” component, lower slope activation curves are assumed to be “multi” component.

To directly assess the relationship between hygroscopicity and activation behavior, activation curve slope was plotted as a function of κ (Figure 3.7). A strong inverse monotonic relationship was observed, with higher κ values corresponding to smaller slope values (i.e., steeper activation transitions). Linear regression yields $R^2 = 0.563$, $R = -0.750$, and a Spearman rank analysis ($n=31$) confirms a significant negative correlation ($\rho = -0.83$, critical value = 0.36, $\alpha = 0.05$). The strength of the inverse κ -slope relationship indicates that temporal variability in effective κ is accompanied by systematic changes in supersaturation range over which 55 nm particles activate. Days with lower κ values exhibit more gradual activation transitions, consistent with a more heterogeneous population of particles spanning a wider range of hygroscopicities. In contrast, higher κ days exhibit steeper activation curves, suggesting a comparatively narrower distribution of particle hygroscopicities and reduced population heterogeneity. This result

demonstrates that variability in activation curve shape systematically tracks changes in bulk hygroscopicity and supports the interpretation that evolving mixing state or compositional heterogeneity contributes to the observed CCN behavior. Having established this κ -slope linkage, we next assess whether wind forcing or temporal evolution better explains the observed variability in activation behavior.

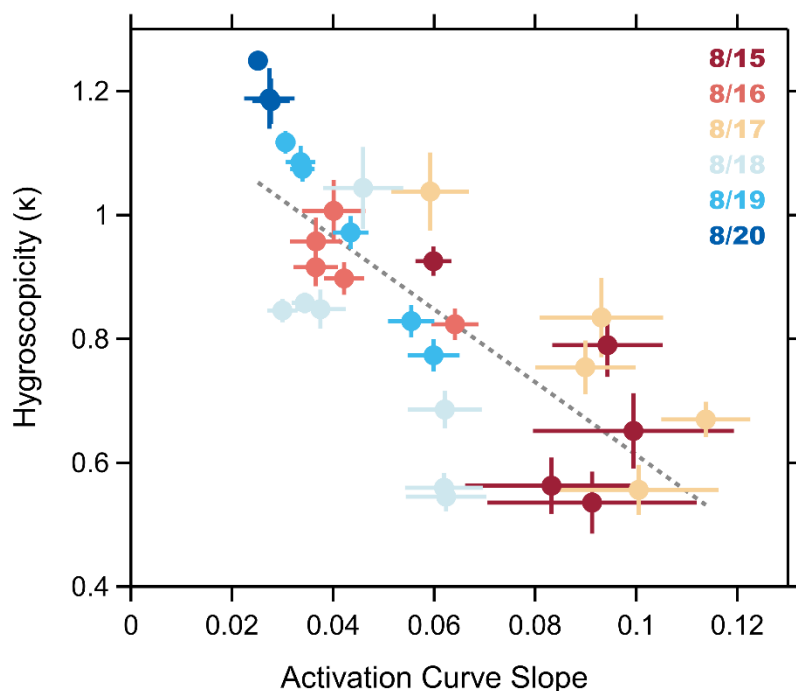


Figure 3.7: Hygroscopicity (κ) vs. Activation curve slope, markers colored by sample date. An added linear trendline is shown with $R^2 = 0.563$. Vertical error bars are added representing $\pm \sigma_{\kappa}$. Horizontal error bars are added representing $\pm \sigma_{\text{slope}}$.

To further evaluate the drivers of the activation curve variability in our experiments, we examined its relationship with both wind speed and sampling date. When plotted against wind speed, the activation curve slope exhibits no discernable trend (Figure 3.8a), and a linear regression yields an R^2 of just 0.002. In contrast, when plotted against sampling date (Figure 3.8b), a modest

downward trend is observed ($R^2 = 0.337$). Because smaller values of this parameter correspond to a steeper activation transition, this trend indicates that activation curves generally become steeper as the experiment progressed. This negative trend was statistically confirmed by a Spearman rank correlation analysis ($n=31$), which yielded a significant negative correlation ($\rho = -0.63$, critical value = 0.36, $\alpha = 0.05$). These results align with the increase of κ over time (Figure 3.3) and suggest that day-to-day changes in aerosol composition or mixing state—not wind speed—are more likely responsible for the evolving CCN activation behavior.

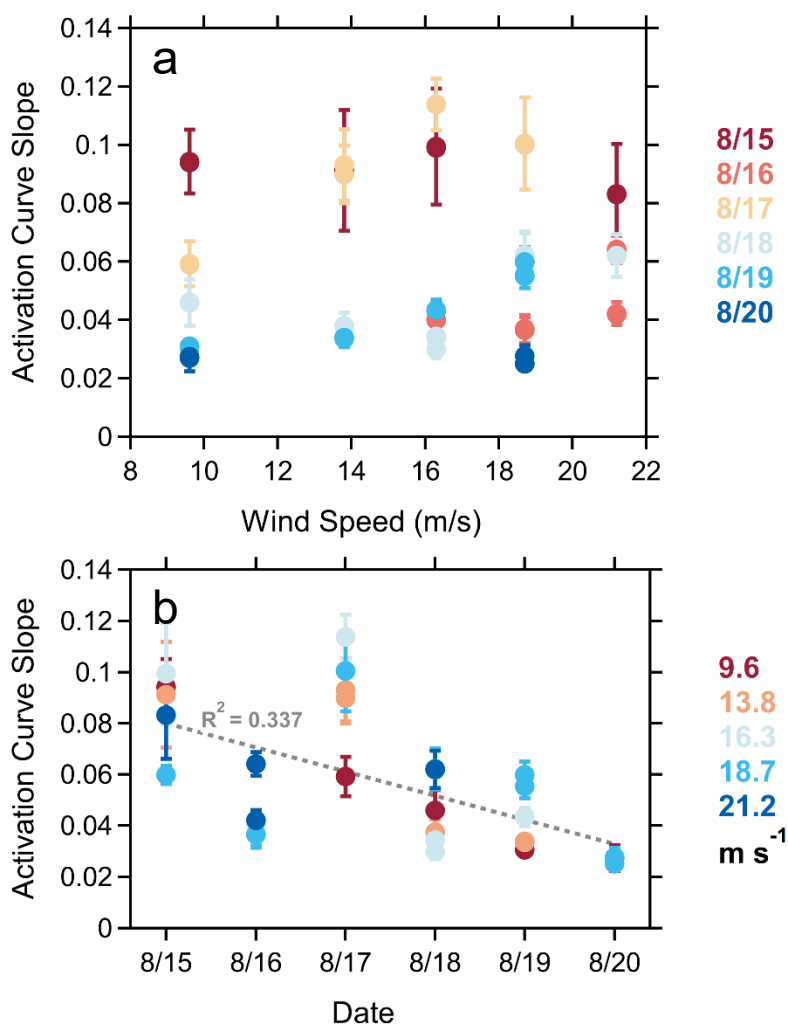


Figure 3.8: (a) CCN Activation curve slope versus wind speed (with different colors representing sample dates). (b) CCN Activation curve slope versus sampling date (with different colors representing wind speeds). Vertical error bars are added representing $\pm \sigma_{\text{slope}}$.

The diversity of CCN activation behavior observed in 55 nm particles is consistent with temporal changes in mixing state and chemical composition occurring within the SOARS system, where biological conditions were allowed to evolve naturally and no bloom was intentionally initiated. Single-particle measurements can provide complementary insight into aerosol mixing state and population heterogeneity that is not captured by bulk CCN metrics alone. During the CHAOS campaign, particles were collected for offline single-particle analysis of morphology and composition, as described by Madawala et al. (2024) (Madawala et al., 2024). These measurements focused on particles between 0.18 - 0.56 μm diameter and therefore do not directly probe the 55 nm particles examined here. Nevertheless, the observed diversity in particle morphology and mixing state at larger sizes provides qualitative support for the presence of heterogeneous SSA populations during the campaign, which may also extend to smaller particle sizes. They identified distinct particle morphologies—including core-shell structures, prism-like particles, and irregular aggregates—associated with differences in chemical composition (Madawala et al., 2024). Oxygenated particles were more likely to exhibit core-shell morphology, whereas aliphatic-rich particles tended to appear as amorphous aggregates.

These compositional differences are consistent with variations in hygroscopic behavior: oxygenated or salt-rich particles are expected to exhibit higher κ values, while particles enriched in less-polar organic material typically exhibit reduced hygroscopicity. Thus, the diversity of particle types identified by Madawala et al., (2024) is qualitatively consistent with the range of κ values observed for the size-selected particles in this study. Importantly, this morphological

diversity was evident even at the smallest sizes accessible to their analysis ($\approx 180\text{-}300\text{nm}$), indicating substantial mixing-state heterogeneity within the SSA population. While these sizes remain larger than the 55 nm particles examined here, the presence of diverse particle types at the lower end of the submicron range is consistent with wind-speed-dependent compositional variability observed in bulk SSA measurements during CHAOS (Palombella et al. *In prep*) and provides contextual support for heterogeneous SSA populations throughout the campaign. In contrast to the wind-speed-dependent trends observed in bulk SSA composition, the variability in κ and activation slope for the size-selected 55 nm particles is more closely associated with temporal changes than wind forcing. This suggests that CCN behavior at Aitken-mode sizes may be particularly sensitive to time-evolving factors such as surface film dynamics, microlayer composition, or subtle changes in particle production processes that are not captured by bulk composition measurements.

Although none of the CCN activation curves exhibited discrete stepwise transitions indicative of clearly separable particle populations, the broader sigmoidal activation curves observed on certain days are consistent with externally mixed particle populations composed of components spanning a range of hygroscopicities. Single-particle morphology measurements from Madawala et al., (2024), while limited to a single day and two wind speeds (10 and 19 m s⁻¹), provide qualitative evidence for the presence of heterogeneous SSA populations under CHAOS conditions, but do not inform the temporal evolution inferred from the CCN measurements. As described by Schill et al. (2015), externally mixed populations can produce smooth activation curves that resemble internally mixed behavior when represented by a single κ value (Schill et al., 2015). In this context, the observed steepening of CCN activation curves over time, together with increasing κ , suggests a gradual reduction in population heterogeneity or a diminishing influence

of less hygroscopic particle components as the experiment progressed, rather than the emergence of discrete activation modes.

Together, these CCN activation results indicate day-to-day changes in the hygroscopicity and activation behavior of submicron SSA that are not readily explained by wind speed or bulk biological indicators alone. To further probe the origin of these temporal differences, we next examine electrical mobility size distributions, which provide an independent perspective on changes in particle production and population structure during the CHAOS experiments.

3.3.3 PARTICLE SIZE DISTRIBUTIONS

Particle size distributions (Figure 3.9) describe the physical size structure of SSA across the sampled size range and serve as a reference for interpreting changes in particle production. These measurements reflect the dry mobility diameter of particles after charge neutralization, ensuring a Boltzmann charge distribution. Particle size distributions measured during the CHAOS campaign are shown in Figure 7, with all distributions normalized to the particle concentration at 150 nm to emphasize changes in relative shape rather than absolute number. Figure 3.9a presents size distributions measured on a single day (8/18) across all sampled wind speeds, allowing assessment of wind-speed-dependent changes in distribution shape under otherwise similar conditions. Figure 3.9b shows size distributions measured at a fixed wind speed of 18.7 m s^{-1} across all sampling days, enabling evaluation of day-to-day variability in SSA size characteristics.

On 8/18 (Figure 3.9a), systematic differences in distribution shape are observed between lower and higher wind speeds. In particular, runs conducted at higher wind speeds ($>17 \text{ m s}^{-1}$) exhibit an enhanced relative abundance of particles smaller than 100 nm compared to low wind speed runs ($<17 \text{ m s}^{-1}$), corresponding to a shift towards smaller modal diameters in the normalized

distributions. At a wind speed of 18.7 m s^{-1} (Figure 3.9b), some day-to-day differences in normalized size distribution shape are apparent, including smaller modal diameters on 8/17 and 8/18 relative to other days. These differences illustrate that temporal variability in particle size can occur at a given wind speed, but they are modest in comparison to the pronounced day-to-day changes observed in electrical mobility size distributions, which reflect changes in particle charging and population structure rather than physical size alone. While the drivers of these day-to-day differences are not well constrained, they may reflect gradual evolution of seawater properties within the channel.

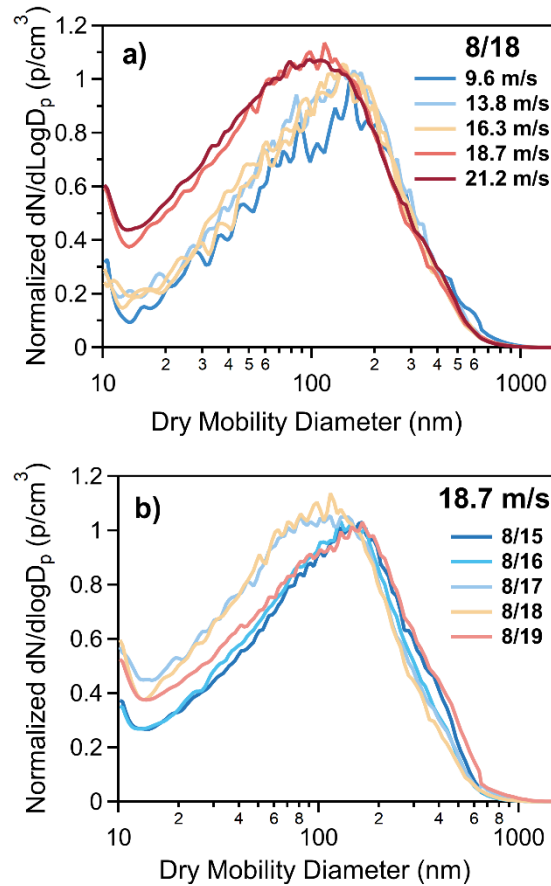


Figure 3.9: (a) Average size distributions for a single date, 8/18/2022 with each wind speed shown as a different color. Normalized at 150 nm. (b) Average size distributions for a single wind speed, 18.7 m/s with each sample date shown as a different color. Normalized at 150 nm.

In contrast to these neutralized measurements, electrical mobility distributions (Figure 3.10) incorporate the influence of particle charge in addition to size. Blanchard et al. (1963) first demonstrated that freshly generated SSA particles are electrically charged, with jet droplets exhibiting a strong natural positive charge and film droplets being more weakly charged (Blanchard, 1963). Although atmospheric ions and ion-aerosol interactions act to neutralize particle charge over time in the ambient atmosphere, the short residence time between SSA production and sampling in the SOARS facility limits this equilibration, allowing freshly emitted particles to retain substantial electrical charge at the point of measurement.

As a result, electrical mobility distributions reflect the combined influence of particle size and charge on observed diameter-resolved aerosol populations (Wang et al., 2017; Woolf et al., 1987). Previous studies have shown that film- and jet-drop production mechanisms overlap substantially in size, extending well into the submicron regime, rather than exhibiting a sharp size-based cutoff near $\sim 2 \mu\text{m}$ (Wang et al., 2017; Woolf et al., 1987). Because electrical charging depends on droplet formation processes and size, this overlap implied that submicron SSA can exhibit a continuum of charging behavior rather than discrete regimes. The particles examined here are all well below 100 nm—where SSA production is dominated by film-drop processes—and therefore the differences observed in our electrical mobility distributions are unlikely to reflect a transition between droplet types. Instead, they most plausibly arise from day-to-day variability in film droplet production and charging behavior. In the SOARS experiments, such temporal variability may be driven by gradual changes in bubble dynamics, surface tension gradients, and/or the enrichment of organic material at the air-water interface, rather than by wind speed alone. These processes can influence film thickness and drainage behavior at bubble burst, thereby modulating particle charging without producing a strong or systematic wind-speed dependence in CCN activity.

At 18.7 m s^{-1} , the electrical mobility distributions (Figure 3.10) exhibit more pronounced day-to-day differences than the corresponding neutralized size distributions, particularly in the sub-100 nm range. Above $\sim 100 \text{ nm}$, the electrical mobility distributions are relatively consistent across sampling days. In contrast, within the $\sim 10\text{-}40 \text{ nm}$ range, the normalized distributions on 8/18 and 8/20 exhibit a greater relative contribution compared to earlier days (with the exception of 8/16). On 8/15, the distribution is characterized by a single dominant mode and weaker relative contribution at the smallest electrical mobility diameters. On 8/16, the relative contribution at smaller electrical mobility diameters increases, and a subtle secondary feature near $\sim 30 \text{ nm}$ becomes more apparent. The distribution on 8/17 maintains a similar overall shape, though the relative prominence of the smaller-diameter feature is reduced. A pronounced change is observed on 8/18, when the feature near $\sim 28 \text{ nm}$ becomes distinctly more prominent, yielding the most clearly bimodal electrical mobility distribution observed during the campaign. On 8/19, the relative prominence of the two features becomes more comparable, reducing the visual separation between them. By 8/20, the distribution is dominated by a primary mode centered near $\sim 25 \text{ nm}$, with a weaker shoulder toward larger electrical mobility diameters, indicating a continued evolution in the relative weighting of charged particle populations rather than the emergence or disappearance of distinct modes.

Shaw and Deike (2024) demonstrated that variability in film droplet production can arise from changes in film thickness at burst driven by bubble lifetime, drainage dynamics, and subtle physicochemical differences, even when bulk conditions such as salinity stay constant (Shaw & Deike, 2024). Such processes provide a plausible physical context for the day-to-day differences observed in the electrical mobility distributions. Importantly, these differences are most evident in

the sub-100 nm regime and are not accompanied by comparably large changes in neutralized size distributions or a systematic wind-speed dependence in CCN activity.

Such changes are consistent with evolving microlayer properties and interfacial dynamics that influence SSA formation processes. Surface-active organic compounds accumulating at the air-water interface are known to modify surface tension and bubble-film stability, altering film drainage behavior and bubble lifetimes without necessarily producing large shifts in modal diameter or the emergence of new particle modes (Sellegrì et al., 2006). Consistent with this framework, the neutralized size distributions show relatively modest variability in shape, whereas the electrical mobility distributions exhibit substantially larger day-to-day differences. This contrast indicates that temporal changes captured by the electrical mobility measurements primarily reflect variations in particle charging and interfacial production processes, rather than substantial changes in particle size or a systematic response to wind forcing.

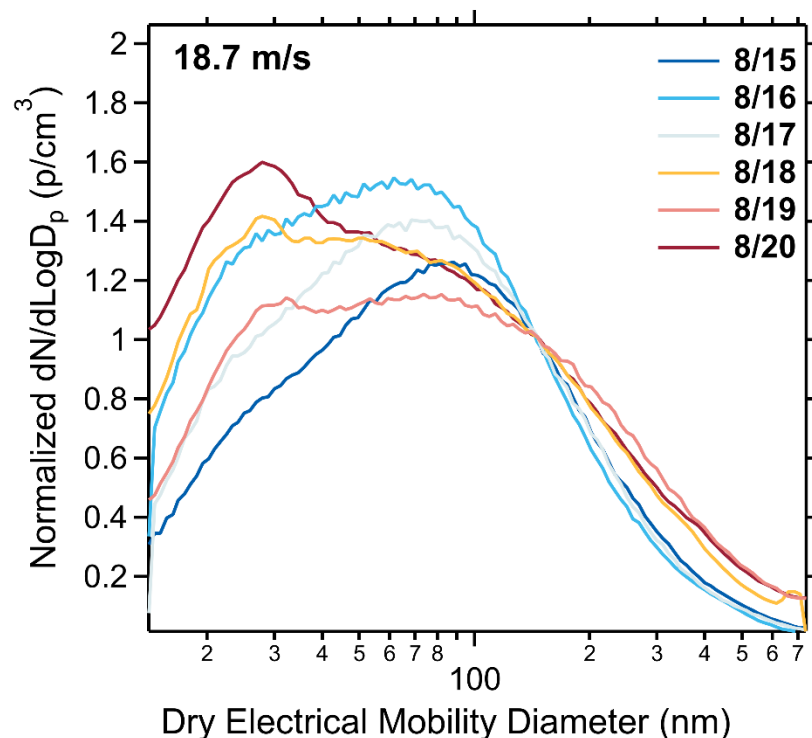


Figure 3.10: Particle Electrical Mobility Size distribution for all sampling days (different colors) at the same wind speed 18.7 m/s. Normalized at 150 nm.

Unlike the CCN measurements, which were conducted on neutralized, size-selected particles at 55 nm, the electrical mobility results reflect both physical and electrostatic properties of non-neutralized particles and therefore do not directly influence κ or activation slope values. Instead, variability in the electrical mobility distributions likely reflects changes in the chemical composition of freshly generated SSA that alter particle charging during film-drop formation, indirectly modulating the population of particles capable of acting as CCN. Comparison of κ values with metrics derived from the non-neutralized electrical mobility distributions does not reveal a clear or systematic relationship. Days exhibiting enhanced ultrafine electrical mobility signal below 100 nm do not consistently correspond to higher or lower κ values. This indicates that while

the electrical mobility measurements provide evidence for temporal variability in particle charging and, by inference, SSA composition, they do not offer a direct or quantitative proxy for CCN hygroscopicity. Thus, the non-neutralized distributions highlight compositional and interfacial variability in SSA production that is not uniquely reflected in CCN activation behavior. Together, these results demonstrate that surface and microlayer processes introduce temporal variability in SSA properties under constant wind forcing. Resolving this variability will require direct measurements of air-water interfacial properties—such as surface tension, microlayer organic enrichment, and SSML film composition—co-measured with CCN-activity, rather than relying solely on bulk aerosol composition or bulk biological abundance metrics.

3.4 SUMMARY AND CONCLUSION

This work presents CCN measurements of submicron SSA generated in the Scripps Ocean-Atmosphere Research Simulator (SOARS) under controlled wind-wave conditions. Measurements were conducted at wind speeds of 9.6, 13.8, 16.3, 18.7, and 21.2 m s⁻¹ and focus on particles with a dry diameter of 55 nm. CCN activation measurements are evaluated alongside neutralized and non-neutralized electrical mobility size distributions to characterize variability in hygroscopicity, activation behavior and particle abundance.

No statistically significant relationship was observed between wind speed and the hygroscopicity parameter κ for 55 nm particles. Linear regression yielded a low coefficient of determination, and a Spearman rank correlation analysis showed a weak, non-significant association between κ and wind speed. The slope of CCN activation curves likewise showed no discernable dependence on wind speed, with both regression and Spearman rank analyses indicating no statistically meaningful relationship. These results suggest that wind speed alone

does not explain variability in CCN activity under the conditions examined here. By contrast, both κ and CCN activation curve slope varied systematically over the course of the experiment. Notably, κ and activation curve slope exhibited a statistically significant negative relationship, with higher κ values corresponding to steeper (lower slope) activation transitions. Spearman rank correlation analyses revealed statistically significant associations between sampling date and κ , as well as between sampling date and activation slope, demonstrating that temporal variability exceeded wind-driven effects. These patterns highlight pronounced day-to-day variability in CCN-relevant particle properties.

Particle size distributions provide complementary evidence for this variability. Neutralized electrical mobility size distributions were generally similar across sampling days at a fixed wind speed, exhibiting comparable modal structure with relatively modest differences in concentration. Non-neutralized electrical mobility size distributions, however, showed substantially greater variability, particularly below 100 nm. At a constant wind speed of 18.7 m s^{-1} , ultrafine particle concentrations ($<100\text{nm}$) varied strongly from day to day, with transient bimodal features appearing on some sampling dates but not others, while particle concentrations above 100 nm remained comparatively stable.

CCN-relevant properties of submicron SSA in SOARS are weakly constrained by wind speed but strongly influenced by temporal variability captured through both CCN activation measurements and electrical mobility size distributions. The contrast between neutralized and non-neutralized measurements highlights variability in ultrafine particle populations that is not evident when particle charge is removed. Together, these results emphasize the role of surface and interfacial processes in governing nascent SSA properties relevant to cloud formation. Laboratory systems such as SOARS, which allow concurrent measurements of CCN activity and size-resolved

particle populations under repeatable wind-wave conditions, provide a valuable framework for isolating these surface-driven influences. Such measurements are critical for improving how CCN-relevant marine aerosol are represented in laboratory studies and for informing model treatments that currently rely on simplified wind-speed-based assumptions. Extending this approach to include concurrent measurements of surface properties and microlayer composition would further clarify how interfacial dynamics modulate CCN activity in nascent SSA.

ASSOCIATED CONTENT

Supporting Information Figures S3.1-S3.3

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3.8 Supplemental information:

Supplemental information for:

Submicron Sea Spray Aerosol CCN Activity in a Wind-Wave Channel: Limited Sensitivity to Wind Speed

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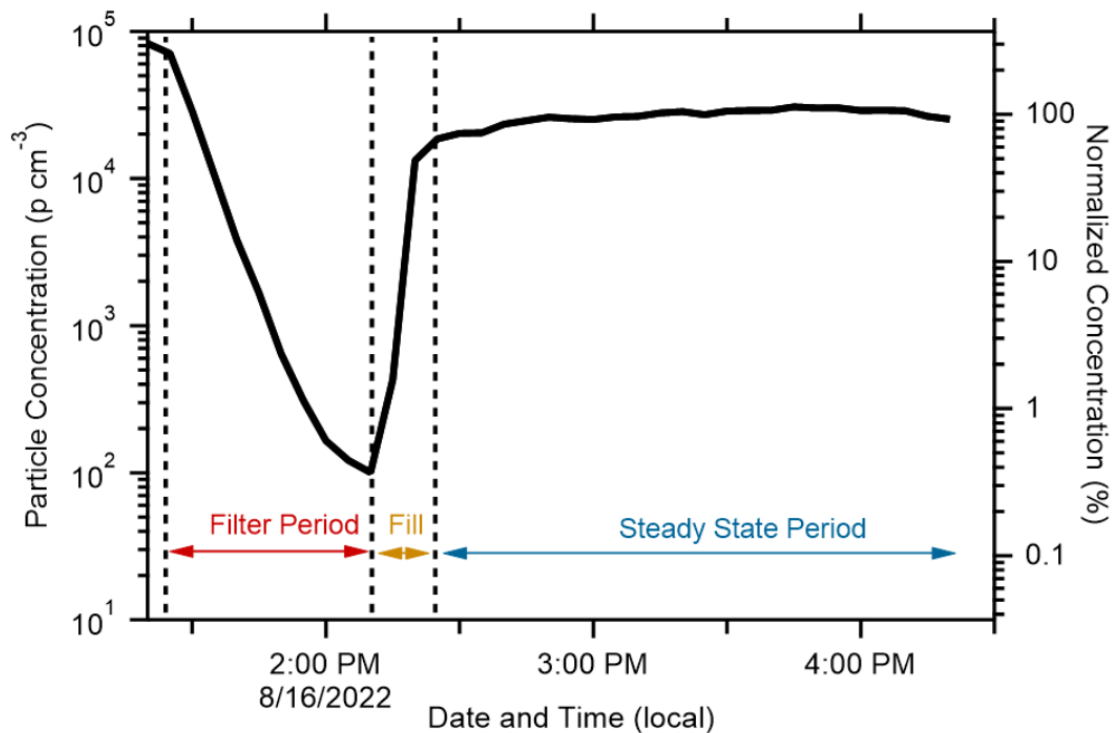


Figure S3.1: Time series of particle number concentration measured on 8/16/2022 during a SOARS wind-speed experiment. An initial low-wind period with active aerosol filtration reduced particle concentrations to below $\sim 100 \text{ p cm}^{-3}$ (less than 1% of steady-state levels). As wind speed increased and wave breaking commenced, particle concentrations rose during a transitional “fill” period. A subsequent steady-state phase was established, during which aerosol sampling was performed. Absolute particle number concentrations are shown on the left axis, while concentrations normalized to the steady-state period are shown on the right axis.

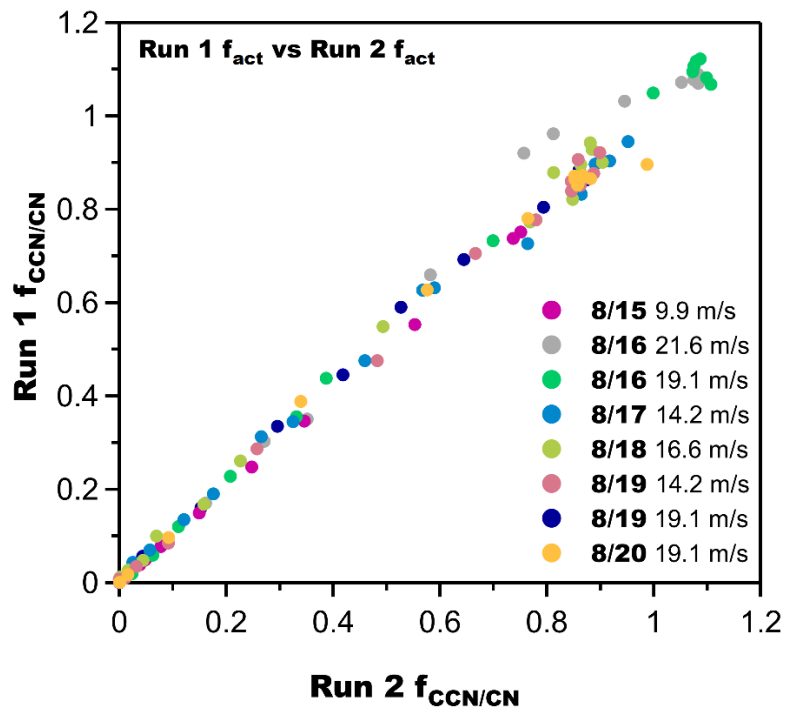


Figure S3.2: CCN activation curve diagnostic graph showing similarities between back-to-back sample runs. The activated fraction $f_{CCN/CN}$ for Run 1 is compared to $f_{CCN/CN}$ for Run 2. Perfect agreement between both runs would be a $y=x$ line, which is almost seen here, without an added trendline.

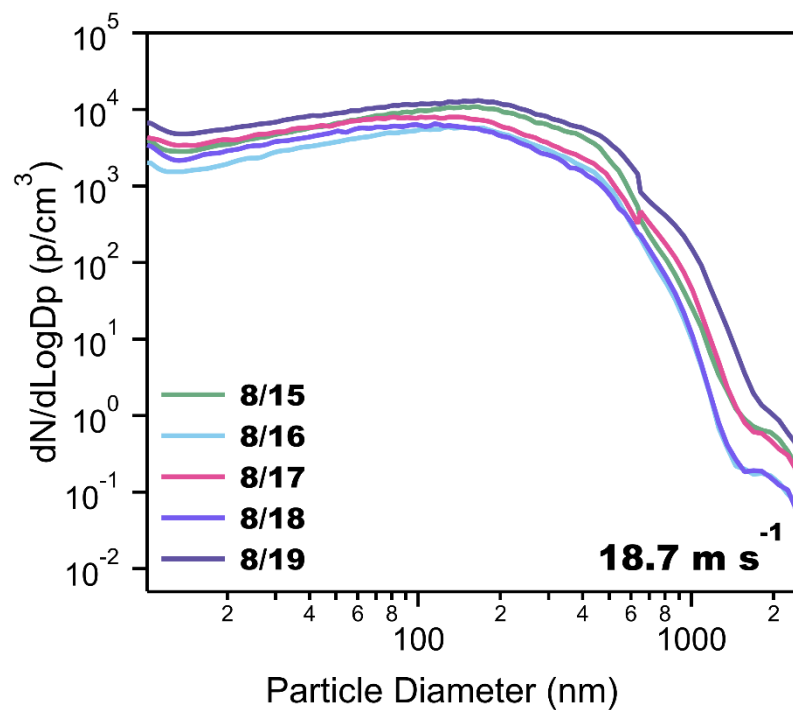


Figure S3.3: Neutralized particle size distributions at one single wind speed 18.7 m s^{-1} . Size distributions are colored by the sample date.

CHAPTER 4: A CASE STUDY OF NEAR-PEER GRADUATE-LED MENTORSHIP IN THE E-SEARCH PROGRAM

Abstract

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Abstract

Many graduate students in engineering struggle to access consistent, empathetic guidance, making confidence and sense of belonging critical factors in persistence. Peer-based mentorship programs may help address these gaps, yet their specific impacts within graduate and undergraduate STEM communities remain understudied. This case study evaluates the E-SEARCH mentorship program, a peer-focused initiative designed to connect undergraduate mentees and graduate student mentors across engineering disciplines. Using an action research framework, the study employed a three-stage survey design to assess changes in participants' confidence, sense of belonging, and motivation to pursue research or advanced study. Although

the overall cohort included 31 participants, matched beginning- and end-of-program responses were obtained for only five individuals (three undergraduate and two graduate). Despite the small sample size, the results suggested that participation in E-SEARCH may positively influence students perceived research self-efficacy, comfort within research environments, and commitment to continued research engagement. These findings highlight the potential of intentional, relationship-centered mentorship structures to supplement traditional advising relationships and support equity, inclusion, and retention within STEM learning spaces.

4.1 INTRODUCTION

Mentorship plays an important role in shaping educational persistence, professional identity, and confidence across academic pathways. Within higher education, mentoring relationships influence how students navigate uncertainty, develop a sense of belonging, and imagine themselves as capable participants in academic and research communities. These processes are particularly salient at transitional points—such as entry into research for undergraduates and progression through graduate training—where access to relational support can strongly shape academic trajectories.

In graduate education, mentoring is most often discussed in relation to faculty advising and doctoral persistence. However, graduate students also routinely serve as mentors to undergraduates through research groups, teaching roles and structured outreach programs. As a result, many graduate students occupy dual positions within academic mentoring systems: they are simultaneously mentees within their own programs and mentors to less experienced students. These dual roles situate graduate students as relational bridges across academic levels, linking undergraduate and graduate experiences in ways that are often overlooked in traditional mentoring frameworks.

Doctoral study is frequently characterized by high levels of individualization and self-direction, conditions that can limit opportunities for sustained social interaction. Many graduate students report feeling isolated and disconnected from their academic communities, a pattern that intersects with broader concerns about psychological distress and well-being in doctoral education (Ehrenberg et al., 2007; Lorenzetti et al., 2019). Within this context, relational support from both faculty and peers plays a crucial buffering role by reducing stress, supporting identity development, and promoting persistence (Lorenzetti et al., 2019). Advising quality has been consistently linked to doctoral completion, with programs demonstrating stronger advising practices showing higher graduation probabilities over time (Ehrenberg et al., 2007). Yet, access to supportive mentoring relationships remains uneven across graduate populations.

At the same time, undergraduate students, particularly those entering research pathways for the first time, often rely on informal or near-peer sources of guidance to navigate academic norms, research expectations, and professional pathways. For many undergraduates, graduate students represent the most accessible models of “who belongs” in research and graduate education. These relationships can provide instrumental guidance as well as social affirmation, helping undergraduates build confidence and a sense of belonging within academic spaces that may otherwise feel opaque or exclusionary.

Despite the centrality of these cross-level interactions, mentoring systems in higher education are frequently fragmented. Faculty-centered advising alone is not always sufficient to meet students’ academic, social and developmental needs, and access to high-quality mentoring varies substantially by gender, race and disciplinary context. Prior research shows that women and other underrepresented groups in graduate programs continue to experience fewer mentoring opportunities, lower quality advising relationships, and limited access to role models compared to

their male peers, patterns linked to higher attrition rates in STEM fields (Bhatia & Amati, 2010). Peer-based and near-peer based mentoring models have been shown to mitigate some of these inequities by reducing isolation, increasing approachability, and providing support grounded in shared or recently navigated experiences.

Scholars describe several forms of peer-based mentoring within higher education, including traditional peer mentoring, group-based or networked models, and near-peer mentoring in which mentors are slightly more advanced in their training. These structures differ in their relational dynamics and intended outcomes, but near-peer mentoring is particularly relevant in academic and research contexts where graduate students mentor undergraduates. In these settings, graduate mentors can provide guidance informed by recent experience while maintaining reduced power distance and greater approachability compared to faculty advisors (Anderson et al., 2015). Empirical research on undergraduate mentored research experiences demonstrates that mentoring quality plays a critical role in shaping student outcomes. Haeger and Fresquez (2016) show that undergraduate researchers who receive mentoring that includes instrumental guidance, socioemotional support, and culturally relevant practices report stronger gains in confidence, sense of belonging and preparedness for future academic and professional pathways (Haeger & Fresquez, 2016). However, access to high-quality mentoring relationships is not evenly distributed. Keku et al., (2021) found that senior undergraduate students from underrepresented backgrounds reported fewer mentoring opportunities and lower quality advising experiences, highlighting persistent inequities in access to relational support (Keku et al., 2021). A recent systematic review similarly identifies peer-based mentoring and near-peer mentoring as particularly beneficial for women and underrepresented students, while emphasizing that outcomes vary with mentoring structure and context (Nabi et al., 2025).

While this body of literature clearly establishes the value of near-peer mentoring for undergraduate development, less attention has been paid to the impacts of mentoring on graduate students who serve in mentoring roles. Graduate mentors occupy a distinctive position within academic mentoring systems, balancing their own training and advising relationships while simultaneously providing guidance, support, and role modeling for undergraduates. Emerging research suggests that peer-based mentoring can support graduate students' leadership development, reinforce research identity, and foster community and belonging within graduate programs. However, the conditions under which these benefits emerge—and how mentoring structures shape graduate mentors' experiences—remain underexplored.

Faculty advising remains central to graduate education, but on its own it is not always sufficient to meet students' social, developmental and professional needs. Peer and near-peer mentoring can supplement traditional advising by providing additional avenues for information exchange, skill development, and relational support. Despite growing attention to doctoral well-being, significant gaps remain in understanding which forms of relational support most effectively promote confidence, persistence, and inclusion across graduate populations (Barry et al., 2018; Lorenzetti et al., 2019). Addressing these gaps requires program-level evaluations that center both mentors' and mentees' experiences.

This chapter responds to these calls by examining how the E-SEARCH mentorship program supports graduate and undergraduate participants through a structured, near-peer mentoring model. Using an action research framework, this study examines how E-SEARCH promotes self-confidence, inclusion, and retention in research pathways, while also examining mentorship as both an interpersonal process and an institutional mechanism for equity in graduate education. By centering the experiences of both undergraduate mentees and graduate mentors, this

case study illustrates how intentional program design can strengthen relational support systems and inform broader approaches to mentoring in higher education.

4.1.1 RESEARCH QUESTIONS

This exploratory case study is guided by the following research questions:

1. Does participation in the E-SEARCH mentorship program influence participants' confidence in academic and research-related contexts?
2. Does participation in E-SEARCH influence participants' sense of belonging and perceived inclusion within research environments?
3. Does participation in E-SEARCH influence participants' motivation to engage in research or pursue graduate study?

These questions are examined descriptively based on participant self-reports and are not intended to support inferential or generalizable conclusions.

4.1.2 CONNECTION TO BROADER DISSERTATION

Although this dissertation primarily focuses on the physical and chemical properties of sea spray aerosol, the research presented in Chapter 2 and 3 was conducted within a collaborative experimental environment that depends on the training and participation of graduate and undergraduate researchers. Large-scale environmental research efforts, such as those described in this dissertation, rely not only on instrumentation and experimental design, but also on the human systems that support knowledge production, including mentorship, training, and collaborative learning.

Within this context, mentorship functions as a component of research infrastructure by shaping how students gain access to research opportunities, develop technical and analytical skills, and persist within scientific fields. Graduate students play a particularly important role in this process, as they often serve as both trainees and mentors within research environments, contributing to the continuity and functionality of collaborative scientific work.

This chapter complements the aerosol-focused analyses by examining a structured mentorship program as a case study of how relational support systems operate within STEM research settings. Rather than directly addressing aerosol processes, this analysis provides insight into the educational and social structures that enable participation in research, support the development of emerging scientists, and contribute to the sustainability of research programs over time.

4.1.3 POSITIONALITY AND MOTIVATION

Throughout my PhD experience, I have actively sought out mentorship not only as a professional development tool but also as a structural support that helped me sustain confidence, belonging and motivation during periods when traditional advising relationships did not provide the level of guidance I needed. Entering graduate school, I felt highly confident and eager to mentor undergraduates pursuing research careers, yet I quickly realized how difficult it can be to maintain that confidence without accessible, empathetic mentorship. This recognition came early in my program and shaped both my personal development and my commitment to understanding how mentorship influences persistence in graduate education.

My initial attempts to find mentorship through formal mentee-mentor matching programs were mixed; while the experience was valuable, I did not develop the kind of supportive relationship I had hoped for. In response, I became increasingly proactive in creating the

mentorship environments that I needed. During my first year, I established a sustainability-focused mentorship program within the Environmental Sustainability Student Coalition (ESSC) to connect undergraduate students with graduate and professional mentors interested in environmental and sustainability issues. The confidence I gained from building and leading this program, and from serving as a mentor in multiple on & off-campus initiatives, became a central anchor throughout my graduate experience. These structured mentorship roles were complemented by critical socioemotional support from close peers and faculty mentors outside my primary advising relationship, whose guidance, including encouragement to seek out community-based support systems, played a decisive role during a period when I had delayed my qualifying exam and was struggling to re-engage with my research. This combination of peer mentorship, faculty support outside my home research group, and engagement in mutual-aid communities ultimately helped me regain stability, rebuild confidence, and persist through major milestones in my program.

These individual experiences reflect broader structural patterns within graduate STEM education. National data show that women remain underrepresented in several STEM doctoral fields, particularly engineering and the physical sciences. According to the National Science Foundation's 2024 Survey of Earned Doctorates, women comprised 22.7% of engineering doctorates and 30.6% of doctorates in the physical sciences, despite earning a substantially larger share of STEM bachelor's degrees. This shift from undergraduate to doctoral training illustrates the early stages of the widely described "leaky pipeline," in which structural and cultural factors shape who is able to persist toward advanced degrees.

Evidence suggests that this imbalance does not arise solely from greater attrition during advanced training but rather reflects cumulative losses around multiple educational and professional transitions. For example, recent analysis indicate that gender differences in

persistence after entering STEM fields account for a relatively small share of overall underrepresentation, while larger losses occur at earlier stages of field entry and in transitions following degree completion (Speer, 2023). Unequal access to supportive mentorship and advising may contribute to these cumulative effects (Bhatia & Amati, 2010). Gender schemas—culturally embedded assumptions about men’s and women’s competence—further influence how women are perceived, evaluated, and included within scientific communities, reinforcing these disparities over time (Valian, 2007).

These barriers can be further compounded for women experiencing mental health challenges or navigating environments where socioemotional mentorship is limited, as insufficient relational support has been shown to exacerbate stress, isolation and academic disengagement (Barry et al., 2018; Lorenzetti et al., 2019). My experience reflects how the absence of accessible, empathetic mentorship can directly affect confidence, persistence, and a sense of belonging in graduate education. My commitment to this case study arises from this intersection of personal experience and disciplinary context: I have directly observed how intentional, (peer-based) mentorship can rebuild confidence, foster belonging, and support persistence in research-focused learning environments when traditional advising structures fall short. This positionality shapes the lens through which I approach the present case study, grounding the analysis in lived experience while situating mentorship as a structural mechanism for promoting equity, self-confidence, and retention in graduate education. Accordingly, this case study examines how the E-SEARCH mentorship program functions as a structured near-peer mentoring model, with particular attention to how participants experience confidence, belonging, and motivation within a program designed around regular engagement, sustained mentor-mentee interaction, and cohort-based participation.

4.2 METHODS

4.2.1 E-SEARCH PROGRAM AND CASE STUDY DESIGN

This case study was designed within an action research framework, meaning that the research process was guided by reflection and evaluation with the intention of applying findings to improve future iterations of the E-SEARCH mentorship program (Meyer, 2000; Spencer & Molina, 2018). The E-SEARCH (Engineering — Supporting Pathways to Research and Career Horizons) mentorship initiative is a structured, cohort-based program designed to expand participation in engineering research pathways, particularly among students historically underrepresented in STEM. Its objectives include increasing undergraduates' exposure to engineering research, strengthening their preparation for graduate study, and supporting graduate students' development as mentors and educators. Within this framework, E-SEARCH was intentionally designed as a mentorship program rather than an informal research placement. Undergraduate mentees were paired with graduate mentors through a structured matching process, expectations for communication and engagement were articulated in advance, and program elements such as regular check-ins, shared research activities, and defined project timelines were incorporated to support sustained mentor-mentee interaction. These design choices were intended to create consistent opportunities for guidance, feedback and reflection, rather than relying on ad hoc or incidental mentoring relationships. In the initial incarnation of E-SEARCH, the research experience spanned a single quarter; however, to allow for more meaningful project development and mentor-mentee engagement, the program was later expanded to a two-quarter format. The case study here examined one of the two-quarter implementations.

The E-SEARCH program is managed by a staff member within the College of Engineering (the "Program Director"). The Program Director has responsibility for organizing E-SEARCH, including selection of participants and the associated process for selection and pairing of

undergraduate-graduate mentee-mentor pairs. Program preparation for the Spring-Summer 2025 cohort began in late January with the development of updated application materials for both mentors and mentees. Recruitment opened on February 3, with outreach directed toward engineering majors and campus organizations through departmental lists and communication networks. To clarify expectations and assist prospective participants in assessing their fit with the program, E-SEARCH hosted mentor and mentee information sessions on February 14 and 20. These sessions provided an overview of anticipated time commitments, responsibilities, and research engagement opportunities.

Graduate mentors completed a structured screening process between February 18 and March 7. Interviews led by the Program Director gathered information about mentors' proposed research activities, availability, mentoring philosophy, and readiness to guide undergraduates in laboratory or project-based environments. The Program Director also documented expectations related to safety training, research tasks, and meeting frequency to ensure that each mentor could provide a substantive and well-scaffolded experience. Final mentor and mentee selections into the E-SEARCH program were made between March 10 and 21. Final mentor-mentee pairings were determined through a structured matching process that combined participant preferences with information gathered from applications and interviews. On April 2, E-SEARCH held an in-person matching event in which mentors and mentees engaged in a series of short, rotating conversations to discuss research interests, project ideas and working styles. Afterward, participants ranked their preferred partners. The Program Director and I synthesized these rankings with interview data and project alignment to assign final mentor-mentee pairs. This hybrid approach was intended to result in more equitable pairings while also giving mentees meaningful agency in selecting mentors aligned with their goals.

The cohort officially launched with a program kickoff on April 7. Rather than relying on frequent centralized meetings, E-SEARCH is structured around autonomous mentor-mentee collaboration: pairs set their own meeting schedules and engaged in research activities suited to their projects and interests. Throughout the quarter, the Program Director provided periodic guidance to participants through email newsletters containing suggested activities, professional development prompts, and reminders about upcoming deadlines. Mentees also participated in a library workshop intended to strengthen information literacy and research skills relevant to their projects.

Research activities varied considerably across mentor-mentee pairs, reflecting the breadth of engineering research represented in the cohort, who come from nearly all Departments in the College of Engineering. Common elements included data analysis, literature review, developing experimental or design ideas, shadowing graduate-level research tasks, and discussing pathways toward advanced study. The program concluded on August 27 with a final in-person project showcase, during which the mentee presented their work with mentor support to peers, faculty and program leadership. To support participation, E-SEARCH provided several material and professional incentives. Each pair was allocated a modest supply budget (up to \$200) to support project costs, and mentees were eligible for \$500-600 awards upon successful completion of the program. Graduate mentors were able to request research-related travel reimbursements up to \$1000 to present or disseminate work developed through the program. These supports were designed to reduce financial barriers and affirm the value of research participation at both the undergraduate and graduate levels.

As part of the action research framework guiding this study, my role within E-SEARCH centered on supporting program evaluation rather than administering program operations. I

contributed to the development and distribution of the beginning, midpoint and end-of-program surveys; communicated with participants to explain the research component; and assisted program leadership with administrative tasks during the cohort. Although I was not directly responsible for recruitment or screening, this embedded role provided insight into participant experiences and program functioning that informed the reflective cycles characteristic of action research (Meyer, 2000; Spencer & Molina, 2015).

Because E-SEARCH is designed to support the development of both graduate mentors and undergraduate mentees, the evaluation design examines the mentoring experience from both perspectives. An important motivation for this research is understanding how near-peer mentoring structures simultaneously support undergraduate mentees' sense of belonging and research identity development, while also shaping graduate mentors' confidence, leadership capacity, and engagement as emerging educators. Although participants were not directly involved in co-developing the research design, the study remains grounded in the action research principle that inquiry should inform and inspire meaningful changes within the studied context. Approval for this study was obtained from the UCD Institutional Review Board and classified as *Exempt Review* due to its minimal risk to participants. Survey instruments were developed in collaboration with the E-SEARCH program director to evaluate how both mentors and mentees experienced mentorship within the program and to assess whether participation enhanced their sense of belonging, academic self-efficacy, and motivation to pursue continued research or graduate study.

Two parallel survey instruments were created, one for graduate mentors and one for undergraduate mentees. Copies of these survey instruments are provided in the Appendix. Although they shared several core constructs (such as belonging, confidence in research-related skills, and perceptions of mentor-mentee interactions), each survey included items tailored to

participants' respective roles. For example, mentee surveys emphasized support, guidance and research identity development, whereas mentor surveys focused on mentoring confidence, pedagogical growth, and professional self-efficacy. The survey included both quantitative and open-ended questions designed to capture participants' perspectives on mentorship quality, confidence in research-related skills, and perceived value of mentor-mentee interactions.

We employed a three-stage survey design consisting of a beginning, midpoint, and end-of-program survey administered over the course of the E-SEARCH mentorship cycle. This structure allowed for ongoing participant reflection throughout the program while enabling comparison of key indicators before and after participation. Although all stages provided valuable feedback for program improvement, only the beginning and final surveys (included in the appendix) were used for quantitative comparison. This decision reflects the fact that the midpoint survey served primarily as a formative assessment tool and did not include parallel items suitable for pre-post analysis, whereas the beginning and end surveys contained matched constructs designed to assess changes in confidence, sense of belonging and motivation to continue research or graduate study.

During the study period, the E-SEARCH mentorship program included a total of 31 participants, consisting of 15 graduate student mentors and 16 undergraduate mentees across a range of engineering disciplines. Twenty participants submitted the beginning-of-program survey, though several responses were incomplete; therefore, only fully completed surveys were considered for potential pairing with end-of-program responses. Because the objective of this study was to evaluate changes over the course of participation, only responses from individuals who completed both the beginning and end surveys were included in the final analysis. A total of five participants (two graduate mentors and three undergraduate mentees) provided matched beginning-end responses. While this subset represents a small portion of the overall cohort, it

provides useful comparative insight into how E-SEARCH may have influenced participants' confidence, sense of belonging, and motivation to pursue research and advanced study. Survey responses were examined to identify general trends and themes related to participants' confidence, sense of belonging, and motivation, providing a preliminary understanding of the mentorship program's influence and informing the interpretation of results presented in the following sections.

To guide the analysis, survey items were organized into three thematic categories reflecting the central aims of the E-SEARCH program and evaluation: self-confidence, inclusivity and sense of belonging, and retention/motivation toward continued research or graduate study. These themes align with the mentoring literature summarized in the introduction and correspond to the primary constructs the study sought to evaluate. Although some survey items differed for mentors and mentees, each instrument contained questions that mapped onto these shared domains. Grouping was conducted qualitatively by reviewing all survey questions and identifying those that captured similar dimensions of the mentoring experience. Items related to perceived competence, skill development, or mentoring self-efficacy were categorized as self-confidence; items describing relational support, comfort within research settings or perceived inclusion were grouped under belonging; and items referencing future research engagement or intentions to pursue graduate study were categorized under retention/motivation. These thematic groupings provided a coherent structure for analyzing participants' reflections and for interpreting changes across the beginning and end surveys. The results that follow are organized around these three themes to illustrate how participants experienced the mentorship program and to explore potential shifts in confidence, belonging, and motivation over the course of E-SEARCH.

Several limitations should be considered when interpreting the findings of this case study. The number of participants who completed both the beginning and end-of-program surveys was small (n=5), which limits the generalizability of the results and precludes formal statistical analysis. In addition, participation in the surveys was voluntary, which may introduce self-selection bias, as individuals with particularly positive or negative experiences may have been more likely to respond. This study also focuses on a single implementation of E-SEARCH within one institutional context, and as such, the findings are specific to this program structure and setting. Finally, as an action research study, my role in supporting program evaluation may shape the interpretation of results, although this position also provided important context for understanding participant experiences. Taken together, these factors suggest that the findings should be understood as exploratory and descriptive, offering preliminary insight into participant experiences rather than definitive evidence of program impact.

4.3 RESULTS

4.3.1. SELF-CONFIDENCE

Improved confidence has been widely identified as a key outcome of mentoring relationships in higher education, particularly within structured research experiences. In their systematic review of graduate student peer mentorship, Lorenzetti et al. (2019) found that participation in peer mentoring programs was consistently associated with positive psychological outcomes, including increased self-confidence, reduced isolation and enhanced motivation to persist through graduate training (Lorenzetti et al., 2019). Complementary work focused on undergraduate researchers has shown that those who receive instrumental, socioemotional and culturally relevant mentoring demonstrate stronger learning outcomes and greater confidence in their ability to work independently as researchers (Haeger & Fresquez, 2016). Although the E-

SEARCH program did not formally operationalize mentoring quality using predefined categories (e.g. instrumental or socioemotional mentoring), this work provides a conceptual framework for interpreting how near-peer mentoring relationships may support confidence development.

In this study, self-confidence is examined for both undergraduate mentees and graduate mentors, reflecting the dual aims of E-SEARCH to support early research identity development among undergraduates while also fostering leadership and mentoring capacity among graduate students. While the literature has more extensively documented confidence gains among mentees, the confidence-building effects of mentoring for those providing mentorship remains less explored. Accordingly, this analysis considers role-specific confidence trajectories for both groups, with particular attention to how mentoring experiences may differently shape confidence maintenance and growth for mentors versus mentees.

Within this framework, mentoring experiences are understood as reciprocal processes that can support confidence development for both those receiving and those providing mentorship. For undergraduate mentees, structured guidance and affirmation can reduce uncertainty and foster academic and professional self-confidence. For graduate mentors, supporting others may reinforce existing expertise while strengthening leadership, communication, and advisory confidence (Bhatia & Amati, 2010; Lorenzetti et al., 2019). These dynamics are particularly salient for women and other underrepresented groups in STEM, for whom mentorship can help counteract the effects of bias and limited access to role models, supporting confidence in both skills and professional identity (Bhatia & Amati, 2010).

Responses from both mentors and mentees in the E-SEARCH program reflected these confidence-building dynamics. End-of-program survey items asked participants to assess how their confidence had changed *relative to when they began E-SEARCH*. Figures 1 and 2 summarize

self-reported changes in confidence for graduate mentors and undergraduate mentees, respectively, based on participants' selections across confidence-related survey items from Q2 (See End-of-Program Survey in Appendix).



Figure 4.1: Self-reported changes in confidence among graduate mentors at the end of the E-SEARCH program. Bars represent the percentage of confidence-related survey responses falling within each category. Percentages are calculated across 34 total responses corresponding to 17 confidence-related survey responses completed by two graduate mentors.

Graduate mentor responses indicated that confidence was largely sustained over the course of the program, with selective gains and no reported decreases (Figure 4.1). Mentors most frequently selected “unchanged,” indicating stability in self-reported confidence across the duration of the mentoring experience rather than widespread shifts in either direction. Instances of

increased confidence were concentrated in domains related to leadership, mentoring, and guiding others through research. Qualitative reflections reinforce this pattern. One mentor noted that “working with my mentee made me more confident answering questions and taking a leadership role in guiding other people’s research”, while the other described mentoring as a process that helped them recognize their existing expertise and the value of their guidance. Together, these responses suggest that mentoring primarily reinforced, and in some cases, extended confidence among graduate mentors, particularly in relational and leadership domains rather than technical competence.

Undergraduate mentees demonstrated a more pronounced pattern of confidence growth (Figure 4.2). Mentee responses were more frequently distributed across “more confident” and “way more confident,” with fewer selections indicating no change. Gains were most evident in areas related to academic communication, research participation, and presenting work. Qualitative responses provide important context for these shifts. Several mentees described beginning the program with hesitation about engaging in research or communicating with faculty. One mentee wrote that they initially felt “too shy to ask professors about research opportunities,” but concluded the program feeling “better prepared to do similar things in the future” after realizing that “doing research wasn’t as intimidating as I thought.” Another mentee described increased confidence in academic communication, explaining that E-SEARCH “gave me more experience and confidence in talking with my peers and mentors, and it marked the first time I presented research.” These reflections indicate that near-peer mentoring supported mentees’ confidence by reducing intimidation and providing structured opportunities for practice, feedback and affirmation.

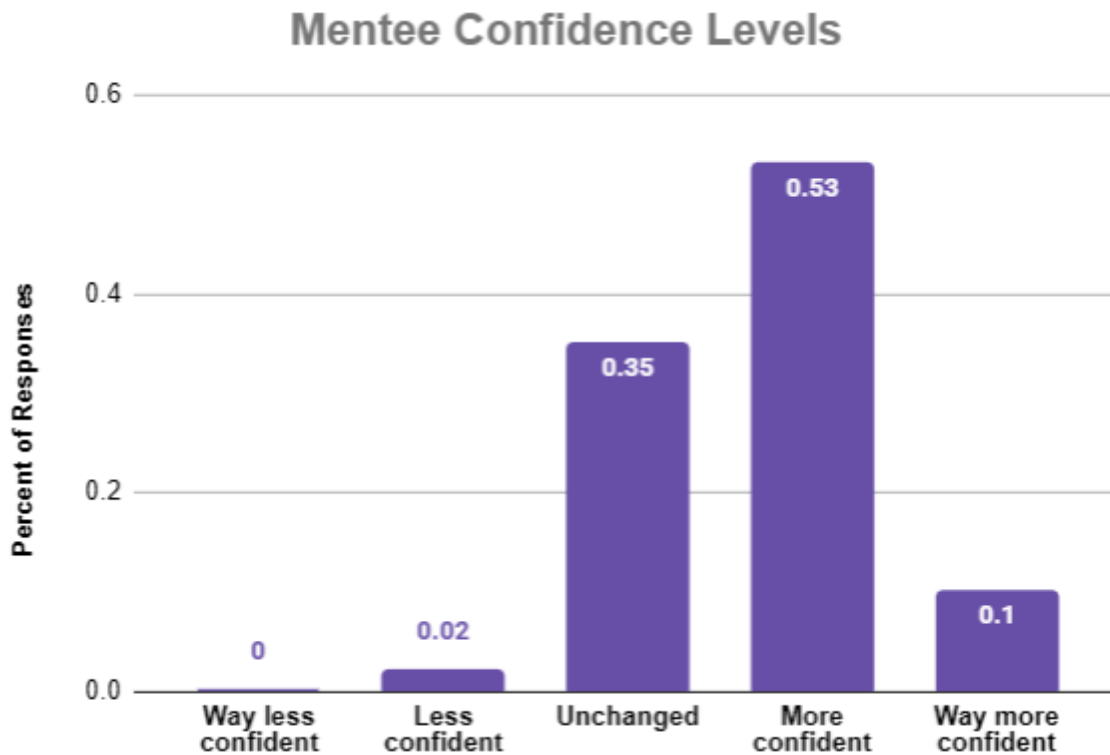


Figure 4.2: Self-reported changes in confidence among undergraduate mentees at the end of the E-SEARCH program. Bars represent the percentage of confidence-related survey responses falling within each category. Percentages are calculated across 51 total responses corresponding to 17 confidence-related survey responses completed by three undergraduate mentees.

Taken together, Figures 4.1 and 4.2 illustrate role-specific confidence trajectories within the E-SEARCH near-peer mentoring structure. Graduate mentors primarily experienced confidence maintenance with targeted gains in leadership and mentoring capacities, while undergraduate mentees reported more substantial perceived increases in confidence related to academic engagement and research participation. These complementary patterns highlight the reciprocal nature of near-peer mentoring, in which providing mentorship may reinforce professional identity

and leadership confidence, while receiving mentorship supports growth in academic self-assurance and belonging.

Overall, participants most often reported either sustained or increased confidence across confidence-related items, with no consistent reports of decline. Because the end-of-program survey captured perceived change relative to program entry, these findings reflect subjective evaluations of confidence development rather than absolute measures of confidence. Differences by role were evident, with graduate mentors more frequently reporting stability alongside targeted gains in leadership domains, and undergraduate mentees more often reporting increased confidence in academic communication and research engagement. Qualitative responses further suggest that near-peer mentoring may support confidence development by reducing intimidation, normalizing early uncertainty, and providing opportunities for practice and feedback within a structured research environment.

4.3.2. INCLUSIVITY AND SENSE OF BELONGING

While E-SEARCH was not designed specifically as a diversity-focused initiative, participants' reflections revealed that structured, peer-based mentorship was associated with a sense of belonging and inclusivity that may support students from a range of backgrounds and experiences. Prior work has shown that mentoring relationships can support inclusion by shaping how norms, expectations, and pathways are communicated within academic communities. Shanahan and Doyle-Kent (2023) describe mentoring as a relational process through which mentees integrate disciplinary knowledge with observed practices and professional identity formation (Shanahan & Doyle-Kent, 2023). Similarly, Haeger et al. (2016) emphasize that socioemotional and culturally relevant mentoring can strengthen learning environments by validating students' experiences and reducing feelings of isolation (Haeger & Fresquez, 2016).

Consistent with the literature, responses from E-SEARCH participants suggest that near-peer mentorship functioned as a relational practice that normalized learning through dialogue and collaboration. It also reinforced mentors' awareness of how their guidance practices shape inclusive research spaces. In this context, mentors' contributions to inclusion are understood primarily in terms of how their existing practices supported inclusive research environments, rather than as evidence of broad changes in mentors' own inclusivity-related skills or orientations.

Research across disciplines has shown that students' sense of belonging is closely tied to persistence in academic programs, particularly in contexts where support is mediated through peer and near-peer relationships. Students who perceive themselves as valued members of their academic communities demonstrate stronger motivation, greater psychological well-being, and higher rates of retention (Barry et al., 2018; Lorenzetti et al., 2019). Conversely, a lack of belonging or poor advising quality increases the risk of disengagement and attrition (Ehrenberg et al., 2007). Peer-mentorship programs are particularly effective in addressing these challenges by providing reciprocal support and shared understanding among students navigating similar barriers (Bhatia & Amati, 2010; Lorenzetti et al., 2019). In this way, peer mentorship can function as a mechanism of inclusivity, creating networks of affirmation and shared growth that allow individuals from a wide range of backgrounds to find common ground and succeed within academic spaces.

Participant reflections from the E-SEARCH mentorship program echoed many of the patterns identified in the literature, indicating that participation in structured near-peer mentoring was associated with increased feelings of belonging and connection within research environments. Survey responses showed that both mentors and mentees reported a stronger sense of connection to the academic community over the course of the program. Mentees frequently described feeling

less intimidated by research settings and more comfortable engaging with faculty and peers, while mentors emphasized the satisfaction of contributing to a supportive and collaborative learning space. Participants attributed these experiences to concrete program features, including regular check-ins, open communication, and sustained mentor-mentee interaction. This pattern was most evident in responses from mentees who reported limited prior research experience, who more frequently described feeling less intimidated by research environments and more comfortable asking questions and engaging with faculty and peers over the course of the program.

To examine inclusivity and belonging within the E-SEARCH program, survey items were grouped thematically based on established dimensions of academic belonging identified in the literature, including comfort in research environments, ease of communication with mentors and peers, and perceived support within the academic community. Items selected for this analysis focused on participants' sense of connection, confidence in interpersonal academic interactions, and perceived inclusion within research spaces. A full list of survey questions and their thematic groupings is provided in the Appendix. Quantitatively, belonging-related survey items—such as “I feel like I belong in research settings,” “I can comfortably communicate with mentors and peers,” and “I feel supported by my academic community”—showed moderate to high increases across matched responses. Mentees, in particular, reported greater comfort interacting with mentors and initiating academic conversations; while pre- and post-survey items differed slightly in framing, shifts from anticipated comfort to reported experience consistently indicated increased ease in initiating and sustaining academic interactions. Mentors also reported changes in how they engaged with mentees, including increased attentiveness to communication and support needs. These results suggest that participation in structured peer mentorship was associated with

increased comfort and connection for mentees, alongside shifts in how mentors described their communication and support practices.

End-of-program survey responses indicated that both graduate mentors reported moderate to high levels of interpersonal and inclusion-related skills at the conclusion of E-SEARCH. On the mentor skill indicators (Q3), which asked respondents to self-assess their current level (beginning, intermediate, advanced), both mentors reported intermediate or advanced proficiency across most items. Change over the course of the program was limited and item-specific: one mentor reported moving from intermediate to advanced in asking for clarification during discussions, while all other skill ratings remained stable.

Comfort-level items related to inclusive practices (Q4) similarly reflected stability rather than broad change. Both mentors reported being comfortable or very comfortable considering different points of view, while one mentor indicated increased comfort addressing issues of discrimination when they arise. Given the small number of mentors and the program's primary focus on mentee development rather than mentor training, limited movement across these items is not unexpected. On the end-of-program belonging scale (Q6), both mentors selected "agree" for all statements related to belonging in research spaces and effectiveness as inclusive mentors. Because these items were not paired with a directly comparable pre-program measure, these responses are interpreted as indicators of perceived belonging at program end rather than as evidence of change. Qualitative reflections aligned with these patterns, with mentors describing empathy towards mentees, confidence in their mentoring role, and appreciation for diverse experiences encountered throughout the program. Collectively, these results suggest that E-SEARCH provided a supportive mentoring context that appeared to maintain mentors' sense of

belonging and supported inclusive interpersonal engagement, rather than producing large shifts in mentor-reported skills.

Mentee responses emphasized the experiential impact of E-SEARCH on inclusion and comfort within research environments. Post-program survey items (Q3) asked mentees to assess their current skill level relative to when they began the program, and participants reported moderate to high perceived improvement across items related to communicating across differences, clarifying expectations and providing and receiving feedback. Because these items combined retrospective comparison with current self-assessment, results are interpreted as perceived development rather than as directly measured pre-post change. Comfort engaging with individuals from diverse backgrounds (Q3) was consistently high across the program, with mentees reporting comfort or strong comfort at both survey points, suggesting that E-SEARCH maintained rather than substantially altered this dimension. On the belonging-related items (Q6), mentees generally agreed that they felt welcomed and supported within their research environments. While not all items within this set map cleanly onto belonging—for example, “E-SEARCH helped me become a better mentee” reflects perceived role development rather than inclusion—responses collectively indicate that mentees experienced the program as supportive and affirming. Qualitative reflections aligned with these findings, emphasizing the relational and structural aspects of mentorship. One mentee described how being introduced to members of their mentor's lab provided exposure to research environments they had not previously experienced, helping make research feel “not as intimidating” (Appendix, End-of-program survey, Q7-Mentee 3). Another mentee emphasized that having a mentor walk them through research tasks and share their own experiences reduced discomfort associated with being new to research (Appendix, End-of-program survey, Q5.5-Mentee 2). The same mentee also noted that interacting with other

participants helped normalize feelings of nervousness, reinforcing that uncertainty was a shared experience rather than an individual shortcoming (Appendix, end-of-program survey, Q5.5-Mentee 2).

Collectively, these comments demonstrate that E-SEARCH's peer-based structure appears to have fostered inclusion by reducing social distance, encouraging collaboration, and cultivating an environment where participants could belong authentically—not only as researchers, but as members of a supportive academic network. Building on these findings, the next section explores how such experiences of belonging intersect with participants' motivation and engagement in research activities.

4.3.3. RETENTION AND MOTIVATION

Motivation is a critical factor in students' engagement with research, particularly during early and exploratory phases when expectations are still forming and confidence is fragile. While long-term persistence in doctoral programs is strongly shaped by faculty advising and institutional structures (Ehrenberg et al., 2007), research also indicates that students' day-to-day motivation is shaped by their immediate learning environments, access to support, and sense of progress and recognition (Barry et al., 2018; Brill et al., 2014). Peer-based mentorship programs do not replace formal advising or supervision, but they may play a complementary role by providing consistent encouragement, informal guidance, and opportunities for validation outside hierarchical advisor-advisee relationships. In the context of E-SEARCH, motivation is examined not as degree persistence or program completion, but as participants' enthusiasm for research, willingness to engage with challenges, and sustained interest in developing as researchers. The following section explores how involvement in E-SEARCH influenced students' motivation and engagement with

research activities, drawing on survey responses and qualitative reflections from both mentees and mentors.

Structured peer-based mentorship programs may play an important complementary role in supporting student motivation, particularly in contexts where access to consistent developmental mentoring is limited. By countering isolation, normalizing uncertainty, and providing regular relational support, these programs can help sustain engagement during early research experiences. In a systematic review focused primarily on mentee outcomes, Lorenzetti et al. (2019) reported that peer mentorship increased self-confidence and motivated degree completion in 51% of studies, alleviated isolation in 29%, supported persistence in coursework or research engagement in 18% while also building career-relevant competencies in 67% of cases (Lorenzetti et al., 2019). Complementing this work, Haeger et al. (2016) found that undergraduate mentees who participated in mentored research experiences demonstrated stronger academic performance and engagement than matched peers (Haeger & Fresquez, 2016). The authors attribute these outcomes not only to research participation itself, but to the presence of instrumental, socioemotional, and culturally relevant mentoring practices embedded within those experiences, highlighting the role of relational support in sustaining student development (Haeger & Fresquez, 2016).

For students from groups historically underrepresented in STEM, including women in engineering, access to peer networks and visible near-peer role models has been shown to mitigate isolation and limited access to support within male-dominated academic environments (Bhatia & Amati, 2010). Through regular interaction, shared experience, and guided participation in academic communities, mentorship has been described as a key mechanism for professional socialization and identity formation among mentees (Shanahan & Doyle-Kent, 2023). Intentional mentoring practices—such as consistent check-ins, explicit expectation-setting, open discussion

of challenges, and validation of diverse pathways—have been shown to shape students’ perceptions of belonging, clarity, and support within mentoring relationships (Stuchiner et al., 2022). Taken together, this literature suggests that faculty advising plays a central role in academic progression, while structured and peer-based mentorship programs may offer complementary relational support that helps students remain engaged when advising relationships are inconsistent or limited. Notably, much of this literature focuses primarily on mentee outcomes, with comparatively limited attention to how serving in mentoring roles shapes graduate students’ motivation or engagement—an area to which the E-SEARCH study contributes additional perspective.

Within E-SEARCH, mentee reflections highlighted the role of mentorship in shaping how participants experienced moments of uncertainty and support during the program. One mentee described initially feeling uncomfortable due to a lack of prior research experience and noted that having a mentor “walk me through it and share their own experiences” helped normalize those feelings (Appendix, end-of-program survey, Q5.5-Mentee 2). Another mentee similarly reflected that exposure to research through the program made the process feel “not as intimidating as I thought,” emphasizing the value of guided participation and reassurance (Appendix, end-of-program survey, Q7-Mentee 3). Mentees also described the importance of peer interaction in reducing isolation. One participant noted that speaking with other mentees and learning that they were “also nervous” was relieving, reinforcing a sense of shared experience during the program (Appendix, end-of-program survey, Q5.5- Mentee 2). Mentees identified opportunities to engage directly in research, receive guidance from graduate mentors, and present their work as the most valuable aspects of the E-SEARCH experience (Appendix, end-of-program survey Q7-Mentees). Graduate mentor reflections, though more limited in number, also suggested motivational benefits

associated with the mentoring role. The mentors who provided qualitative feedback described observing increased confidence in their mentees over the course of the program (Appendix, End-of-program survey, Q5.3 – Mentor 1 & 2). In separate reflections focused on their own experience, a mentor also noted that working with a mentee increased their confidence in taking on leadership and mentoring roles (Appendix, End-of-program survey, Q2.2 – Mentor 2). Although based on a small number of responses, these accounts suggest that mentorship may operate reciprocally, providing reassurance and structure for mentees while also reinforcing mentors' connection to the academic community.

In addition to these reciprocal mentor–mentee dynamics, mentors' own persistence-related confidence provides further insight into how the mentoring role was experienced within E-SEARCH. Among graduate mentors, end-of-program responses indicated high levels of confidence related to persistence and academic continuity, suggesting a strong baseline of self-efficacy at the conclusion of E-SEARCH. On items assessing confidence in staying motivated, persisting through challenges, and completing degree requirements (Appendix, End-of-Program survey, Q2), mentors reported being confident or very confident, reflecting perceived readiness to navigate academic demands. Because these items were framed as post-program self-assessments rather than paired pre-post measures, results are interpreted as indicators of mentor confidence at program end rather than evidence of change over time. Qualitative reflections provided additional context for how mentors experienced motivation during the program. One mentor reflected that “working with my mentee made me more confident answering questions and taking a leadership role in guiding other people’s research,” (Appendix, End-of-program survey, Q2.2 – Mentor 2). The same mentor described developing mentoring skills through the process, noting that “I learned how to determine a mentee’s strengths and encourage him to pursue related tasks while helping

him build confidence with new skills” (Appendix, end-of-program survey, Q1.1 – Mentor 2). These reflections suggest that serving as a mentor within E-SEARCH may have reinforced mentors’ leadership confidence and sense of purpose within the mentoring relationship, even in the absence of large measurable shifts in overall confidence.

For mentees, motivational experiences associated with mentorship were more varied and more explicitly articulated in qualitative responses. On persistence-related survey items assessing confidence in staying motivated, persisting through challenges, and continuing academic work despite setbacks, mentees generally reported moderate to high confidence by the end of the program. Because these items combined retrospective comparison with current self-assessment, results are interpreted as perceived persistence-related confidence rather than as directly measured pre-post change. Mentees’ open-ended responses provided clearer insight into how mentorship shaped motivation during periods of uncertainty. One student who began the program unsure about approaching professors reflected that the experience “made research less intimidating” and left her “better prepared to do similar things in the future” (Appendix, end-of-program survey, Q7 – Mentee). Another mentee described E-SEARCH as helping him “navigate research needs and stay motivated even when [they] felt stuck,” while a third participant reflected that “doing research alongside my mentor gave me the push I needed to stay on track” (Appendix, end-of-program survey, Q7). These comments suggest that mentorship supported persistence by reducing intimidation, providing structure, and offering encouragement during challenging moments. Importantly, one mentee reported a decrease in motivation, explaining that participation in the program helped them realize that research was not their preferred career path, leaving them feeling less confident about continuing in research. Rather than indicating program failure, this response reflects mentorship’s role in supporting informed academic decision-making. In this context,

persistence is understood not simply as continued participation in research, but as sustained engagement with intentional academic pathways—whether that involves continuing in research or redirecting goals based on clarified interests. This framing aligns with prior work showing that mentored undergraduate research experiences are associated with stronger engagement and continued participation in research activities and related academic pathways (Haeger & Fresquez, 2016).

Across measures of confidence, belonging and motivation participants' responses point to structured mentorship as a relational feature of the research experience rather than a single outcome-driven intervention. Mentors and mentees described how regular interaction, shared research activities, and ongoing communication helped reduce uncertainty, made challenges feel more manageable, and supported engagement across different stages of training. Within this context, mentorship appeared to shape how participants experienced research environments by providing continuity, guidance, and interpersonal connection. Rather than eliminating challenges, these relationships helped participants navigate them more confidently, clarifying their goals and supporting continued engagement in academic communities over the course of the program.

4.4 SUMMARY AND CONCLUSION

This case study suggests that structured, peer-based mentorship has the potential to support key dimensions of student development across multiple stages of the academic pathway, including confidence, sense of belonging and motivation to engage in research and advanced study. Within the E-SEARCH program, mentorship was intentional in the sense that it was deliberately designed rather than informal or incidental: mentors and mentees were purposefully matched, expectations for engagement were articulated, and regular check-ins and shared activities were built into the program structure. While substantial literature has examined graduate school retention and

persistence, far less attention has been paid to how relatively small-scale, relational interventions may shape students' day-to-day experiences once enrolled. The findings from E-SEARCH contribute to this body of work by illustrating how even short-term, peer-based mentorship initiatives can generate meaningful socioemotional and academic benefits for participants, complementing—rather than replacing—formal advising structures.

Although the matched survey sample was limited, patterns across beginning- and end-of-program responses suggest that participation in E-SEARCH may support students' perceived confidence in research-related skills, strengthen their sense of belonging within engineering and research communities, and reinforce motivation to continue research or pursue graduate education. These trends align with prior research underscoring the role of mentoring relationships in fostering persistence in STEM fields, particularly for students who may lack access to consistent, empathetic, or developmentally oriented advising (Haeger & Fresquez, 2016; Lorenzetti et al., 2019). Importantly, these findings highlight that mentoring does not need to originate exclusively from a single formal advisor-advisee relationship. Rather, peer mentors, near-peer mentors, and community-based mentors—such as graduate students, postdoctoral researchers, or cross-departmental peers engaged through structured programs—can collectively form mentoring networks that provide complementary forms of support. Such networks distribute guidance, accountability, and encouragement across multiple relationships, reducing reliance on any one advisor and providing more frequent and accessible points of connection. This networked approach to mentoring underscores the value of structured, group-based advising and community-centered mentorship models that extend beyond traditional milestones, supporting students' day-to-day engagement and resilience within graduate education.

This study was guided by an action-oriented, reflective approach to program evaluation rather than a fully completed action research cycle. In this initial phase, participant feedback was used to observe and interpret how structured peer mentorship was experienced, with particular attention to factors shaping confidence, belonging, and motivation. Responses highlighted the importance of clear expectations, consistent communication, and opportunities for authentic relationship-building as central components of the E-SEARCH experience. Within an action research framework, these findings represent the reflect and observe stages of an iterative process, generating insights that can inform future planning and refinement rather than constituting a finalized intervention. Incorporating participant-identified priorities—such as clearer role definition, more consistent engagement structures, and expanded opportunities for peer interaction—offers a concrete pathway for strengthening future iterations of E-SEARCH. As with any small, exploratory case study, the results presented here are preliminary. The limited number of matched survey responses constrains the generalizability and highlights the need for improved participant retention and more robust data collection in future cycles. Subsequent research could benefit from higher response rates, more systemic qualitative interviews, and repeated program implementation to assess how refinements influence mentor and mentee experiences over time. Nonetheless, the patterns identified in this initial cycle provide early evidence that structured mentorship programs like E-SEARCH may support confidence, inclusion, and persistence-related experiences among both undergraduate mentees and graduate mentors.

More broadly, this study reinforces the need for graduate education models that prioritize holistic mentorship—models that recognize students not only as researchers, but as individuals navigating complex personal, academic, and socioemotional landscapes. For students who may not have access to consistent, empathetic or developmentally oriented advising relationships,

structured peer-based programs like E-SEARCH can serve as meaningful sources of support, affirmation and connection. E-SEARCH functioned as an equity-oriented intervention in this context not by targeting specific demographic groups, but by intentionally lowering barriers to participation, normalizing uncertainty, and providing accessible near-peer mentoring relationships that validated diverse pathways into research and graduate education. At the same time, E-SEARCH required coordination, time, and modest financial resources, raising important questions about scalability and sustainability across institutional contexts.

While the full E-SEARCH model may not be feasible everywhere, the findings suggest that its core elements—structured mentor-mentee matching, clear expectations for engagement, and regular opportunities for peer interaction—may be adaptable in lower-cost or less formal formats. For example, structured peer check-ins, cohort-based mentoring spaces, or facilitated connections between undergraduates and graduate researchers within existing labs or programs may provide similar relational benefits without the need for extensive funding or centralized coordination. In this way, E-SEARCH offers insight not only into the value of formal mentorship programs, but also into how intentional structure can strengthen and legitimize informal mentoring networks that already play a critical role in supporting undergraduates and graduate students in research settings. The results of this case study highlight the potential of peer-based mentorship to benefit both mentees and mentors by fostering confidence, belonging, and sustained engagement within academic communities—core elements of success in graduate education.

4.5 LIMITATIONS AND REFLECTION

Reflecting on the design and implementation of this study, several opportunities for improvement emerged that would strengthen future iterations of both the E-SEARCH program and its evaluation. Participant recruitment and retention within the study itself could be enhanced

through clearer communication about the purpose of the surveys, more consistent reminders, and integration of data collection into existing program activities rather than relying on optional, stand-alone surveys. Embedding evaluation more fully within the program structure may help reduce attrition across pre- and post-survey responses and yield more robust matched data.

Survey design would benefit from greater alignment between pre- and post-program instruments. In particular, several items combined retrospective comparison with current self-assessment, which limited the ability to interpret changes over time. Future studies would prioritize fully paired questions with consistent wording and response scales to enable clearer comparison, while still retaining open-ended prompts that capture participants' reflective experiences.

An additional limitation of the present study relates to the depth of qualitative feedback obtained from graduate mentors. While mentors reported consistently high confidence across persistence- and skill-related survey items, these measures showed limited variation over the course of the program. As a result, quantitative indicators alone provided relatively little insight into how mentors experienced growth, challenge, or change through their participation. Greater emphasis on mentor-specific qualitative data—such as targeted open-ended prompts or follow-up interviews—would have allowed for richer interpretation of these stable survey patterns and a more nuanced understanding of how mentoring roles influence mentors' motivation, leadership development, and professional identity. In future iterations, intentionally designing data collection to elicit mentors' reflective perspectives would help balance the evidentiary weight between mentee and mentor experiences and more fully capture the reciprocal dimensions of peer-based mentorship.

Incorporating additional qualitative methods—such as semi-structured interviews or facilitated reflection sessions—would allow for deeper exploration of how participants interpret

confidence, belonging, and motivation within mentoring relationships. These approaches could also clarify how mentoring experiences influence mentors and mentees differently over time. Together, these refinements would strengthen the methodological rigor of future studies while remaining consistent with the action-oriented, reflective framework that guided this initial evaluation. These reflections represent the foundation for a subsequent action research cycle, in which program refinements and evaluation strategies would be iteratively tested and reassessed.

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4.7 Appendix for Chapter 3: Graduate mentorship

E-SEARCH Mentor/Mentee evaluation - Beginning

Highlights are for question themes

CONFIDENCE

INCLUSIVITY

RETENTION

Start of Block: Default Question Block

Start of Block: Default Question Block

Q0 Welcome to the E-SEARCH mentorship program! On behalf of the College of Engineering (COE) and E-SEARCH, we are gathering information from the E-SEARCH mentor and mentee students about their experiences in the E-SEARCH program before, during and after participation. You are being invited to join a research study. The purpose of this study is to evaluate the impact of graduate mentorship programs on diversity, self-confidence, and retention in graduate education. If you agree to participate, you will be asked to complete a survey about your experiences in the E-SEARCH mentorship program. It will take less than 10 minutes to complete the survey. There is no direct benefit to you from taking part in this study. However, your participation may contribute to improving mentorship programs for future graduate and undergraduate students. The risks of this research are minimal. Some of the questions might make you feel uncomfortable or upset. You do not have to answer any of the questions you do not want to answer. Please note that, even though the survey asks for personally identifying information (name, student ID, email), we will keep individual students' responses confidential. Analyses of the data will not include individually identifying information, and reports will only include aggregate results. If you have questions about this survey, please contact Elise Palombella directly at espalombella@ucdavis.edu.

Q0.1 Title of study: Evaluating Graduate Mentorship in Engineering Fields: An Action Research approach **Investigator:** Elise Palombella, PhD Candidate espalombella@ucdavis.edu **Confidentiality** As with all research, there is a chance that confidentiality could be compromised; however, we are taking precautions to minimize this risk. Your responses to the survey and questions will include information that identifies you. This identifiable information will be handled as confidentially as possible. However, individuals from UC Davis who oversee research may access your data during audits or other monitoring activities. To minimize the risks of breach of confidentiality, we will: *Store all responses in a password-protected database Remove identifying information from survey responses Destroy all identifier information within six months of data collection.* **Your responses will remain confidential to the extent permitted by law.** We will use your information to conduct this study. Leftover data collected for this research may also be used for future research studies. We will not share any personally identifiable information. Our goal is to make more research possible. These studies may be done by researchers at this institution or other institutions. Data may be placed in one or more external scientific databases for access and use. We will not ask you for additional permission to share de-identified information. **Compensation** You will not be paid for taking part in this study. **Rights** *Taking part in research is completely voluntary.* You are free to decline to take part in the project. You can decline to answer any questions, and you can stop taking part in the project at any time. Whether or not you choose to take part, or answer any question, or stop taking part in the project, there will be no penalty to you or loss of benefits to which you are otherwise entitled. **Questions** If you have any questions about this research, or you believe that you've been injured or harmed as a participant of this research, please contact the investigator at espalombella@ucdavis.edu. If you have any questions about your rights or treatment as a research participant in this study, please contact the UC Davis, Institutional Review Board by phone: (916) 703 9158 or by email: HS-IRBEducation@ucdavis.edu. **If you agree to take part in the research, please enter your name below.**

Q3 Enter your name here to indicate your consent.

Page Break

Q1 What are you most hoping to gain from participating in E-SEARCH? (Check all that apply)

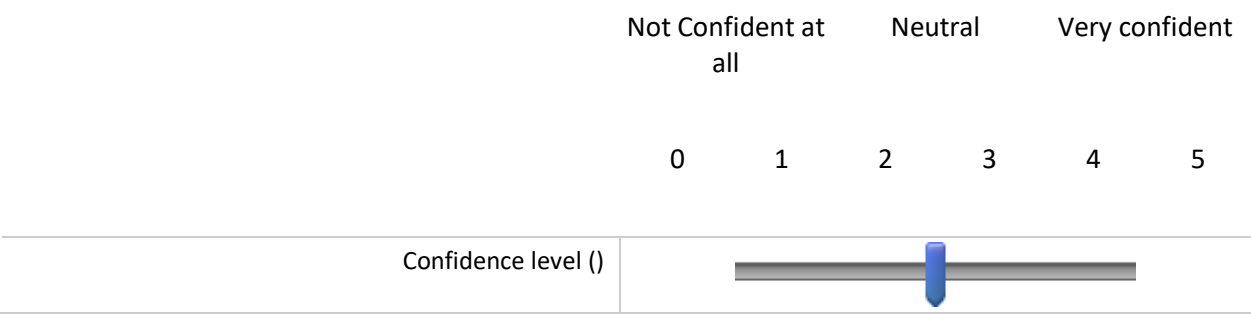
- ☐ Build confidence in discussing and presenting research (1)
- ☐ Gain experience in academic writing (abstracts, etc) (2)
- ☐ Develop technical skills related to research (3)
- ☐ Learn how to navigate academia and research culture (4)
- ☐ Connect with mentors who understand my background and experiences (5)
- ☐ Other (please specify) (6)

Display this question:

If What are you most hoping to gain from participating in E-SEARCH? (Check all that apply) = Other (please specify)

Q1.1 If you answered "other" in the last question, please specify below.

Q2 How confident are you in your ability to complete a research poster and abstract by the end of E-SEARCH?



Page Break

Q3 Please indicate your confidence levels in completing or doing the following tasks. **In (undergraduate or graduate) school, I have the ability to:**

	Very unconfident (1)	Unconfident (2)	Neutral (3)	Confident (4)	Very Confident (5)
Use critical thinking to solve problems (2)	☐	☐	☐	☐	☐
Stay motivated throughout (graduate) school (3)	☐	☐	☐	☐	☐
Persist in (graduate) school even if I fail one class (5)	☐	☐	☐	☐	☐
Successfully pass my exams (6)	☐	☐	☐	☐	☐
Manage my time effectively enough to maintain a high GPA (7)	☐	☐	☐	☐	☐
Build relationships with peers, mentors and others outside of my current network (9)	☐	☐	☐	☐	☐
Obtain my ideal job after graduating (10)	☐	☐	☐	☐	☐
Complete my degree despite challenges that may arise (11)	☐	☐	☐	☐	☐
Meet one-on-one with a professor multiple times per week (13)	☐	☐	☐	☐	☐
Ask a professor or peer to mentor me (14)	☐	☐	☐	☐	☐

Make a significant contribution to a conversation with a group of professors (15)

☐ ☐ ☐ ☐ ☐

Introduce myself to a prominent or important person (17)

☐ ☐ ☐ ☐ ☐

Seek out and obtain help from a professor (18)

☐ ☐ ☐ ☐ ☐

Approach a group of people I don't know and introduce myself to them (20)

☐ ☐ ☐ ☐ ☐

Participate in extra-curricular activities (21)

☐ ☐ ☐ ☐ ☐

Hold a leadership position in a professional or campus organization (22)

☐ ☐ ☐ ☐ ☐

Presenting research in an academic setting (4)

☐ ☐ ☐ ☐ ☐

Display this question:

If Please indicate your confidence levels in completing or doing the following tasks. In (undergradu... = Very unconfident

Or Please indicate your confidence levels in completing or doing the following tasks. In (undergradu... = Unconfident

Q3.1 Please explain what prompted you to select "Very Unconfident" or "Unconfident" above. (Choose 1 or 2 tasks if multiple)

Page Break

Q4 Please select the choice which best represents **your current skill level** for each of the following.

	Beginning (1)	Intermediate (2)	Advanced (3)	Not Applicable (4)
Balancing academic and personal responsibilities (2)	☐	☐	☐	☐
Communicating with people from different backgrounds (3)	☐	☐	☐	☐
Setting goals for learning or research (4)	☐	☐	☐	☐
Asking for clarification about goals and expectations (7)	☐	☐	☐	☐
Accepting constructive feedback (8)	☐	☐	☐	☐

Display this question:

If Please select the choice which best represents your current skill level for each of the following. = Beginning

Q4.1 What resources would help you develop your skill level for the item(s) marked "beginner" above?
(Select all that apply)

☐

Having a trusted mentor (1)

☐

Serving as a mentor to someone else (2)

☐

Practicing the skill with others (3)

☐

Practicing the skill alone (4)

☐

Asking for help from peers (5)

☐

Asking for help from a mentor (6)

☐

Asking for help from a professor (7)

Page Break

Q5 Please select the choice which represents **your current level of comfort** with each of the following.

	Very uncomfortable (1)	Uncomfortable (2)	Comfortable (3)	Very comfortable (4)	Not applicable (5)
Making an effort to get to know people from diverse cultural, spiritual or personal backgrounds (1)	☐	☐	☐	☐	☐
Considering different points of view (2)	☐	☐	☐	☐	☐
Addressing issues of discrimination when they arise (5)	☐	☐	☐	☐	☐
Reflecting on your own perspectives, including potential biases (9)	☐	☐	☐	☐	☐
Engaging in meaningful conversations with individuals of different backgrounds (6)	☐	☐	☐	☐	☐

Display this question:

If Please select the choice which represents your current level of comfort with each of the following. = Very uncomfortable

Or Please select the choice which represents your current level of comfort with each of the following. = Uncomfortable

Q5.1 Please explain what prompted you to select "Very uncomfortable" or "Uncomfortable" above.
(Choose 1 or 2 if multiple)

Q6 How often have you received direct mentorship from a graduate student, peer or professor before E-SEARCH?

- ☐ Never (1)
- ☐ A few informal conversations (2)
- ☐ Structured mentorship (e.g. research assistantship, formal program, etc) (3)

Q7 In what ways do you think access to resources impact students' experiences in research?

Q8 What factors—whether personal, academic or program-related—might make it harder for you to fully participate in or benefit from this program?

End of Block: Default Question Block

Start of Block: Block 1

Q9 Please provide your contact information.

NOTE: Analyses of the data will not include individually identifying information, and reports will only include aggregate results.

☐ First Name (1) _____

☐ Legal Last Name (2) _____

End of Block: Block 1

Beginning-of-program Participant Responses **MENTOR**/**MENTEE**

Q1.1 if you answered “other” in the last question, please specify below.

“To receive advice from my mentor on the graduate school application” – Mentee 1

“getting experience being a mentor” – Mentor 3

“learn mentorship skills” – Mentor 6

“gain mentorship experience”

“impart soft and technical skills, experience mentoring, get some assistance for lab work requiring more than 2 hands” – Mentor 1

“I’d like to gain experience supervising the development and execution of a research project in collaboration with my mentee. I don’t have much experience with project management outside of my own research, and I look forward to developing soft skills associated with helping someone else set goals and manage their time” – Mentor 5

Q3.1 Please explain what prompted you to select “Very unconfident or “Unconfident” above

“I think I have some imposter syndrome especially since I do not see a lot of people like me in my field. So it makes it difficult for me to feel like I can be successful on my own” – Mentor 2

“I don’t have good self esteem and I have social anxiety, so interpersonal things are challenging for me especially for the first time” – Mentee 6

“I don’t feel confident talking to my professors one on one such as in office hours. Although I’ve always been interested in undergraduate research, I’m always too shy to ask my professors about research opportunities” – Mentee 2

“the job market for a computer science role is very bad at this moment, so I am not confident in finding my ideal job. I am also not very confident in talking to professors outside of class” – Mentee 4

“One of my best friends died almost a year ago and it greatly affected my mental health and put me through an existential crisis where I don’t know what I want to do anymore since every engineering job out there feels like it somehow relates to supporting weapons manufacturing,

either directly through the design process or indirectly by data published for entirely different research. I am not confident in graduating or finding a 'dream job' since it doesn't feel like any jobs exist that don't harm people or the planet." – Mentor 1

"My lack of experience in research and familiarity with the field made me choose unconfident since it would be my first time in those kinds of situations without any previous preparation." – Mentee 3

"In graduate school I imagine the workload to be immense, likely a good bit larger than the workload I have right now, I think that I need to adapt accordingly to be able to build new meaningful relationships entering graduate school." – Mentee 8

Q5.1 Please explain what prompted you to select very uncomfortable or uncomfortable above

"I have a hard time speaking up when I experience injustice" – Mentee 6

"I am non-confrontational and afraid of creating direct conflict, especially when it involves myself, let alone others. I wouldn't defend myself, but might if a friend or someone I care about was being discriminated against" – Mentor 1

"In the case of addressing issues with discrimination, I consider myself someone that has it difficult standing up to what I believe in when I don't have a previous preparation on what I will say and when I feel that my arguments might not be clear to address the issues." – Mentee 3

"I don't know for sure if I would be the type to step up if I felt discriminated against unless it was blatant and I knowingly had support." – Mentee 8

Q7 In what ways do you think access to resources impacts students' experiences?

"It allows them to see what type of research is out there. It also allows them to broaden their scope and understand the interdisciplinary nature of research" – Mentor 2

"Access to resources makes learning faster, deeper, and more effective. It also boosts motivation and confidence in tackling research challenges." – Mentor 4

"Access to resources enhances research by increasing the breadth, depth and overall quality of the students' investigations." – Mentee 1

"It will give them experience and ability to use machines and obtain skills that would otherwise be unable to get. It also will develop skills that they can use in their career" – Mentor 3

“it helps demystify the process and show it as something that anyone can do” – Mentee 6

“students may feel discouraged from pursuing research without adequate resources and mentorship” – Mentee 2

“making resources easily accessible can allow students to progress a lot faster during their research experience” – Mentee 4

“I think that access to resources greatly improves experiences in research. Having upperclassmen and a supportive student advisor has made me much more confident in the decisions I make. Know that I have their support and expertise makes me more willing to put myself out there to try new things” – Mentee 7

“makes little issues easier to deal with, less boundaries” – Mentor 1

“Lack of experience in it might be seen as a problem for some people who are not familiar with the field since it takes them longer to start learning the ropes” – Mentee 3

“I think having limited access to resources likely prevents students from accessing research opportunities at all. As an undergraduate, I was able to connect with graduate students at other universities through a program sponsored by my college (we did not have graduate programs, so my college provided funds for students to spend summers at R1 universities). Without this financial support, it would have been much more difficult to find faculty willing to let me work in their lab, and to gain the lab experience necessary to apply to graduate school. I think that programs such as E-SEARCH or other formalized programs, such as REUs, are indispensable in providing undergraduates with research exposure that they may otherwise not know how/be able to access” – Mentor 5

“I think that the opportunity to explore research is an excellent experience for nearly all students. At the very least allowing students to become aware that these opportunities exist and a soft introduction to the work that goes behind it is something that I have nothing but positive thoughts about.” – Mentee 8

Q8 What factors—whether personal, academic or program-related—might make it harder for you to fully participate in E-SEARCH

“Lack of interaction with other mentors” – Mentor 2

“As a graduate mentor and a teaching and research assistant, I have many responsibilities that can make time management challenging. However, I’m committed to balancing my time because I truly value this program and believe it’s beneficial for both mentors and mentees” – Mentor 4

“none” – Mentee 1

“I just have a lot scheduled this quarter but I am good at time management so I do not see any issues” – Mentor 3

“I am part of sdc so I have an extra hard time with classes and I’m taking 3 upper division engineering classes, so my time and my energy is limited to do stuff beyond that.” – Mentee 6

“Very busy schedule during spring quarter and working full-time during the summer” – Mentee 2

“Class time conflicts, personal emergencies” – Mentee 4

“My biggest obstacle in fully participating in this program is that I have other commitments that require much more of my time” – Mentee 7

“time and energy” – Mentor 1

“if my classes have a heavy load of work and leave no time for it”

“my research schedule is very full, so it’s challenging to find times that my mentee and I are both free to meet” – Mentor 5

“I think that balancing an increasingly large number of responsibilities as I continue my undergraduate experience has always been something that I have had trouble with and always needed to adapt to, but I will nonetheless make my best effort to contribute and get the most out of” – Mentee 8

E-SEARCH Mentor/Mentee evaluation - End

Start of Block: Default Question Block

Start of Block: Default Question Block

Q0 Welcome to the E-SEARCH mentorship program! On behalf of the College of Engineering (COE) and E-SEARCH, we are gathering information from the E-SEARCH mentor and mentee students about their experiences in the E-SEARCH program before, during and after participation. You are being invited to join a research study. The purpose of this study is to evaluate the impact of graduate mentorship programs on diversity, self-confidence, and retention in graduate education. If you agree to participate, you will be asked to complete a survey about your experiences in the E-SEARCH mentorship program. It will take less than 10 minutes to complete the survey. There is no direct benefit to you from taking part in this study. However, your participation may contribute to improving mentorship programs for future graduate and undergraduate students. The risks of this research are minimal. Some of the questions might make you feel uncomfortable or upset. You do not have to answer any of the questions you do not want to answer. Please note that, even though the survey asks for personally identifying information (name, student ID, email), we will keep individual students' responses confidential. Analyses of the data will not include individually identifying information, and reports will

only include aggregate results. If you have questions about this survey, please contact Elise Palombella directly at espalombella@ucdavis.edu.

Page Break

Q0.1 Title of study: Evaluating Graduate Mentorship in Engineering Fields: An Action Research approach **Investigator:** Elise Palombella, PhD Candidate espalombella@ucdavis.edu **Confidentiality** As with all research, there is a chance that confidentiality could be compromised; however, we are taking precautions to minimize this risk. Your responses to the survey and questions will include information that identifies you. This identifiable information will be handled as confidentially as possible. However, individuals from UC Davis who oversee research may access your data during audits or other monitoring activities. To minimize the risks of breach of confidentiality, we will: *Store all responses in a password-protected database Remove identifying information from survey responses Destroy all identifier information within six months of data collection.* **Your responses will remain confidential to the extent permitted by law.** We will use your information to conduct this study. Leftover data collected for this research may also be used for future research studies. We will not share any personally identifiable information. Our goal is to make more research possible. These studies may be done by researchers at this institution or other institutions. Data may be placed in one or more external scientific databases for access and use. We will not ask you for additional permission to share de-identified information. **Compensation** You will not be paid for taking part in this study. **Rights** *Taking part in research is completely voluntary.* You are free to decline to take part in the project. You can decline to answer any questions, and you can stop taking part in the project at any time. Whether or not you choose to take part, or answer any question, or stop taking part in the project, there will be no penalty to you or loss of benefits to which you are otherwise entitled. **Questions** If you have any questions about this research, or you believe that you've been injured or harmed as a participant of this research, please contact the investigator at espalombella@ucdavis.edu. If you have any questions about your rights or treatment as a research participant in this study, please contact the UC Davis, Institutional Review Board by phone: (916) 703 9158 or by email: HS-IRBEducation@ucdavis.edu. **If you agree to take part in the research, please enter your name below.**

Q0.2 Enter your name here to indicate your consent.

Page Break

Q1 What did you gain from participating in E-SEARCH? (Check all that apply)

- ☐ Build confidence in discussing and presenting research (1)
- ☐ Gain experience in academic writing (abstracts, etc) (2)
- ☐ Develop technical skills related to research (3)
- ☐ Learn how to navigate academia and research culture (4)
- ☐ Connect with mentors who understand my background and experiences (5)
- ☐ Other (please specify) (6)

Display this question:

If What did you gain from participating in E-SEARCH? (Check all that apply) = Other (please specify)

Q1.2 If you answered "other" in the last question, please specify below.

Page Break

Q2 Please indicate your confidence levels in completing or doing the following tasks after the E-SEARCH program. **Compared to when I started E-SEARCH, I am (more/less confident) about my ability to do the following tasks:**

	Way less confident (1)	Less confident (2)	Unchanged (3)	More Confident (4)	Way more Confident (5)
Use critical thinking to solve problems	☐	☐	☐	☐	☐
Stay motivated throughout (graduate) school	☐	☐	☐	☐	☐
Persist in graduate school even if I fail one class	☐	☐	☐	☐	☐
Successfully pass my exams	☐	☐	☐	☐	☐
Manage my time effectively enough to maintain a high GPA	☐	☐	☐	☐	☐
Build relationships with peers, mentors and others outside of my current network	☐	☐	☐	☐	☐
Obtain my ideal job after graduating	☐	☐	☐	☐	☐
Complete my degree despite challenges that may arise	☐	☐	☐	☐	☐
Meet one-on-one with a professor multiple times per week	☐	☐	☐	☐	☐
Ask a professor or peer to mentor me	☐	☐	☐	☐	☐

Make a significant contribution to a conversation with a group of professors

☐☐☐☐☐

Introduce myself to a prominent or important person

☐☐☐☐☐

Seek out and obtain help from a professor

☐☐☐☐☐

Approach a group of people I don't know and introduce myself to them

☐☐☐☐☐

Participate in extra-curricular activities

☐☐☐☐☐

Hold a leadership position in a professional or campus organization

☐☐☐☐☐

Presenting research in an academic setting (4)

☐☐☐☐☐

Display this question:

If Please indicate your confidence levels in completing or doing the following tasks after the E-SEA... = Way less confident

Or Please indicate your confidence levels in completing or doing the following tasks after the E-SEA... = Less confident

Q2.2 Please explain what prompted you to select "Way less confident" or "less confident" above. (Select 1 or 2 if multiples)

Display this question:

If Please indicate your confidence levels in completing or doing the following tasks after the E-SEA... = More Confident

Or Please indicate your confidence levels in completing or doing the following tasks after the E-SEA... = Way more Confident

Q2.3 Please explain what prompted you to select "Way more confident" or "more confident" above. (Select 1 or 2 if multiples)

Page Break

Q3 Compared to when you started, please select the choice which best represents **your current skill level** for each of the following.

	Beginning (1)	Intermediate (2)	Advanced (3)	Not Applicable (4)
Balancing academic and personal responsibilities	☐	☐	☐	☐
Communicating with people from different backgrounds	☐	☐	☐	☐
Setting goals for learning	☐	☐	☐	☐
Asking for clarification about goals and expectations	☐	☐	☐	☐
Accepting constructive feedback	☐	☐	☐	☐

Page Break

Q4 After the E-SEARCH program, please select the choice which represents **your current level of comfort** with each of the following.

	Very uncomfortable (1)	Uncomfortable (2)	Comfortable (3)	Very comfortable (4)	Not applicable (5)
Making an effort to get to know people from diverse cultural, spiritual or personal backgrounds	☐	☐	☐	☐	☐
Considering different points of view	☐	☐	☐	☐	☐
Addressing issues of discrimination when they arise	☐	☐	☐	☐	☐
Reflecting on your own perspectives, including potential biases	☐	☐	☐	☐	☐
Engaging in meaningful conversations with individuals of different backgrounds	☐	☐	☐	☐	☐

Display this question:

If After the E-SEARCH program, please select the choice which represents your current level of comfo... = Very uncomfortable

Or After the E-SEARCH program, please select the choice which represents your current level of comfo... = Uncomfortable

Q4.2 Please explain what prompted you to select "Very uncomfortable" or "Uncomfortable" above.
(Select 1 or 2 if multiples)

Page Break

Q5 Are you a mentor or mentee?

☐ Mentor (1)

☐ Mentee (2)

☐ Neither (3)

Page Break

Display this question:

If Are you a mentor or mentee? = Mentor

Q5.2 For mentors: How well did your mentee engage with the research process? (1 - Not engaged, 5 - highly engaged)

0 1 2 3 4 5

Engagement with the research process ()



Display this question:

If Are you a mentor or mentee? = Mentor

Q5.3 Did you notice changes in your mentee's confidence or sense of belonging over the course of the program?

Display this question:

If Are you a mentor or mentee? = Mentee

Q5.4 For mentees: how well did your mentor support you in navigating academic challenges? (1 - Not helpful, 5 - Extremely helpful)

0 1 2 3 4 5

Click to write Choice 1 ()



Display this question:

If Are you a mentor or mentee? = Mentee

Q5.5 For mentees: did participating in E-SEARCH make you feel more like you belong in research spaces?
Why or why not?

Page Break

Q6 E-SEARCH helped me do the following:

	Strongly disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
Feel a sense of belonging in research spaces	☐	☐	☐	☐	☐
Be more inclusive	☐	☐	☐	☐	☐
Be a better mentor or mentee	☐	☐	☐	☐	☐

Page Break

Q7 What part of the E-SEARCH mentorship program was the most valuable to you?

Page Break

Q8 What can be improved to make the program more supportive or inclusive? Any other suggestions?

End of Block: Default Question Block

Start of Block: Block 1

Q9 Please provide your contact information.

NOTE: Analyses of the data will not include individually identifying information, and reports will only include aggregate results.

☐ First Name (1) _____

☐ Legal Last Name (2) _____

End of Block: Block 1

End-of-Program Participant responses **MENTOR/MENTEE**

Q1.1 if you answered “other” in the last question, please specify below.

“I learned how to determine a mentee’s strengths and encourage him to pursue related tasks while helping him build confidence with new skills” – Mentor 2

Q2.1 Please explain what prompted you to select “way less confident” or “less confident” above

“Realizing that research isn’t my most desired path to go down in the future” – Mentee 3

Q2.2 Please explain what prompted you to select “way more confident” or “more confident” above

“I gained confidence after experiencing these new things for the first time, so now I feel better prepared to do similar things in the future” – Mentee 3

“Working with my mentee made me more confident answering questions and taking a leadership role in guiding other people’s research” – Mentor 2

“(I can’t remember the items I selected and I can’t go back)” – Mentor 1

“I feel the program really helped me to develop research skills” – Mentee 1

“Participating in E-SEARCH gave me more experience and confidence in talking with my peers and mentors, and it marked the first time I presented research.” – Mentee 2

“1. E-SEARCH has allowed me to get out of my comfort zone and challenge myself in unfamiliar fields which was time consuming so it taught me to manage my time and learn to ask for help and learn to learn” – Mentee 4

Q5.3 Did you notice changes in your mentee’s confidence or sense of belonging over the course of the program?

“My mentee was very curious over the whole program and asked lots of questions. He became much more confident discussing our methods and results by the end of the program, and gave

a poster presentation to our lab group. The whole group was impressed with his depth of knowledge, poise, and thoughtful way of answering questions.” – Mentor 2

“I think my mentee was already quite confident in some areas, such as sticking up for her ideas and asking questions until she understood what was being discussed. In other areas such as interpersonally and just being in lab, her confidence did increase after these became more familiar.” – Mentor 1

Q5.5 For mentees: did participating in E-SEARCH make you feel more like you belong in research spaces? Why or why not?

“No, it made me realize this isn’t the path I most desire to take in the future. I did E-SEARCH concurrently with industry work and didn’t have the same passion for research as I did industry work” – Mentee 3

“I feel like I belong in research spaces because I first felt uncomfortable since this would be my first time doing research, and it helped to have a mentor walk me through it and share their own experiences. I also talked with the other mentees and was relieved to know that they were also nervous” – Mentee 2

“Yes because I was exposed to research and academia world” – Mentee 4

Q7 What part of the E-SEARCH mentorship program was the most valuable to you?

“I was able to meet and connect with a lot of people in the lab my mentor introduced me to, and it showed me a perspective of research I had never seen before. It also showed me that doing research wasn’t as intimidating as I thought.” – Mentee 3

“I enjoyed meeting my mentee every week and seeing how his understanding and comfort progressed with every meeting. I hope that the program gave him a positive impression of research and helped him feel more comfortable with the idea of applying to grad school.” – Mentor 2

“Gaining valuable help in the lab with someone dedicated to excellence” – Mentor 1

“Being so flexible with the research needs” – Mentee 1

“The opportunity to conduct research and present it to others. Getting advice from my mentor on how to do research and learning about their own grad school application experience” – Mentee 2

“Completing the project and presenting” – Mentee 4

Q8 What can be improved to make the program more supportive or inclusive?
Any other suggestions?

“The program was well organized and supportive. Alin was very accommodating of our research schedule and summer plans” – Mentor 2

“Since a majority of mentees were looking for projects that used or worked with machine learning, and not all mentors have experience with that, a workshop on machine learning by a knowledgeable graduate student or faculty member would have been useful. This was an area I could not support my mentee and I felt bad to not have any resources” – Mentor 1

“Maybe expand the number and majors of mentees. It seems that this cohort had a lot of Computer science mentees and only a handful of mentors studying computer science” – Mentee 2

“add more diverse group of graduate students” – Mentee 4