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Bubbles, Droplets, Climate: Tellus's Enduring Influence on Sea Spray Aerosol Research

COLLECTION: TELLUS 75TH JUBILEE SPECIAL COLLECTION: CELEBRATING LEGACY AND SHAPING THE FUTURE OF EARTH SYSTEM SCIENCE

PERSPECTIVE

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ABSTRACT

Sea spray aerosol (SSA) is an important aspect of air–sea exchange. It influences atmospheric chemistry, cloud formation, biogeochemical cycling, and the long-range transport of both natural and anthropogenic material. A number of early studies on SSA were published in *Tellus*, including the first direct evidence that bursting bubbles at the ocean surface generate particles. Critically, these fundamental studies, which reach across the fields of bubble physics, interfacial chemistry, and air–sea interaction, initiated decades of subsequent research. In this Perspective article, I outline how the results of these studies have led to today's mechanistic understanding of SSA production. I trace key developments, from the demonstration of jet and film drop formation, through evidence for selective chemical fractionation during bubble bursting, to modern field techniques that link the physical, chemical, and biological drivers of SSA production. I also highlight the emergence of mesocosm systems, advanced analytical methods, and dedicated wave-channel facilities, which have enabled a molecular-level understanding of nascent SSA composition and the transfer of surface-active pollutants. Throughout the article, I explore how insights from the field, rooted in early *Tellus* publications, help frame a number of outstanding challenges. These include quantifying size-resolved SSA emissions in a changing climate, assessing how microbial and biogeochemical processes shape SSA composition and properties, and constraining the climatic relevance of SSA. The latter is particularly pertinent given the increasing interest in marine cloud brightening. By revisiting the trajectory from early *Tellus* studies to present-day research, this contribution underscores the journal's continuing influence on air–sea interaction science and outlines opportunities for future SSA studies.

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When I was invited to write this perspective on *Tellus* and its influence on air–sea interaction research, I felt both a sense of privilege and responsibility. As a researcher who has dedicated the last two decades to this field, I recognise the importance of doing justice to the pioneering studies that established its foundations. Since its inception, *Tellus* has published numerous seminal papers across the broad scope of research defining this field, from the early studies that established the physical foundations of air–sea gas exchange and the ocean's role in regulating atmospheric CO_2 (Bolin, 1960; Broecker and Peng, 1974; Revelle and Suess, 1957) to later advances coupling these insights with biogeochemical and isotopic perspectives on the global carbon cycle (Krakauer et al., 2006).

I am, however, perhaps best known for my work on sea spray aerosol (SSA), and it is here that I will focus this reflection. This focus is fitting, as SSA production is one of the principal pathways through which air–sea exchange occurs: bubbles generated by wave breaking mediate the transfer of gases, heat, and momentum between the ocean and atmosphere, while also scavenging dissolved and particulate material from the surface ocean. When these bubbles burst, they eject droplets that become airborne particles, linking physical hydrodynamics to atmospheric chemistry and ultimately to climate.

In what follows, I revisit how research published in *Tellus* has shaped our understanding of SSA, from the first photographic evidence of bursting bubbles to the evolving recognition of their biogeochemical and climatic significance, and I reflect on how these foundations continue to inform the field's future directions.

1 EARLY FOUNDATIONS: THE JET DROP MECHANISM

Given the breadth of SSA research today, it is easy to overlook how the field began and how pivotal early *Tellus* papers were in defining its direction. More than 150 years have passed since Beck (1819), Sigerson (1870), and Aitken (1881) first suggested that the ocean could itself be a source of atmospheric particles. Their ideas began to gain wider scientific attention only after Jacobs (1937) identified air bubbles as the mechanism capable of producing sea-salt aerosol. By the mid-twentieth century, the prevailing view held that bursting bubbles at the sea surface were the primary source of marine aerosol, but the detailed physics of droplet formation remained unresolved.

This gap was addressed by Kientzler, Arons, Blanchard, and Woodcock (1954) in their landmark *Tellus* paper, *Photographic Investigation of the Projection of Droplets by Bubbles Bursting at a Water Surface*. Using still photographs with ~ 30 μs exposures and high-speed motion pictures (3,000 fps), they captured the collapse of a bubble cavity and the formation of a narrow jet capable of ejecting droplets several diameters above the surface (see Figure 1). Upon evaporation, these droplets yielded salt residues matching the smallest particles observed in marine air (Woodcock, 1952), providing the first direct mechanistic link between bubble bursting and atmospheric sea-salt aerosol.

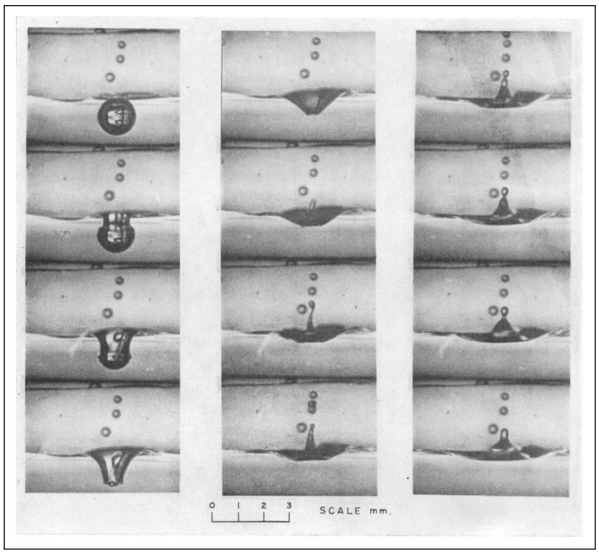

Figure 1 High-speed motion pictures of bubble bursting dynamics, reproduced from Kientzler et al. (1954) under CC BY (https://doi.org/10.3402/tellus.v6i1.8717). Sequence shows 1.5 mm diameter bubbles bursting in fresh water with a clean surface, captured horizontally through a glass microscope slide. The images were taken at 3,340 frames per second, revealing the progressive stages of bubble cavity collapse and jet formation. The stationary droplets visible in the image sequence are droplets adhering to the inner surface of the glass observation window, produced by earlier bubble-bursting events.

Kientzler and colleagues also introduced the empirical "10% rule," which states that the average droplet radius is approximately one-tenth the radius of its parent bubble. This simple geometric relationship took qualitative observations and turned them into a quantitative framework, allowing aerosol fluxes to be estimated from measurable bubble-size distributions. Although later work refined this scaling to account for viscosity, surface tension, and film dynamics, the principle remains fundamental to understanding how bubble-scale dynamics give rise to airborne sea-salt particles (Blanco-Rodríguez and Gordillo, 2020; Wang et al., 2017).

Although Kientzler et al. primarily documented jet-drop formation, subsequent work showed that bursting bubbles also generate film drops during rupture of the bubble cap. Film drops are generally much smaller and more numerous than jet drops and have long been considered the principal source of submicron SSA, although recent work indicates that jet drops can also make a substantial contribution to this size range (e.g., Wang et al., 2017). In contrast, jet drops contribute more strongly to larger particle sizes. The distinction between film and jet drops, established during the formative decades of SSA research and subsequently refined through fluid-mechanical studies, remains central to understanding aerosol size distributions, chemical composition, and emission processes (e.g., Deike, 2022).

2 BEYOND THE JET: EMERGING CHEMICAL AND INTERFACIAL COMPLEXITY

Although the work of Kientzler et al. (1954) established a direct physical mechanism linking bubble bursting to sea-salt aerosol production, it isolated the microphysics of a single bubble from the macroscopic complexity of the open ocean. The next challenge was to understand how bubbles are generated and modified under natural conditions, and how these processes influence the size and properties of the resulting droplets. This broader framework was developed in another seminal *Tellus* paper, Blanchard and Woodcock (1957), *Bubble Formation and Modification in the Sea and Its Meteorological Significance*. Their study extended the mechanistic picture by examining natural bubble-generation processes such as whitecaps, rainfall, and gas supersaturation, and by analysing how bubble dissolution and modification affect the resulting droplet-size distribution (see Figure 2).

Crucially, Blanchard and Woodcock moved beyond a purely physical description to incorporate the chemical and electrical properties of the emitted droplets. They observed that jet drops, often carrying appreciable charge and enriched in biological material, differ fundamentally from film drops, which are smaller, chemically distinct, and typically contain the highest fraction of organic matter. These insights reframed the central problem: the number, size, and composition of airborne sea-salt aerosol are controlled not only by bubble dynamics but also by surface chemistry and biological modification. At the time, these observations were pioneering but not widely appreciated, and their relevance to air–sea exchange became evident only gradually.

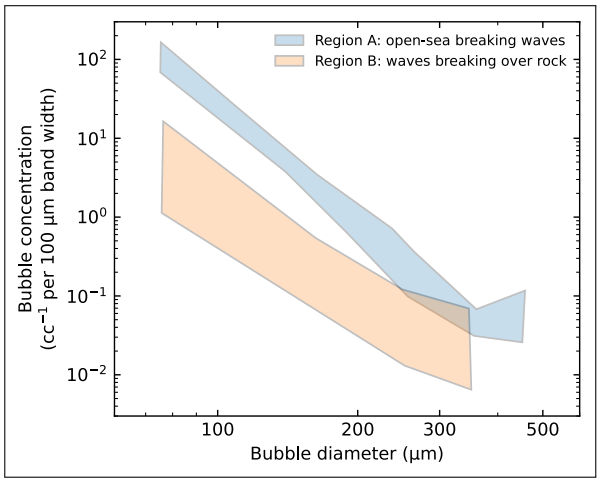

Figure 2 Bubble concentration (cc^{-1} per 100 μm band width) in seawater produced by breaking waves. Shaded regions show bubble concentrations from different wave conditions: breaking waves on the open sea (Region A) and waves breaking over a rock (Region B), demonstrating the variability in bubble production mechanisms. Redrawn from data digitised from Figure 4 of Blanchard and Woodcock (1957) under CC BY (https://doi.org/10.3402/tellus.v9i2.9094).

The broader significance became clearer as it was increasingly realised that droplets ejected from the sea surface contain more than water and salt. As early as the 1940s, Woodcock (1948) reported that respiratory irritation during "red-tide" events was associated with aerosolised material from seawater enriched in dinoflagellates. Despite this early evidence that biological material could be transferred to the atmosphere, the prevailing view still held that SSAs consisted only of salt and water. This perspective shifted with the work of Blanchard and colleagues, who showed through laboratory and field experiments that surface-active organic compounds are efficiently transferred into the atmosphere by bubble bursting (Blanchard, 1963, 1964). Their results revealed a direct chemical and biological connection between the ocean surface and airborne particles, establishing the conceptual basis for a new line of research into the partitioning of specific chemical species across the air–sea interface.

In the following decade, attention turned to "fractionation," the apparent selective enrichment of certain elements and compounds in SSA relative to bulk seawater (Barker and Zeitlin, 1972; Duce and Hoffman, 1976; MacIntyre, 1970). Early studies suggested that bubble bursting might preferentially eject ions such as magnesium, calcium, or potassium, leading to hopes that aerosol composition could provide clues to bubble dynamics and interfacial chemistry (e.g., Komabayasi, 1964). Although later work identified sampling artefacts in many of these observations, the experiments confirmed that bubble bursting is a highly efficient pathway for transferring organic carbon from the ocean to the atmosphere (Barker and Zeitlin, 1972; Duce and Hoffman, 1976; Hoffman and Duce, 1977). As a result, sea spray research expanded beyond its physical roots to include the coupled biogeochemical and chemical processes linking ocean ecology with atmospheric composition and climate.

3 THE WHITECAP ERA: EMPIRICAL PARAMETERISATIONS

By the 1980s, the physical, chemical, and biological complexity of SSA was broadly recognised, but integrating these insights into predictive models remained a major challenge. Building on the hypothesis of Blanchard (1963), that aerosol production scales with whitecap coverage, Monahan and colleagues developed the first empirical SSA source functions based on controlled "whitecap simulation" experiments. Their framework expressed the rate of droplet production as

$$\frac{dF_0}{dr} = W(U)\tau^{-1}\frac{dE}{dr}, \tag{1}$$

where $(W(U))$ is the fraction of the sea surface covered by whitecaps, (τ) is the characteristic whitecap decay time, and (dE/dr) is the differential aerosol productivity of a decaying

whitecap. Whitecap coverage was parameterised as

$$W(U) = 3.84 \times 10^{-6} U^{3.41}, \quad (2)$$

where (U) is the wind speed at 10 m elevation (Monahan, Spiel and Davidson, 1986). This formulation provided a practical means to estimate global SSA emissions from readily available meteorological variables and quickly became the standard approach for representing SSA production in climate models.

The resulting parameterisation, however, was dominated by coarse-mode salt fluxes and thus obscured the smaller, organic-rich particles emphasised in earlier laboratory and field work. By framing SSA production primarily in terms of these larger particles, the Monahan model successfully captured the dominant salt component but not the number distribution that governs aerosol–cloud interactions. The subsequent shift toward number-based source functions and the inclusion of organic enrichment reconnected the modelling framework to the biogeochemical and microphysical processes first explored in *Tellus*.

4 REVISITING THE FINE MODE: ORGANIC ENRICHMENT AND SEASONALITY

By the turn of the century, emerging theoretical and observational approaches revived long-standing questions about the chemical heterogeneity of SSA first posed by Blanchard and colleagues. Two complementary developments transformed our understanding of SSA composition: (1) the development of mechanistic models that explained the microscale processes governing aerosol heterogeneity, and (2) new field and analytical techniques that revealed direct biological modulation of aerosol composition.

On the theoretical front, researchers began to formulate mechanistic explanations for the size-dependent chemical composition of marine aerosols, first hinted at in earlier studies. Oppo et al. (1999) introduced a thermodynamic model in which an organic surface film enriches smaller droplets more strongly than larger ones, while Ellison, Tuck and Vaida (1999) proposed a complementary view of marine aerosol particles as aqueous cores encapsulated by organic surface layers of biological origin. Although simplified, these models provided the first quantitative framework linking microscale interfacial processes to aerosol composition and laid the foundation for later process-based approaches, such as competitive Langmuir adsorption frameworks, that now connect ocean biogeochemistry directly to emission parameterisations (e.g., Burrows et al., 2014).

Simultaneously, advances in field and analytical capability, particularly the combination of long-term coastal monitoring, size-resolved chemical analyses, and satellite chlorophyll-a (Chl-a) correlation, provided detailed observational evidence of biologically modulated aerosol composition (O'Dowd et al., 2004). Measurements at coastal observatories, such as Mace Head, Ireland, showed that submicron SSA contained 60–85% organic matter by mass during periods of high biological activity, with total organic carbon contributing up to 83% in the fine mode (0.06–0.125 μm) compared with the salt-dominated aerosols of winter (O'Dowd et al., 2004). The organic material was largely water-insoluble, indicating a primary, bubble-mediated source linked to the sea-surface microlayer and surface-ocean biology (Facchini et al., 2008). The recognition that organic enrichment is both size-dependent and biologically controlled marked a conceptual reconvergence between the physical "whitecap" framework and the biogeochemical complexity that early *Tellus* papers first illuminated. These results, in turn, motivated the development of biologically modulated source functions using chlorophyll-a as a proxy for surface-ocean productivity (O'Dowd et al., 2008; Russell et al., 2010).

5 FROM LEGACY TO MECHANISTIC SYNTHESIS: THE LAST TWO DECADES

The publication of O'Dowd et al. (2004) marked a defining moment in SSA research. What began in *Tellus* as a question of bubble physics and droplet ejection had, by the mid-2000s, evolved into a problem of chemical complexity and biological control (De Leeuw et al., 2011). This realisation initiated a new era of process-based inquiry, one concerned not only with how much SSA is emitted, but also with what it is composed of, how it forms, and why it varies (Quinn et al., 2015). Analytical advances soon allowed researchers to identify the molecular signatures of organic matter in SSA, including polysaccharides, proteins, lipids, and gel-like colloids, most of which were traced to the sea-surface microlayer (Bertram et al., 2018).

With the chemical complexity of nascent SSA firmly established, attention turned to quantifying how ocean biology shapes its composition. Researchers sought to determine how variations in surface-ecosystem state, from bloom conditions to oligotrophic waters, influence the quantity and character of aerosolised organic matter. Numerous investigations have since examined these links (see review by Bertram et al., 2018), leading to two broad perspectives. One group of studies reported a strong dependence of SSA organic enrichment on biological activity, with elevated organic-carbon-to-sodium (OC/Na^+) ratios during periods of high phytoplankton biomass or bloom conditions (e.g., Facchini et al., 2008; O'Dowd et al., 2004; O'Dowd et al., 2015). Supporting this view, observations at sites such as Mace Head showed that the water-insoluble organic-matter (WIOM) fraction of submicron aerosol increased markedly during bloom periods (O'Dowd et al., 2004), a pattern echoed by Van Pinxteren

et al. (2017) in the North Atlantic under high-chlorophyll-a conditions.

In contrast, other studies have found little or no systematic variation in OC/Na^+ ratios between oligotrophic and productive regimes (e.g., Quinn et al., 2014; Russell et al., 2010) or in mesocosm experiments simulating bloom cycles (Jayarathne et al., 2016). These results point to an alternative interpretation: in many oceanic settings, the large and persistent reservoir of dissolved and colloidal organic carbon exerts the dominant control on SSA composition, masking the influence of local biological variability (e.g., Beaupré et al., 2019).

Global and regional datasets have sharpened this debate. Measurements from the North Atlantic Aerosol and Marine Ecosystem Study (NAAMES) revealed that seasonal variability in plankton ecosystems had little effect on either the organic fraction or cloud-condensation-nuclei (CCN) activity of freshly emitted SSA (Bates et al., 2020). Complementary results from the Atmospheric Tomography (ATom) mission extended this picture globally, showing that submicron SSA organic-mass fractions over the remote Atlantic and Pacific Oceans were typically below 10% in the marine boundary layer and exhibited weak seasonal variability (Lawler et al., 2024). Collectively, these findings suggest that in the open ocean, biological control of nascent SSA composition is limited, with organic enrichment largely reflecting the background pool of dissolved organic matter (Beaupré et al., 2019).

These apparently conflicting observations need not imply that biological control is either dominant or negligible. Instead it may suggest that the transfer of organic matter to SSA depends not only on phytoplankton biomass, but also on the timing and transformation of biogenic material within the surface ocean. Phytoplankton exudation, cell lysis, viral infection, grazing, and heterotrophic bacterial degradation all alter the solubility and surface activity of organic matter, thereby modulating its partitioning into bubble films and nascent aerosol. From this perspective, Chl-a is an incomplete proxy for SSA composition because it captures autotrophic biomass but not the microbial processing that governs whether organic material becomes aerosolisable.

Reconciling strong local biological influence with weak global-scale variability has therefore become one of the field's central challenges. Addressing it requires decoupling the co-varying physical and biological drivers that confound open-ocean observations, a challenge that has motivated experiments under reproducible conditions. Mesocosm and related controlled-bloom studies have demonstrated direct causal links between plankton-bloom dynamics, microbial activity, organic-exudate production, and aerosol emissions (e.g., Lee et al., 2015; Prather et al., 2013; Wang et al., 2015). These experiments show that SSA organic enrichment is not simply tied to standing phytoplankton biomass, but can depend on bloom phase and on the balance between production of surface-active, labile organic compounds and their microbial transformation into more soluble or less surface-active forms. Consistent with this interpretation, shifts toward organic-rich SSA mixing states and reduced hygroscopicity have been observed during periods when Chl-a declined and heterotrophic bacterial concentrations increased (Prather et al., 2013). Other studies indicate that organic enrichment may be enhanced during bloom senescence or decay, when cell lysis, viral infection, and grazing release fresh organic material that can be processed within the microbial loop before transfer to the aerosol phase (Miyazaki et al., 2020; O'Dowd et al., 2015). Subsequent laboratory work has further refined this picture by showing that the conventional association of submicron SSA with film-drop production is incomplete. Jet drops can contribute substantially to the submicron SSA number concentration, in some cases up to 43%, and transfer more soluble, oxygenated organic material from bulk seawater, whereas film drops preferentially carry hydrophobic, aliphatic surfactants from the bubble-cap film (Wang et al., 2017). The resulting submicron SSA population may therefore be externally rather than internally mixed, with important consequences for climate-relevant properties such as hygroscopicity and ice-nucleating activity (e.g., Collins et al., 2013; Wang et al., 2017; Wex et al., 2010).

Beyond natural organic surfactants, recent work has shown that SSA also serves as an efficient pathway for the atmospheric transfer of persistent anthropogenic pollutants. Laboratory studies have been instrumental in establishing that perfluoroalkyl acids (PFAAs), a class of highly surface-active contaminants, are strongly enriched in nascent SSA. Enrichment factors (EFs) relative to bulk seawater have been found to exceed 10^5 in some cases (e.g. Johansson et al., 2019; Sha et al., 2020). Complementary field observations, including measurements along the Norwegian coast (Sha et al., 2021) and across the Atlantic Ocean (Sha et al., 2024), have confirmed that PFAAs are consistently enriched in SSA. Recent work has also demonstrated that SSA can aerosolise coastal water pollution more broadly, including both chemical contaminants and microbial agents, with implications for environmental fate and public health (Pendergraft et al., 2023).

The need for controlled, mechanistic studies has driven the development of a new generation of laboratory and field-deployed systems that effectively bring the ocean into the laboratory. Studies now use diverse methods to generate nascent SSA under contamination-free conditions, including sintered-glass frits (e.g., Mårtensson et al., 2003; Sellegri et al., 2006), pressurised atomisers (e.g. Svenningsson et al., 2006), impinging jets (e.g. Salter et al., 2014), plunging waterfalls (e.g. Stokes et al., 2013), and mechanically generated breaking waves (e.g., Prather et al., 2013). Each approach offers distinct advantages, together forming a methodological toolbox for probing the coupled physical, chemical, and biological processes that govern aerosol production.

Comparative studies have been central to this effort. They allow systematic evaluation of the physicochemical

differences among generation schemes and show, for instance, that plunging-jet and mechanically generated breaking-wave systems most closely reproduce the bubble-size distributions and aerosol properties characteristic of natural wave breaking (e.g., Collins et al., 2014). Despite this, simpler devices such as sintered-glass frits and atomisers remain widely used because of their adaptability for shipboard applications, including the Sea Sweep and related onboard bubble generators (e.g., Bates et al., 2012), as well as their simplicity to operate in the laboratory. Facilities such as the Marine Aerosol Reference Tank (MART) (Stokes et al., 2013) and its derivatives (e.g., miniMART Stokes et al., 2016) apply the pulsed-plunging-waterfall technique to create controlled, repeatable analogues of breaking waves. These specialised systems provide an unprecedented opportunity to connect SSA production with physical factors (e.g., sea-surface temperature, air-entrainment rate), chemical partitioning (organic speciation, mixing state), and biological properties (microbial activity, plankton dynamics).

The mechanistic perspective enabled by these systems has further refined the understanding of the inorganic fraction of SSA. Divalent cations such as calcium and magnesium have been shown to be preferentially incorporated into smaller droplets, suggesting subtle chemical fractionation during bubble bursting, an echo of the fractionation debates that animated the field in the 1960s and 1970s (Jayarathne et al., 2016; Salter et al., 2016). Whereas earlier investigators debated whether such effects reflected artefacts or bubble dynamics, modern analytical techniques have confirmed that they arise from genuine interfacial processes (Carter-Fenk et al., 2021; Schill et al., 2018). These results have broadened SSA research from physical descriptions toward molecular-level understanding of aerosol formation.

At the same time, these experimental approaches have enabled researchers to move beyond wind speed alone and isolate physical controls that are difficult to disentangle in the field. Sea-surface temperature is one important example, because its influence on SSA production appears to depend on particle size, generation mechanism, and seawater composition (Forestieri et al., 2018; Salter et al., 2014, 2015). Together with wave state and the presence of organic surfactants, such physical controls affect bubble lifetime, droplet formation, and aerosol yield. Collectively, these findings have built a bridge linking physical generation mechanisms, chemical partitioning, and biological modulation, laying the foundation for the modern synthesis that now connects microscale laboratory studies to global climate relevance.

6 CRITICAL UNCERTAINTIES FOR CLIMATE APPLICATIONS

The mechanistic advances described above reveal a central tension for climate modelling: the properties that are easiest to measure in laboratory and field studies are not always those that most strongly control cloud responses. This is especially apparent in the relationship between SSA chemical composition and cloud droplet activation. A large body of work has shown that biological activity can alter the organic fraction, molecular composition, and mixing state of nascent SSA. However, the extent to which this chemical variability modifies CCN concentrations appears more limited. Mesocosm studies, for example, have shown that the apparent hygroscopicity parameter of primary SSA can remain relatively stable across changing biological states, with resulting changes in expected CCN concentrations of only a few percent under typical marine cloud supersaturations (Collins et al., 2016). This suggests that, for cloud droplet formation, the physical production flux, size distribution, and number concentration of SSA—alongside the formation of secondary marine aerosol from biogenic volatile organic compounds (Mayer et al., 2020)—may often exert a stronger control than biologically mediated changes in primary chemical composition. Composition nevertheless remains climatically relevant, particularly where it affects particle mixing state, heterogeneous chemistry, the transfer of specific organic and anthropogenic compounds, or ice-nucleating activity, which can be highly sensitive to biological material (e.g., DeMott et al., 2016).

A second major uncertainty concerns the response of SSA production to sea-surface temperature. Field observations and model-derived parameterisations often imply enhanced SSA abundance at higher SST, whereas laboratory studies have reported positive, negative, non-monotonic, size-dependent, and composition-dependent temperature responses (e.g., Forestieri et al., 2018; Liu et al., 2021; Salter et al., 2014, 2015). This disagreement likely reflects the fact that temperature does not act in isolation: it modifies viscosity, density, surface tension, bubble rise and residence times, film drainage, jet formation, and the biological and chemical state of seawater. The model-relevant question is therefore not simply whether warmer water produces more or less SSA, but how SST interacts with wind speed, wave state, air entrainment, bubble-size distributions, and seawater composition to determine the size-resolved number flux of particles capable of influencing clouds.

These uncertainties help explain why global SSA emissions remain poorly constrained. Different source functions yield global annual SSA mass fluxes that differ by more than an order of magnitude, with estimates for particles smaller than 10 μm dry diameter spanning roughly 3–70 Pg yr^{-1} (Grythe et al., 2014). For climate applications, the priority is therefore to move beyond parameterisations based primarily on wind speed or bulk organic enrichment and toward source functions that explicitly represent the coupled controls on size-resolved number flux: wave breaking and whitecap properties, bubble-plume dynamics, SST, salinity, surfactants, and biologically mediated changes in seawater composition. Efforts to parameterise fluxes using the wind-sea Reynolds number, which encapsulates friction velocity, wave height, and temperature-dependent

viscosity (Ovadnevaite et al., 2014), represent a promising step in this direction. Such models need not resolve every molecular detail of SSA composition, but they must identify which compositional features affect cloud activation, ice nucleation, atmospheric processing, or radiative properties at scales relevant to climate models.

Looking back across these decades of discovery, it is remarkable how far the field has advanced since the early work, much of it published in *Tellus*, that established the fundamental physics of bubble bursting and the formation of jet and film drops. The pioneering 1954 study by Kientzler, Arons, Blanchard, and Woodcock used high-speed photography to demonstrate a key mechanism: the ejection of droplets from collapsing bubble cavities. Their results provided the first direct evidence linking bubble bursting at the ocean surface to the formation of atmospheric salt particles, laying the experimental and conceptual foundation for subsequent SSA research. What began as a rigorous investigation of fluid-mechanical processes at the air–sea interface has evolved into a multidisciplinary science linking hydrodynamics, chemistry, biology, and climate. The central challenge now is to translate this mechanistic understanding into predictive parameterisations that capture the size-resolved fluxes, mixing states, and activation properties of SSA across different oceanic and environmental regimes.

These unresolved questions now take on heightened significance in the context of a changing climate and increasing anthropogenic influence on the ocean. How will size-resolved SSA emission fluxes respond to ocean warming and shifting ecosystem structure? To what extent do biological and microbial processes, far beyond simple proxies such as chlorophyll-a, regulate aerosol composition? And how does the legacy of human pollution manifest in SSA, particularly through the long-range atmospheric transport of persistent contaminants such as per- and polyfluoroalkyl substances (PFAS)? These same uncertainties also underpin emerging proposals for marine cloud brightening as a form of solar climate intervention, a technique that relies on the controlled generation of submicron SSA to enhance cloud albedo. Yet, as underscored by recent analyses (e.g., Feingold et al., 2024), the feasibility of such interventions depends on the same factors that govern natural SSA, including the size distribution and activation behaviour of emitted particles, and their interaction with background aerosol and meteorological variability. In this respect, the field returns to the same core problem posed by the earliest *Tellus* studies, but at a much broader scale: linking bubble-scale physical processes to chemical partitioning, number fluxes, biological modulation, and ultimately to climate-relevant aerosol properties.

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