The effect of seawater salinity on sea spray aerosol production

Julika Zinke¹, E. Douglas Nilsson¹, Paul Zieger¹, and Matthew Edward Salter¹

¹Stockholm University

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Abstract

To improve our understanding of the impact of sea spray aerosols (SSA) on the Earth's climate, it is critical to understand the physical mechanisms which determine the size-resolved sea spray aerosol source. Of the factors affecting SSA emissions, seawater salinity has perhaps received the least attention in the literature and previous studies have produced conflicting results. Here, we present a series of laboratory experiments designed to investigate the role of salinity on aerosol production from artificial seawater using a continuous plunging jet. During these experiments, the aerosol and surface bubble size distributions were monitored while the salinity was decreased from 35 to 0 g/kg. Three distinct salinity regimes were identified: 1) A high salinity regime, 10-35 g/kg, where decreasing salinity only resulted in minor reductions in particle number emissions but significant reductions in particle volume; 2) an intermediate salinity regime, 5-10 g/kg, with a local maximum in particle number; 3) a low salinity regime, < 5 g/kg, characterized by a rapid decrease in particle number as salinity decreased and dominated by small particles and larger bubbles. We discuss the implications of our results through comparison of the size-resolved aerosol flux and the surface bubble population at different salinities. Finally, by varying the seawater temperature at three specific salinities we have also generated a simple parameterization of the particle number concentration and effective radius as a function of seawater temperature and salinity that can be used to estimate the sea spray aerosol flux in low salinity regions like the Baltic Sea.

The effect of seawater salinity on sea spray aerosol production

J. Zinke^{1,2}, E. D. Nilsson^{1,2}, P. Zieger^{1,2}, and M. E. Salter^{1,2}

⁴ [1]Department of Environmental Sciences, Stockholm University, Stockholm, Sweden

⁵ [2]Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden

6 Key Points:

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7	•	The concentrations and size distributions of sea spray aerosol depend on the sea-
8		water salinity and temperature
9	•	Three salinity regimes with distinct patterns in particle number, volume and sur-
10		face bubble spectra were identified
11	•	A parameterization has been derived for total sea spray particle number and ef-
12		fective radius as a function of water temperature and salinity

Corresponding author: E. Douglas Nilsson, douglas.nilsson@aces.su.se

Corresponding author: Julika Zinke, julika.zinke@aces.su.se

13 Abstract

To improve our understanding of the impact of sea spray aerosols (SSA) on the Earth's cli-14 mate, it is critical to understand the physical mechanisms which determine the size-resolved 15 sea spray aerosol source. Of the factors affecting SSA emissions, seawater salinity has 16 perhaps received the least attention in the literature and previous studies have produced 17 conflicting results. Here, we present a series of laboratory experiments designed to inves-18 tigate the role of salinity on aerosol production from artificial seawater using a continuous 19 plunging jet. During these experiments, the aerosol and surface bubble size distributions 20 were monitored while the salinity was decreased from 35 to $0 \,\mathrm{g \, kg^{-1}}$. Three distinct salinity 21 regimes were identified: 1) A high salinity regime, $10-35 \,\mathrm{g \, kg^{-1}}$, where decreasing salinity 22 only resulted in minor reductions in particle number emissions but significant reductions in 23 particle volume; 2) an intermediate salinity regime, $5-10 \,\mathrm{g \, kg^{-1}}$, with a local maximum in 24 particle number; 3) a low salinity regime, $< 5 \text{ g kg}^{-1}$, characterized by a rapid decrease in 25 particle number as salinity decreased and dominated by small particles and larger bubbles. 26 We discuss the implications of our results through comparison of the size-resolved aerosol 27 flux and the surface bubble population at different salinities. Finally, by varying the seawa-28 ter temperature at three specific salinities we have also generated a simple parameterization 29 of the particle number concentration and effective radius as a function of seawater temper-30 ature and salinity that can be used to estimate the sea spray aerosol flux in low salinity 31 32 regions like the Baltic Sea.

33 1 Introduction

Along with mineral dust, sea spray aerosol (SSA) is the major component of Earth's 34 natural aerosol in terms of mass and has the potential to influence the Earth's climate sys-35 tem by scattering incoming solar radiation and acting as cloud condensation nuclei (e.g. 36 Schwartz, 1996; Murphy et al., 1998; Quinn et al., 1998). These impacts are strongly influ-37 enced by the number and size of the sea spray aerosol particles. Therefore, understanding 38 the physical mechanisms which determine the source strength of sea spray aerosol as a func-39 tion of particle size is critical if we are to determine the influence of sea spray aerosol on 40 climate. Along with wind speed, the water temperature, salinity, and the physico-chemical 41 and biological state of the ocean have been shown to influence the production of sea spray 42 aerosol. Of these variables salinity has perhaps received the least attention in the literature 43 and previous studies that have attempted to determine the effect of seawater salinity on sea 44 spray aerosol production have produced conflicting results. 45

The main studies concerned with the effect of salinity on the production flux of sea 46 spray aerosol have been conducted using laboratory sea spray simulation systems where 47 bubbles have been generated from artificial seawater utilizing frits (e.g. Mårtensson et al., 48 2003; Tyree et al., 2007; Park et al., 2014) or from NaCl solutions utilizing plunging jet 49 systems (e.g. Zábori et al., 2012; May et al., 2016). An overview of previous experiments 50 can be found in Table S1. It is important to note that the bubble size distributions generated 51 with frits are very sensitive to the characteristics of the specific frits used and likely differ 52 markedly from the bubble size distributions found under oceanic breaking waves (e.g. Collins 53 et al., 2014). In contrast plunging jet systems have been shown to generate bubble size 54 distributions more similar to breaking waves (Hultin et al., 2010; Stokes et al., 2013) as 55 well as sea spray aerosol that is chemically more similar to that found over breaking waves 56 (Collins et al., 2014; Facchini et al., 2008). 57

In terms of the dependence of the SSA production flux on salinity, Mårtensson et al. (2003) reported an increase in the SSA production flux as the salinity was increased, which is most evident for particles with dry diameter $D_p > 0.1 \,\mu\text{m}$. For particles with $D_p < 0.1 \,\mu\text{m}$ there was little difference in the particle number between the experiments with seawater salinity 9.2 and 33 g kg⁻¹. However, the aerosol size distribution exhibited a slight shift to larger particle sizes at the higher salinity. Both Tyree et al. (2007) and Zábori et al. (2012) also observed a shift to larger particle sizes when the salinity was increased from 1
to 10 g kg⁻¹ and 0 to 15 g kg⁻¹, respectively. However, neither Park et al. (2014) nor May
et al. (2016) observed such a shift in particle size with increasing salinity.

⁶⁷ More recently, Nilsson et al. (2021) compared the observed eddy covariance aerosol ⁶⁸ fluxes in the Baltic Sea at salinity ~ 8 g kg⁻¹ with the parameterizations by Mårtensson et ⁶⁹ al. (2003) and Salter et al. (2015) and concluded that the observed number emission fluxes ⁷⁰ agreed with the parameterizations when they were corrected by the cube root of the salinity ⁷¹ S. This suggests that the mass emissions are proportional to the salinity.

Despite these rather conflicting findings, one similarity across many of the previous 72 studies is that the SSA production flux is most sensitive to changes at lower salinities 73 $(< 10 \text{ g kg}^{-1})$ (Mårtensson et al., 2003; Tyree et al., 2007; Zábori et al., 2012). This is 74 not surprising given the significant changes in bubble coalescence that have been noted 75 across this range of salinities (Lewis & Schwartz, 2004; Craig et al., 1993). In essence, 76 bubble coalescence is reduced in seawater compared to freshwater which results in the former 77 containing more small bubbles than the latter (e.g. Slauenwhite & Johnson, 1999). The 78 reason for this difference has been attributed to the existence of electrolytes in seawater 79 and recent evidence appears to support this view (Katsir et al., 2015). Critically, this range 80 in salinity is interesting from the perspective of modeling the production of SSA from low 81 salinity waters such as the central and northern Baltic Sea where the salinity is lower than 82 10 g kg^{-1} . 83

Other examples of low to moderate salinity seawaters are the Black Sea $(14-19 \text{ gkg}^{-1})$ 84 and the Hudson Bay and Strait $(26-31 \text{ g kg}^{-1})$. Indeed, these regions along with areas such as 85 Baffin Bay (30-32 g kg⁻¹ in summer), the Labrador Sea (30-34 g kg⁻¹) and other Arctic and 86 Antarctic surface waters are predicted to become less saline with climate change (Lavoie et 87 al., 2013; Kniebusch et al., 2019). To this end, the intention of this study was to investigate 88 the production of SSA from artificial seawater with salinities between 0 and 35 $g kg^{-1}$ using 89 a well-characterized plunging jet sea spray chamber. Given the aforementioned transition in 90 bubble coalescence behavior between salinities 0 and 10 $g kg^{-1}$ particular focus was placed 91 on these lower salinities. Alongside measurements of the size and number of SSA produced, 92 we have also measured the bubble size distribution at the air-water interface of the sea spray 93 chamber with the aim of understanding the processes that link changing salinity and the 94 size-resolved aerosol flux. 95

⁹⁶ 2 Materials and Methods

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2.1 The Sea Spray Chamber

Sea spray aerosols were generated in a temperature-controlled sea spray generation
 chamber using a plunging jet. This system has been described in detail by Salter et al.
 (2014) and details are provided in the supplementary information.

2.2 Particle Size Distribution Measurements

Aerosol particle-laden air was sampled through 0.8 m of tubing, a 1 m long Nafion dryer 102 (MD-700-36F, Perma Pure, USA), followed by another 1.9 m of tubing after which the flow 103 was split. A condensation particle counter (CPC, MCPC 1720, Brechtel Inc., USA) with 104 a flow rate of 0.36 Lmin^{-1} situated 0.4 m behind this split was used to enumerate the to-105 tal number concentration for particles with diameters $> 0.01 \ \mu m$. The size distribution 106 of aerosol particles with dry electrical mobility diameters $0.015 \,\mu\text{m} < D_p < 0.906 \,\mu\text{m}$, dis-107 tributed over 37 size bins, was measured with a custom-built differential mobility particle 108 sizer (DMPS), consisting of a 28 cm long Vienna type differential mobility analyzer (DMA) 109 and a condensation particle counter (CPC, MCPC 1720, Brechtel Inc., USA) with a flow 110 rate of $0.36 \text{ L} \text{min}^{-1}$. A scan over all size bins was completed in 12 minutes and the measured 111

size distributions were inverted and multiple-charge corrected using custom-built software.
 The DMPS was situated 0.5 m behind the split.

An optical particle size spectrometer (OPSS) with a flow rate of 5 $L \min^{-1}$ (WELAS 114 2300 HP sensor and Promo LED 2000 H, Palas GmbH, Germany) was mounted 0.7 m above 115 the sea spray chamber and measured the particle size distribution in the optical diameter 116 size range $0.150 \,\mu\mathrm{m} < D_p < 10 \,\mu\mathrm{m}$, distributed over 59 bins. The optical diameter measured 117 by the OPSS depends on the wavelength-dependent refractive index of the sampled aerosol. 118 Therefore, we have converted the measured optical diameters to volume equivalent diameters 119 by assuming a refractive index of m = 1.54 - 0i for sea salt particles, which corresponds 120 to the value of NaCl (Abo Riziq et al., 2007). The correction was conducted using the 121 software provided by the manufacturer (PDAnalyze, Palas GmbH, Version No 2.024). A 122 1.3 m long Nafion dryer (MD-700-48F, Perma Pure, USA) with a sheath flow of $10 \, \mathrm{L\,min^{-1}}$ 123 was mounted horizontally in front of the OPSS in order to reduce the humidity of the sampled 124 air so that the measured particle diameters can be considered as dry diameter. Temperature 125 and relative humidity were monitored with two sensors (HYTELOG-USB, B+B Thermo-126 Technik GmbH) mounted in front of the sampling inlets of the OPSS and DMPS system. The 127 humidities measured in front of the DMPS and OPSS were $21.3 \pm 0.38\%$ and $17.1 \pm 0.31\%$, 128 respectively (mean \pm standard deviation for the entire experiment). Since SSA particles are 129 typically non-spherical when dried, the diameters obtained from the DMPS and OPSS were 130 shape corrected using a dynamic shape factor calculated according to Zieger et al. (2017). 131 All sizing instruments were calibrated with polystyrene latex (PSL) spheres. Following all 132 corrections, the data of the DMPS and OPSS were combined at 0.5 µm. 133

Aerosol sampling efficiencies were estimated with the Particle Loss Calculator Software 134 (von der Weiden et al., 2009) and are shown in Figure S3. The losses of the larger particles 135 measured by the OPSS were expected to be highest in the horizontally aligned Nafion 136 dryer. The estimated losses also depend on the particle density, which is in turn dependent 137 on how quickly the water within the particles evaporates during transit through the drier 138 (i.e how much time the particles spend as droplets in the drier versus how much time 139 they spend as salt crystals). Since the drying of the particles is a continuous process, we 140 have considered a density range from that of seawater, $1000 \,\mathrm{kg}\,\mathrm{m}^{-3}$, to that of dry sea salt 141 particles, $2017 \,\mathrm{kg}\,\mathrm{m}^{-3}$ (Zieger et al., 2017). Note, while these values provide upper and 142 lower limits for the estimated sampling efficiency, we have not corrected the data presented 143 in this study for any particle losses. 144

MATLAB software version 2019a was used to conduct statistical tests on the size dis tributions. The Mathworks Curve Fitting Toolbox 3.5.9, which uses the method of least
 squares when fitting data, was used to establish empirical relationships. All fits presented
 in this study are non-weighted.

¹⁴⁹ 2.3 Surface bubble spectra

The bubble size distribution at the water surface was determined photographically in a similar fashion to that described in Salter et al. (2014). Details can be found in the supplementary information.

153 2.4 Experimental Setup

The experiments were conducted with artificial seawater consisting of Sigma sea salt (Sigma Aldrich, S9883; with ionic mass ratios comparable to those in seawater: 55% Cl⁻, 31% Na⁺, 8% SO₄²⁻, 4% Mg²⁺, 1% K⁺, 1% Ca²⁺, < 1% other) that was dissolved in low organic carbon standard deionized water (MilliQ, > 18.2 MΩ), hereafter referred to as DIW. Previous studies have shown that there are no substantial amounts of organics in the salt (e.g. Salter et al., 2016). In order to estimate the effect of salinity on sea spray production the salinity was gradually decreased from 35 to 0 g kg⁻¹ while the temperature was kept constant at 20°C. This experiment was repeated at a higher salinity resolution in the range 10-5 g kg⁻¹ where significant impacts of changing salinity on the aerosol and bubbles were expected. Each experiment started when the measured salinity had settled to a constant value. We chose to decrease the salinity rather than increase it since dilution of 100 L of artificial seawater with DIW proceeds much more quickly to steady state than the dissolution of additional salt.

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In addition to the experiments conducted at a constant temperature, three temperature 168 ramps were conducted at salinities $35 \,\mathrm{g \, kg^{-1}}$, $17 \,\mathrm{g \, kg^{-1}}$ and $6 \,\mathrm{g \, kg^{-1}}$ to investigate the impact 169 of changing the water temperature on particle production at different salinities. These 170 salinities were chosen because they are representative of the global average oceanic salinity 171 as well as lower salinity waters such as the Black Sea and the Baltic Sea. During these 172 temperature ramps the water temperature was slowly decreased from 30 to 0° C over a 173 period of approximately 40 hours. Two temperature ramps were conducted at salinity 174 $35 \,\mathrm{g \, kg^{-1}}$ to examine the reproducibility of the measurements. 175

3 Results and Discussion

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3.1 Impact of seawater salinity on particle production

By varying the amount of sea salt dissolved in DIW and measuring the particle size 178 distribution we have probed the impact of changing salinity on particle production. Figure 179 1 presents the aerosol particle number, surface and volume size distributions for seawater 180 salinities between 0 and $35 \,\mathrm{g \, kg^{-1}}$. For seawater salinities $\geq 15 \,\mathrm{g \, kg^{-1}}$ the number size dis-181 tribution had a local maximum at 146 nm and a second local maximum at 403 nm when 182 presented in the form $dN/dlogD_p$ where N is the number of particles and D_p is the volume 183 equivalent diameter (see also Figure S4). As the seawater salinity decreased below $15 \,\mathrm{g \, kg^{-1}}$ 184 the first local maximum shifted to 66-74 nm and the second local maximum ceased to ex-185 ist. When presented in the form $dA/dlogD_p$, the surface size distribution exhibited a mode 186 that was centered around 3 μm at salinities $\geq 15\,{\rm g\,kg^{-1}}$ and shifted to 2 μm at salinities 187 ties $\leq 15 \,\mathrm{g \, kg^{-1}}$. The magnitude of dA/dlogD_p decreased notably at seawater salinities < 188 $15 \,\mathrm{g \, kg^{-1}}$. Similarly, the particle volume size distribution exhibited a mode that was cen-189 tered around 5 µm at salinities $\geq 15 \,\mathrm{g \, kg^{-1}}$, which shifted to 3 µm for salinities $\leq 10 \,\mathrm{g \, kg^{-1}}$ 190 and simultaneously decreased in magnitude. Another prominent feature of the size distri-191 butions was a substantial increase in the concentration of particles <100 nm at seawater 192 salinities 6 and 8 $g kg^{-1}$ relative to both higher and lower seawater salinities. 193

A comparison to previous studies conducted by Mårtensson et al. (2003), Tyree et 194 al. (2007), Zábori et al. (2012) and Park et al. (2014) is provided in Figure 2. Tyree et 195 al. (2007) observed a shift to larger particle sizes from 62.5 nm to 98 nm (center of the 196 mode) as the seawater salinity was increased from 1 to 10 $g kg^{-1}$. Similarly, Zábori et al. 197 (2012) observed a shift in the center of the mode from about 142 to 225 nm as the seawater 198 salinity was increased from 0-3 g kg⁻¹ to 12-15 g kg⁻¹. Our study supports the findings of 199 both these studies. With that said, it should be noted that Zábori et al. (2012) observed 200 that the mean relative humidity was 43% during their experiments in the seawater salinity 201 range $0-18 \,\mathrm{g \, kg^{-1}}$. At such high relative humidities the particles were unlikely to be dry 202 and should not be referred to as particles at "dry diameter". Therefore, we have converted 203 their diameters to dry diameters assuming a growth factor of 1.22 at RH=43% (Zieger et 204 al., 2017). By doing so we have calculated dry diameters of 116 nm for the salinity range 205 $0-3 \,\mathrm{g \, kg^{-1}}$ and $184 \,\mathrm{nm}$ for the salinity range $12-15 \,\mathrm{g \, kg^{-1}}$. These values compare reasonably 206 well with the shift from $\sim 70 \,\mathrm{nm}$ to 140 nm observed in the current study. While Tyree et 207 al. (2007) used a frit to generate sea spray aerosols, Zábori et al. (2012) used a plunging 208 jet. Mårtensson et al. (2003) also observed a shift in the mode diameter from 60 nm to 125 209 nm as seawater salinity increased. However, in this study the shift to larger sizes occurred 210 at higher seawater salinities between 9.2 and 33 $g kg^{-1}$. In the current study, although we 211



Figure 1. Mean particle (a) number size distribution, (b) surface size distribution, and (c) volume size distribution measured at different salinities at a water temperature of 20°C. The diameters are volume equivalent diameters.

observed a shift in the main particle number mode diameter with changing salinity (see 212 Figure 1), we did not observe a monotonic increase in the main particle number mode with 213 increasing seawater salinity which has been observed in previous studies (e.g. Tyree et al., 214 2007; Park et al., 2014; May et al., 2016). Since two of these previous studies used frits to 215 produce bubbles (Tyree et al., 2007; Park et al., 2014), the bubble spectra present during 216 their experiments were very likely different from those in experiments utilizing plunging jets 217 (such as the current study). May et al. (2016) used multiple plunging jets and the authors 218 make note of the shallow bubble plume which resulted. This likely impacted the bubble 219 lifetime in this system and potentially explains the difference in their observed particle 220 distributions compared to the current study. 221



Figure 2. Comparison of the normalized size distributions for different salinities obtained from this study with the results from (a) Mårtensson et al. (2003), (b) Tyree et al. (2007), (c) Zábori et al. (2012) and (d) Park et al. (2014).

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The particle size distributions presented in Figure 1 highlight that changing seawater salinity induced complex changes in the particle size distribution following bubble bursting. Therefore, in order to visualize these changes, Figure 3 presents particle number, surface and volume concentrations that were obtained by integrating over the whole size range of the combined size distributions measured by the DMPS and OPSS as well as the effective particle radius as functions of seawater salinity. Here, the effective radius r_e was calculated following Grainger et al. (1995): $r_e = \frac{3V}{4}$.

From Figure 3a, three distinct regimes can be identified, each with a different relation-230 ship between seawater salinity and integrated particle number. The first regime occurred at 231 seawater salinities greater than 10 $g kg^{-1}$ where the integrated particle number decreased 232 only gradually with decreasing seawater salinity. The second regime occurred in the salinity 233 range 5-10 $g kg^{-1}$ where a peak in integrated particle number production occurred in the 234 first set of experiments. Finally, a third regime was observed at seawater salinities <5 g kg⁻¹ 235 where the integrated particle number decreased rapidly as seawater salinity decreased. The 236 integrated concentrations were compared to the total number concentration measured by 237 the CPC (see Figure S5). The measured total number concentrations exhibited the same 238 three regimes, although shifted downward in magnitude by an average of $17\% \pm 2\%$ for all 230 salinities except 0 $g kg^{-1}$. 240



Figure 3. The impact of salinity on the (a) particle number, (b) surface, (c) volume concentration and (d) effective radius including fits. All values are presented as mean values and standard deviation. The dotted lines in panel (a) and (c) mark regimes with different relationships between seawater salinity and particle number or volume.

In order to investigate the local maxima in particle production in the seawater salinity 241 range 5-10 $g kg^{-1}$ more deeply, a second experiment was carried out with increased salinity 242 resolution in this range. This experiment also showed a local maximum in particle pro-243 duction in this range. However, the exact salinity at which this local maximum in particle 244 production occurred differed between the two experiments (6 $g kg^{-1}$ for the first experiment, 245 4.5 gkg^{-1} for the second experiment). This suggests that some property of the seawater 246 used in the two experiments differed. Since seawater temperature was controlled we can 247 exclude this as a factor. Instead, it may have been that slight changes in the organic matter 248 unintentionally present in the seawater impacted the bubble bursting process. 249

²⁵⁰ Zábori et al. (2012) observed a local maximum in particle number production in the ²⁵¹ salinity range $3-9 \,\mathrm{g \, kg^{-1}}$ that is consistent with the increased particle production at seawater ²⁵² salinities 6 and $8 \,\mathrm{g \, kg^{-1}}$ observed in the current study. Note that the salinity bins in Zábori ²⁵³ et al. (2012) are wider than the steps used in the current study.

We suspect that the observed changes in particle number with salinity result from changes in the bubble spectra that are discussed in section 3.2.

Both particle surface and volume decreased monotonically as seawater salinity decreased 256 (Figures 3b and c). The strong dependence of both particle surface and volume concentra-257 tion on seawater salinity likely results from the lower ion concentrations and subsequent 258 lower solute concentrations of the dried particles (assuming the initial droplet was the same 259 size) as seawater salinity decreased as previously hypothesized by Mårtensson et al. (2003) 260 and Slade et al. (2010). Although Mårtensson et al. (2003) only measured the impact 261 of seawater salinity on particle production at three different salinities, they also observed 262 monotonically decreasing particle volume with decreasing salinity. Closer inspection of Fig-263 ure 3c reveals two distinct salinity regimes. At seawater salinities $\geq 6 \,\mathrm{g \, kg^{-1}}$ the particle 264 volume concentration decreased more rapidly as salinity decreased compared to salinities 265 lower than $6 \,\mathrm{g \, kg^{-1}}$. The effective radius r_e (Figure 3d) decreased non-linearly as seawater 266 salinity decreased. 267

In order to parameterize the effect of salinity on sea spray aerosol production, we have attempted to describe the integrated particle number concentration as a function of seawater salinity by defining the following empirical equation

$$N_p = 188.5 \text{ cm}^{-3} \cdot \log(S) + 401.6 \text{ cm}^{-3}$$
(1)

where N_p denotes the particle number concentration, S denotes the salinity of the water and log is the common logarithm. As is clear from Figure 3a this empirical relationship does not account for the local maxima in particle production we observed at seawater salinities between 5 and 10 g kg⁻¹ despite being a reasonable fit to the data at other seawater salinities (r²=0.88, which describes the goodness of fit). This suggests that the local maximum is caused by processes other than the overall gradual change.

For salinities $\geq 10 \text{ g kg}^{-1}$ the relationship between seawater salinity and particle production can be described with the empirical linear equation

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 $N_p = 3.4 \text{ cm}^{-3} \text{ kg}_{\text{water}} \text{ g}_{\text{salt}}^{-1} \cdot S + 536.4 \text{ cm}^{-3}, \ r^2 = 0.90$ (2)

for the first experiment. The second experiment has only three data points in this range, but indicates a linear relationship similar to that in the first experiment.

For the two distinct regimes observed in the particle volume, we have defined the following empirical relationships to describe the dependence of particle volume on seawater salinity:

$$V = k \cdot S + m \tag{3}$$

where k=8.6 µm³ cm⁻³ kg_{water} g_{salt}⁻¹ (95% confidence bounds: 7.6 µm³ cm⁻³ kg_{water} g_{salt}⁻¹, 9.6 µm³ cm⁻³ kg_{water} g_{salt}⁻¹ and m=1 µm³ cm⁻³ (95% confidence bounds: -2.18 µm³ cm⁻³, 4.08 µm³ cm⁻³) for S<6 g kg⁻¹ (r²=0.99) and k=21.8 µm³ cm⁻³ kg_{water} g_{salt}⁻¹ (95% confidence bounds: 17.2 µm³ cm⁻³ kg_{water} g_{salt}⁻¹, 26.5 µm³ cm⁻³ kg_{water} g_{salt}⁻¹ and m=-82.8 µm³ cm⁻³ (95% confidence bounds: -181.1 µm³ cm⁻³, 15.4 µm³ cm⁻³) for S≥6 g kg⁻¹ (r²=0.95) for the first experiment. For the second experiment k=12 µm³ cm⁻³ kg_{water} g_{salt}⁻¹ and m=-30.5 µm³ cm⁻³ (95% confidence bounds: -56.5 µm³ cm⁻³, -4.5 µm³ cm⁻³) for S≥6 g kg⁻¹ (r²=0.97).

The linear relationship between V and S suggests that the mass flux is directly proportional to the salt mass in the water as indicated by Mårtensson et al. (2003) and Nilsson et al. (2021). The difference in dV/dS suggests that two different particle formation processes may have dominated above and below 6 g kg⁻¹.

The effective radius appears to be directly proportional to the cube root of the seawater salinity as follows:

$$r_e = \alpha \cdot S^{1/3} \tag{4}$$

where α is a proportionality constant with units of $\operatorname{mkg}_{water}^{1/3} \operatorname{g}_{salt}^{-1/3}$ if the r_e is in units of m and S is in units of $\operatorname{g_{salt}} \operatorname{kg}_{water}^{-1}$. For our first experiment $\alpha = 0.47 \cdot 10^{-6} \operatorname{mkg}_{water}^{1/3} \operatorname{g}_{salt}^{-1/3}$ (95% confidence bounds: $0.45 \cdot 10^{-6} \operatorname{mkg}_{water}^{1/3} \operatorname{g}_{salt}^{-1/3}$, $0.49 \cdot 10^{-6} \operatorname{mkg}_{water}^{1/3} \operatorname{g}_{salt}^{-1/3}$; $r^2=0.96$) while for our second experiment $\alpha = 0.40 \cdot 10^{-6} \operatorname{mkg}_{water}^{1/3} \operatorname{g}_{salt}^{-1/3}$ (95% confidence bounds: $0.38 \cdot 10^{-6} \operatorname{mkg}_{water}^{1/3} \operatorname{g}_{salt}^{-1/3}$, $0.43 \cdot 10^{-6} \operatorname{mkg}_{water}^{1/3} \operatorname{g}_{salt}^{-1/3}$; $r^2=0.87$). These fits are consistent with particle formation where the particle mass M_p is proportional to seawater salinity:

$$S \propto M = V \cdot \rho = \rho \frac{4\pi}{3} r^3 = \rho \frac{\pi}{6} D_p^3 \tag{5}$$

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3.2 Dependence of the surface bubble spectra on seawater salinity

Figure 4a presents the bubble density as a function of the bubble film radius for the measured range of salinities in the field of view. As the the water salinity decreased there was



Figure 4. The impact of salinity on (a) the surface bubble density versus bubble film radius, (b) the integrated bubble volume and (c) the number of particles produced per bubble per field of view. All values are presented as mean values and standard deviation that were determined by averaging across a number of images at each salinity.

a shift toward larger bubble sizes and a decrease in bubble number density, particularly for 311 bubbles $< 1 \,\mathrm{mm}$ peaking at a bubble radius of about 0.3-0.4 mm. The experiment conducted 312 at a salinity of 6 $g kg^{-1}$ exhibited higher bubble densities at bubble radii > 1 mm compared 313 to all other salinities which otherwise exhibited a monotonic decrease in bubble density for 314 bubbles with radii larger than 1 mm. The change in the bubble spectra as a function of 315 salinity is more clearly demonstrated in Figure 4b, where we can see that the dependence of 316 the integrated surface bubble volume on salinity exhibits similar behavior to the dependence 317 of aerosol particle number on salinity (e.g. Figure 1a). That is, as the salinity decreased from 318 35 to 10 g kg^{-1} the surface bubble volume was nearly constant with salinity. Then, as the 319 salinity decreased from 10 to 5 $g kg^{-1}$, a local maximum in bubble volume was observed. 320 Finally, as the salinity decreased below 5 $g kg^{-1}$ a rapid decrease in the surface bubble 321 volume was observed. A similar decrease in the bubble concentration with decreasing salinity 322 that is presented in Figure 4a has been reported in several previous studies. A summary 323 of these studies is given in Lewis and Schwartz (2004). Many of these investigators (e.g. 324 Marrucci & Nicodemo, 1967; Monahan & Zietlow, 1969; Carey et al., 1993; Cartmill & 325 Su, 1993; Asher et al., 1997; Slauenwhite & Johnson, 1999) reported a higher number of 326 smaller bubbles with radii < 1 mm in seawater than in freshwater which is consistent with 327 our bubble size distribution. The higher abundance of smaller bubbles in seawater than 328 in freshwater has been attributed to coalescence inhibition and an increased break-up of 329 bubbles in seawater (e.g. Lessard & Zieminski, 1971; Slauenwhite & Johnson, 1999; Lewis 330 & Schwartz, 2004). The inhibition of coalescence in seawater relative to freshwater has been 331 attributed to the different electrolytic properties of fresh- versus seawater. The transition 332 in bubble coalescence has been observed to happen in the salinity range 0 to $10\,\mathrm{g\,kg^{-1}}$ 333 (Lessard & Zieminski, 1971; Craig et al., 1993) which is in agreement with the observations 334 in the current study. Notably, previous studies (Marrucci & Nicodemo, 1967; Lessard & 335 Zieminski, 1971; Drogaris & Weiland, 1983; Craig et al., 1993; Carey et al., 1993) have 336 observed that bubble coalescence is significantly reduced at ionic strengths in the range 337 0.1-0.2 mol kg⁻¹_{seawater} which corresponds to salinities between 5 and $10 \, \mathrm{g \, kg^{-1}}$. This agrees 338 well with the peak in particle concentrations and bubble volume observed in the current 330 study. Inline with our observations, this suggests that in regions with salinities $> 10 \,\mathrm{g \, kg^{-1}}$ 340

(e.g. the Western Baltic Kattegat, Black Sea or Hudson Bay) SSA production is likely to
 differ only marginally from the major oceans.

If we had imaged the entire surface of the water generating particles during our ex-343 periments we could have combined our measurements of the surface bubble number with 344 our particle measurements to provide an estimate of the impact of salinity on the amount 345 of particles produced per bubble. However, since our photographs cover only a fraction 346 of the water surface, that is located close to the plunging jet, and the bubble density de-347 clines toward the edges of the sea spray tank to avoid wall effects on the bubble spectra 348 349 (see Figure S2), it was not possible to estimate the total amount of bubbles at the water surface at any one time. As such, we were not able to provide such an estimate. Instead, 350 we have estimated the number of particles produced per bubble in the area imaged (Figure 351 4c) to provide an estimate of the rate of change of the number of particles per bubble with 352 varying salinity. These estimates indicate that the number of particles produced per bubble 353 was approximately constant for $S > 10 \,\mathrm{g \, kg^{-1}}$. In contrast, as the salinity decreased below 354 10 gkg^{-1} the number of particles produced per bubble increased rapidly with decreasing 355 salinity reaching a maximum at a salinity of $\sim 2\,\mathrm{g\,kg^{-1}}$. The transition regime at salinities 356 $5-10 \,\mathrm{g \, kg^{-1}}$ that was so evident in both particle number (Figure 1) and bubble volume (Fig-357 ure 4c) also exhibits notably different behavior for this metric. One possible explanation for 358 the occurrence of this transition regime is a rapid change in the surface bubble size distribu-359 tion from the predominance of many small bubbles at higher salinities, to the predominance 360 of fewer larger bubbles at lower salinities. 361

The number of jet drops and film drops produced when a bubble bursts depends on the 362 bubble size (Lewis & Schwartz, 2004). Bubbles with radii > 1 mm tend to produce more film 363 drops while bubbles $< 1 \,\mathrm{mm}$ produce more jet drops (Lewis & Schwartz, 2004). As such, our 364 observation that more sub-millimeter bubbles were present at salinities $> 10 \,\mathrm{g \, kg^{-1}}$ likely 365 coincided with an increased production of jet drops. Since we observed no notable changes 366 in super-millimeter bubble density we conclude that film drop emissions were less impacted 367 by changes in salinity than jet drops, which is in line with the observations of Harb and 368 Foroutan (2019). Since jet drops tend to expel super-micron particles (Lewis & Schwartz, 369 2004), a higher proportion of jet drops will shift the particle size distribution mode to larger 370 particles. This agrees well with the shift to larger particle sizes for salinities $> 10 \,\mathrm{g \, kg^{-1}}$ that 371 we observed. However, it is important to note that other studies (e.g. Wang et al., 2017) 372 have observed that a substantial fraction of sub-micrometer particles can also be produced 373 from jet drops. 374

Figure 5 presents our bubble size spectra at salinity 0 and 35 $g kg^{-1}$ alongside those of 375 Harb and Foroutan (2019), who used a plunging sheet of water to entrain air, and Salter 376 et al. (2014), who used the same experimental setup as that used in the current study. All 377 of these experiments were conducted at temperatures of around 20°C. The bubble size dis-378 tribution obtained in the current study at 35 $g kg^{-1}$ agrees fairly well with the bubble size 379 distribution measured by Harb and Foroutan (2019), whereas we observe considerably fewer 380 bubbles at all sizes for salinity 0 g kg^{-1} than Harb and Foroutan (2019). In the observations 381 made by Salter et al. (2014) at 35 g kg⁻¹, fewer bubbles of all sizes were present than in the 382 current study. This is surprising given that Salter et al. (2014) used the same experimental 383 set-up used in the current study. Further, Salter et al. (2014) observed slightly higher par-384 ticle concentrations than those obtained in the current study suggesting that, if anything, 385 more bubbles may have been present in their study. Their pictures were re-analyzed in the 386 current study, leading to the same results. We can only speculate on the possible expla-387 nations for this. For example, the bubbles imaged by Salter et al. (2014) may have been 388 slightly smaller than those of the current study and therefore outside the range of detection. 389 390



Figure 5. Comparison of bubble densities at salinities 0 and 35 g kg⁻¹ with data from Harb and Foroutan (2019) and Salter et al. (2014). Values in panel (a) and (b) are presented as mean values and standard deviation. Error bars in panel (c) denote propagated standard errors.

3.3 Temperature dependence of particle production at three distinct salinities

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Temperature ramps were conducted at salinities of 35 $\,\mathrm{g\,kg^{-1}}$, 17 $\,\mathrm{g\,kg^{-1}}$ and 6 $\,\mathrm{g\,kg^{-1}}$ 393 (Figure S6). Since we have previously conducted a temperature ramp at a salinity of 35 394 $g kg^{-1}$ we were able to compare these two experiments for consistency. To do so we have 395 used the Kolmogorov-Smirnov test to compare the integrated particle number, surface and 396 volume concentrations as well as the effective radii at each temperature of these two temper-397 ature ramps. The integrated particle number concentrations and effective radii were found 398 to have the same distribution with temperature at probability values of p=0.48 and p=0.34399 (at a significance level of 5%), respectively. It is worth noting that the integrated number 400 concentrations for both experiments were almost identical for temperatures $\geq 14^{\circ}$ C, while 401 they differed slightly at lower temperatures. The surface and volume concentrations were 402 found to be different ($p=2.6 \cdot 10^{-4}$ and $p=2.7 \cdot 10^{-3}$ at a significance level of 5%, respectively). 403 The change in sea spray particle number with water temperature (decreasing with increas-404 ing temperature) agrees qualitatively with many earlier studies (e.g. Bowyer et al., 1990; 405 Mårtensson et al., 2003; Hultin et al., 2011; Zábori et al., 2012; Salter et al., 2014, 2015). 406 We note that the difference between dN/dT for the 17 and 35 g kg⁻¹ experiments is small, 407 while the 6 g kg⁻¹ experiment has a significantly smaller amplitude in dN/dT. Salter et 408 al. (2014) concluded that it was changes to the bubble size distribution that were driving 409 changes to particle production at seawater temperatures around $\sim 10^{\circ}$ C. In a similar fash-410 ion the data generated during the current study suggest that it is changes to the bubble 411 spectra, especially the ratio between bubbles with radii larger than 1 mm and bubbles with 412 radii smaller than 1 mm, that are driving changes to the particle size and number as salinity 413 changes (see Figures 3 and 4c). However, the fact that the experiment at $S = 6 \text{ g kg}^{-1}$ 414 exhibits the weakest trend in number concentration with water temperature suggests that 415

the temperature effect might be proportionally smaller at salinities representative for large parts of the Baltic Sea than it is for high salinity oceans.

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3.3.1 Particle number and effective radius as a function of temperature and salinity

We have attempted to derive a parameterization of the particle number and effective radius as a function of temperature and salinity.

Figure 6. Effect of temperature on (a) integrated particle number for three different salinities with three fitted empirical equations and (b) effective radius normalized by the mean effective radius of the three salinities. The values in panel (a) are presented as mean values and standard deviation, while values in panel (b) are normalized to the value at $T=20^{\circ}C$ with propagated error bars.

⁴²² The dependence of total particle number concentration on water temperature could be ⁴²³ described with an equation building on the inverse tangent function (arctan) with correlation ⁴²⁴ coefficients of $r^2 \ge 0.99$ for all three salinities (see also Figure 6a):

$$N_p = \int_{D,min}^{D,max} \frac{\mathrm{d}N}{\mathrm{dlog}D_p} d\mathrm{log}D_p = a - b \cdot \arctan\left(\frac{c(T^d) - e}{f}\right) \tag{6}$$

where N_p is the number concentration integrated over the whole size range (D, min = 0.015 µm and D, max = 10 µm in this study), T is the water temperature and the coefficients a to f are given in Table 1.

By normalizing the r_e with $r_e(T = 20^{\circ}\text{C})$ for each salinity experiment, we observe notable agreement between the experiments (see Figure 6b). By averaging the curves for the three salinities we were able to make a polynomial fit through the mean curve to produce r_e as function of T:

$$r_e = r_e(20^\circ C) \cdot \sum_{i=1}^n \beta_i \cdot T^i.$$
(7)

434 The coefficients β_i are given in Table 2.

Table 1. Coefficients a to f for the parameterization of the number concentration for three different seawater salinities (see equation 6) as shown in Figure 6a, as well as the coefficient of determination, r^2 .

$\overline{S~(gkg^{-1})}$	a	b	с	d	е	f	r^2
6 17 35	1800 1800 1800	-734 859.2 820	$17.4 \\ 6.674 \cdot 10^5 \\ -2.342 \cdot 10^4$	2.467 0.3561 0.6871	$-1.7794 \cdot 10^3$ $1.47 \cdot 10^6$ -81700	$\begin{array}{r} -1.434{\cdot}10^4 \\ 1.309{\cdot}10^5 \\ -1.595{\cdot}10^4 \end{array}$	$\begin{array}{c} 0.9958 \\ 0.9882 \\ 0.9921 \end{array}$

Table 2. Coefficients for the parameterization of the effective radius (equation 7) as shown inFigure 6b.

	Coefficients for eq. 7
β_0	0.596
β_1	$3.022 \cdot 10^{-2}$
β_2	$-8.178 \cdot 10^{-3}$
β_3	$2.109 \cdot 10^{-3}$
β_4	$-1.754 \cdot 10^{-4}$
β_5	$5.801 \cdot 10^{-6}$
β_6	$-6.72 \cdot 10^{-8}$

Now through combination of equation 7 with equation 4, which is valid at $T = 20^{\circ}$ C, we obtain

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$$r_e = \alpha \cdot S^{1/3} = r_e(20^{\circ}C) \cdot \sum_{i=1}^n \beta_i \cdot T^i$$
 (8)

which provides the effective radius as a function of both S and T from 0-35 gkg⁻¹ and 0-30°C, respectively. In combination with equation 6 we have generated a simple parameterization of the sea spray particle number and effective radius as function of both water temperature and salinity assuming that one wishes to represent sea spray aerosol using a single mode. That however offers a less detailed parameterization than for example Mårtensson et al. (2003) or Salter et al. (2015).

444 4 Summary and conclusions

In this study we have performed a series of laboratory experiments to investigate the 445 role of salinity on particle production and bubble spectra using a continuous plunging jet. 446 We were able to describe the changes in particle number, volume and effective radius with 447 salinity and identified three distinct salinity regimes in the particle number production. For 448 salinities between 10 and 35 $g kg^{-1}$, the produced particle number was nearly constant. 449 Between salinities 5 and 10 $g kg^{-1}$ we observed a local maximum in particle number concen-450 tration that coincided with a transition in the surface bubble spectra toward larger bubble 451 sizes and decreased bubble density at lower salinities. Below 5 $g kg^{-1}$ we observed a rapid 452 decrease in particle number, but only a gradual decrease in particle volume. Above salinity 453 5 g kg^{-1} this decrease in volume with decreasing salinity was considerably steeper. Further-454 more, we have observed a shift of the particle mode centered at 140 nm to ~ 70 nm and a 455 decrease in particles > 200 nm as the salinity was decreased below 15 g kg⁻¹. The observed 456 shift to smaller particles with decreasing salinity is attributed to the linear relationship 457 between salinity and dry particle volume and the cubic relationship between salinity and 458 effective radius. Changes in the particle production were further associated with changes in 459 the surface bubble spectrum that exhibited higher numbers of bubbles with radii <1 mm 460

at higher salinities, while the number of droplets produced per bubble peaked at salinities 461 below 5 $g kg^{-1}$. Additionally, temperature ramps were conducted at three distinct salini-462 ties (35, 17 and $6 \,\mathrm{g\,kg^{-1}}$). In terms of aerosol production, the experiments conducted at 463 salinity $35 \,\mathrm{g \, kg^{-1}}$ and $17 \,\mathrm{g \, kg^{-1}}$ did not differ markedly and exhibit a similar $\mathrm{d}N/\mathrm{d}T$ trend to Bowyer et al. (1990), Mårtensson et al. (2003), Hultin et al. (2011), Zábori et al. (2012) 465 and Salter et al. (2014, 2015). Salter et al. (2014) explained this temperature trend with a 466 shift in the surface water bubble population with changing temperature. The temperature 467 ramp at $S = 6 \,\mathrm{g \, kg^{-1}}$ exhibited aerosol production that was qualitatively similar to the 468 17 and $35 \,\mathrm{g \, kg^{-1}}$ ramps, but with a weaker amplitude (smaller $\mathrm{d}N/\mathrm{d}T$ values). It may be 469 that the two different processes both mediated through changes in bubble population by 470 either changes in temperature or salinity interfere with each other for low salinity waters. 471 Finally, we have derived a simple sea spray source parameterization of particle number and 472 particle effective radius as function of salinity and water temperature based on the observed 473 relationships that can be used to model the impact of salinity on sea spray production. 474

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The data of this study are available on the Bolin Centre for Climate Research Database (https://doi.org/10.17043/zinke-2021-laboratory-1).

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Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

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Supporting Information for

The effect of seawater salinity on sea spray aerosol production

J. Zinke ^{1,2}, E. D. Nilsson ^{1,2}, P. Zieger ^{1,2}, and M. E. Salter ^{1,2}

[1] Department of Environmental Science, Stockholm University, Stockholm, Sweden[2] Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden

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S2 Overview of the salinity experiments and temperature ramps conducted during this study.

Introduction

The supplementary information contains a description of the sea spray generation chamber that was used to conduct the experiments (Section S1) as well as a schematic of the chamber (Figure S1). Furthermore, we have added a description of the surface bubble spectrum measurements (Section S2) including a photograph of the water surface (Figure S2). Additional figures were included to depict the estimated particle losses in the sampling set up (Figure S3), the location of the size distribution modes at different salinities (Figure S4), a comparison of the measured total number by the CPC and the integrated number (Figure S5) and the effect of temperature at different salinities on aerosol number, surface, volume and effective radius (Figure S6). All figures result from the same dataset that was used in the main manuscript. Moreover, a table was added to provide an overview on previous studies on the effect of salinity (Table S1), as well as an overview table on the experiments conducted in this study (Table S2).

S1 Description of the Sea Spray Chamber

A temperature-controlled sea spray generation chamber fabricated from stainless steel was generating sea spray aerosols using a plunging jet. The jet, exiting a stainless steel nozzle with an inner diameter of 4.3 mm that was situated 30 cm above the air-water interface, was used to entrain air into the water. The plunging jet was generated by circulating the water from the bottom of the tank through the nozzle using silicone tubing and a peristaltic pump (620S, Watson–Marlow, Sweden) at a flow rate of 1.73 litres per minute. The inside of the tank was coated in polytetrafluoroethylene (PTFE) below the waterline, and was rinsed thoroughly with reagent grade ethanol and deionized water. Both seawater salinity and temperature were measured continuously using a conductivity sensor (model number 4120, Aanderaa, Norway) located halfway between the tank base and the air-water interface. Furthermore, concentrations of dissolved oxygen concentration were measured with an oxygen optode (model number 4175, Aanderaa, Norway). Relative humidity and temperature were measured using a Vaisala model HMT333 probe situated in the headspace of the sea spray chamber. Dry zero-sweep air entered the tank at 10 L min–1 after passing through an ultrafilter (Type H cartridge, MSA) and an activated carbon filter (Ultrafilter, AG-AK). A mass flow controller (Brooks, 5851S) was used to maintain and quantify the airflow rate. The particle-laden air was sampled through ports in the lid of the sea spray chamber and transferred to all aerosol instrumentation under laminar flow. Before entering the aerosol instrumentation, the particle-laden air was passed through nafion dryers (MD-700-48F/MD-700-36F, Perma Pure, USA) in order to reduce the relative humidity to well below 30%. The sea spray chamber was operated under slight positive pressure by maintaining the sweep air flow several litres per minute greater than the sampling rate to prevent contamination by room air and the excess air was released through a valve on the lid of the system. Figure S1 is a schematic of the set-up used.

S2 Surface bubble spectra measurements

The bubble size distribution at the water surface was determined by photographing the bubbles using a Pentax K-7 Digital Single Lens Reflex camera (DSLR) equipped with a SMC Pentax-DFA Macro 100 mm F/2.8 lens. The camera was located 40 cm above the water surface and approximately 10 cm from the centerline of the plunging jet. The aperture was closed to F/11 to increase the focal depth, and the lens was automatically focused on the water surface. The bubbles were illuminated against the dark background using a Pentax AF-540FGZ flashlight that was positioned in front of a submerged viewing window in the tank wall. Photos were taken every 60 s using the PK-Tether software (Tether Tools Inc.) to ensure that the same bubbles were not counted more than once. Circles were manually fit to each bubble in an imaging software (Inkscape editor) and their radii were read from the respective SVG-files. The mean number and standard deviation of bubbles at each salinity was estimated by averaging across 20 pictures at salinities \leq 4 g kg⁻¹, where the number of bubbles was low, and across five pictures at higher salinities, where the bubble density was much higher. The captured images had a resolution of 3104x4672 pixels corresponding to a monitored water surface area of 61x92 mm. Based on the pixel size and resolution of the camera sensor, the minimum discernable bubble film radius was estimated to be 0.02 mm.

Figure S1. Schematic of the sea spray simulation chamber used for the experiments.

Figure S2. Water surface photographed with a wide angle lens with picture frame used in this study for reference. The picture was taken at $S=35gkg^{-1}$ and $T=20^{\circ}C$.

Figure S4. The location of the modes at different salinities for (a) the number size distribution, (b) surface size distribution and (c) volume size distribution.

Figure S5. Comparison of particle concentrations measured by the total CPC and integrated over the combined size distribution.

Figure S6. Integrated concentrations of aerosol (a) number, (b) surface, (c) volume and (d) effective radius as a function of temperature at salinity 35 g kg⁻¹, 17 g kg⁻¹ and 6 g kg⁻¹.

Study	Simulation system	Sea water composition	Salinity range
Mårtensson et al. (2003)	Frit	Tropic Marin aquarium sea salt	0, 9.2, 33 g kg ⁻¹
Tyree et al. (2007)	Frit	Analytical grade salt mixture	1, 10, 20, 33, 70 g kg ⁻¹
Zábori et al. (2012)	Plunging jet	NaCl	0-35 g kg ⁻¹ , intervalls of 3 g kg ⁻¹
Park et al. (2014)	Frit	Sigma Aldrich sea salt	2, 5, 15, 32 g kg ⁻¹
May et al. (2016)	Plunging jet	NaCl	0.05, 0.15, 0.5, 10, 35 g kg ⁻¹

Table S1. Overview of previous studies on the effect of salinity on sea spray production.

Type of experiment	Salinity	Temperature	Duration		
First set of experiments					
Temperature ramps	35, 6 g kg ⁻¹	30-0 °C	46.5, 41.5 h		
Salinity experiments	35, 30, 25, 20,	20 °C	On average 2.5-3 h		
	15, 10, 8, 6, 5,		or over night		
	4, 3, 2, 1, 0 g kg ⁻¹				
Second set of experiments					
Temperature ramps	35, 17 g kg ⁻¹	30-2 °C	36.5 <i>,</i> 43 h		
Salinity experiments	35, 17, 10, 9,	20 °C	On average 2.5 h		
	8, 7, 6, 5.5, 4.5 g kg ⁻¹		or over night		

Table S2. Overview of the salinity experiments and temperature ramps conducted during this study.