



Smart distributed marine spray networks for atmospheric humidification: Droplet evaporation dynamics and nanotechnology-relevant aerosol formation

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The arid and semi-arid lands of Iraq are prone to severe hydrological strain and growing desertification. This study investigates the scientific possibility of establishing a widespread coastal evaporation system for seawater sprays to increase water evaporation in the atmospheric boundary layer and decrease the level of condensation during suitable atmospheric conditions. This paper combines the Schiller-Naumann hydrodynamic drag equations with the Ranz-Marshall convection-enhanced mass transfer model to overcome the standard simplifications of classical projectiles. The nanotechnology-related aspects of the proposed system are also considered by examining the potential formation of fine and nanoscale marine aerosols during seawater evaporation. Particular attention is given to the relationship between initial droplet dimensions, residual salt-particle formation, and their possible implications for atmospheric transport and environmental monitoring.

The results show that the evaporation efficiency of droplets between 200 and 500 μm is highly sensitive to atmospheric drag. The efficiency is above 80% for droplets smaller than 200 microns. For the 500 μm droplets, however, it goes down to about 21.4% because they reach terminal velocity earlier. For constant-mass-flow models, concentrated fields show a local vapor choke of approximately 7,300 m^3/day per 1000 m^2 of frontal area. This limitation forces you to work with a distributed geometry. We also followed the movement of moisture in space and time by using the ERA5 dataset and Lagrangian models so that we could see where the moisture is deposited. Calculations of hard deposits show that evaporation can produce about 1,058 metric tons of dry salt per m^3/second of seawater with particles ranging in size from 50 to 130 microns. This adds a lot to the aerosol population in the atmosphere, which includes nanoparticles, and changes the levels of $\text{PM}_{2.5}$. To limit operations that enable the most efficient transport of moisture, thus keeping coastal salinity and local air quality at high levels, the Moisture Opportunity Index (MOI) is created.

Keywords: Nanotechnology; Marine Aerosols; Nanoscale Salt Particles; Coastal Spray Evaporation; Moisture Opportunity Index (MOI).

1. INTRODUCTION

Central and southern parts of Iraq have developed into one of the world's most severe water crises. The causes of this large-scale problem include climate change, dwindling river flows coming into central/southern areas of Iraq from other countries and desertification, which is encroaching on more land with each passing year [1-3]. There is some evidence that cloud seeding can help alleviate shortages such as those seen today; however, this method does little or nothing during long-term droughts. Cloud seeding needs a large amount of moisture (rain) and stormy weather. Long periods of drought do not provide either of these factors [4]. Consequently, this lack of sufficient rainfall severely diminishes soil moisture and alters soil temperature profiles across the region [5]. To provide solutions for this issue, researchers in the last few years have developed the concept of “technologically enhanced atmospheric moisture” (TEAM) [6], which is an alternative to using natural clouds in arid areas. The concept of TEAM relies on adding artificial water vapor and nanostructure aerosols into the atmosphere at the edge of deserts. Artificially evaporating oceans and/or marine cloud seeding (MCB) are concepts already studied by scientists. As such, previous research has applied these technologies either to increase solar radiation reflection and thus lower global temperatures or assumed an infinite amount of moisture would be available for use, which does not account for real-world drought situations [7]. Past approaches failed due to their treatment of drip thermodynamics and moisture tracking as two independent issues [8].

In addition, past approaches did not consider the environmental consequences of salt depositions nor the established limits of how much water can be absorbed from the atmosphere by air [9]. Nanotechnology provides insight into the environmental effects of artificial seawater evaporation. Marine spray droplets may leave salt aerosols after evaporation, including possible nanoscale particles below 100 nm. These particles move, diffuse, grow hygroscopically and deposit themselves in very different ways. So, understanding how aerosols affect the environment is important, so characterizing them and modeling the atmosphere is important. This study provides a solution by proposing a control system which can control and manage distributed coastal spray systems in effective utilization of seawater. It produces the 'Moisture Opportunity Index' (MOI), which is a decision-making tool. It constantly monitors atmospheric conditions and uses MOI to determine when to release water into the environment. It determines when to activate the spray system using calculations that take into account the vapor pressure deficit (VPD), the depth of mixing, wind conditions, and the probability of rain. This index also ensures that all environmental rules are being followed and salt is not polluting the air. The novelty of this study is the consideration of droplet evaporation, capacity of atmospheric moisture, operational control and evaluation of aerosols by nanotechnology. The framework evaluates the performance of humidification and the possible impacts of fine and nanoscale salt particles, and offers a multiscale foundation for future research on atmospheric modeling, aerosol characterization and environmental monitoring in marine environments.

2. THEORETICAL FRAMEWORK

2.1 Droplet dynamics and hydrodynamic drags

Seawater droplet dynamics strongly affect residence time, evaporation and atmospheric transport. Some models only consider air resistance, but this study looks at both gravity and air resistance. The droplet is assumed as a spherical particle with instantaneous diameter (d) and its upward motion is described by the force-balance equation [10];

$$\frac{dv}{dt} = g - \frac{3\rho_a C_d |v|v}{4\rho_w d} \quad (1)$$

where v is velocity of the droplet, g is acceleration due to the gravity, ρ_a and ρ_w are densities of air and sea water, C_d is drag coefficient and d is diameter of the droplet. Drag opposes gravity driven motion. In the case of ($Re < 1000$), the correlation of Schiller-Naumann is used to calculate (C_d) [11], which gave a realistic reading of the resistance changing with the flow conditions. Droplet size strongly affects aerodynamic drag, settling velocity, and evaporation. Smaller droplets experience greater relative drag, increasing atmospheric residence time, whereas larger droplets settle faster. As evaporation reduces diameter, droplet dynamics continuously change. Therefore, motion and evaporation are coupled to estimate residence time, evaporation efficiency, and residual salt-particle size.

2.2 Droplet-bound evaporation mechanics

Seawater droplet evaporation is modeled using the modified (d^2)-law, describing progressive diameter reduction during mass transfer to unsaturated air. Because droplets move through the atmospheric boundary layer, the Ranz–Marshall correlation is included to account for forced-convection enhancement of evaporation. The squared-diameter reduction rate is then calculated accordingly [10]

$$\frac{d(d^2)}{dt} = - \frac{8D_v Sh(\rho_{v,s} - \rho_{v,\infty})}{\rho_w} \quad (2)$$

where d represents the instantaneous droplet diameter, D_v is the diffusion coefficient of water vapor in air, Sh denotes the Sherwood number, and ρ_w represents seawater density. The parameters $\rho_{v,s}$ and $\rho_{v,\infty}$ correspond to the water vapor densities at the droplet surface and in the surrounding atmosphere, respectively. The Sherwood number is determined using the Ranz–Marshall correlation, incorporating the Reynolds and Schmidt numbers to account for the combined effects of droplet motion and vapor diffusion [9,10].

Droplet evaporation depends on diameter, temperature, humidity, and residence time. Smaller droplets evaporate faster due to higher surface-area-to-volume ratios. Evaporated mass fraction is used to evaluate humidification efficiency. Progressive evaporation also concentrates dissolved salts, potentially forming fine residual marine aerosols, including nanoscale particles under favorable atmospheric conditions.

3. MASS CARRYING CAPACITY AND ENVIRONMENTAL LIMITATIONS

3.1. Air carrying capacity limits for water vapor

Atmospheric moisture capacity limits large-scale seawater spray performance. If mixing is allowed to continue indefinitely, the potential for evaporation and humidification may be overestimated [9]. Thus, the maximum amount of vapor that could be introduced is determined by measuring the flow of air, the humidity level and the amount of moisture that could be carried. The governing equation of atmospheric capacity is used to calculate the maximum water-vapor mass flux.

$$\dot{m}_{vap,max} = \rho_a S A (w_{out} - w_{in}) \quad (3)$$

where $\dot{m}_{vap,max}$ is the max mass flow rate of water vapor, ρ_a is the density of air, S is the speed of the incoming wind and A is the cross-sectional area of the airflow in the atmosphere. The parameters w_{in} and w_{out} represent the initial and the maximum humidity, and are given as the mass of water vapor per unit mass of dry air. The maximum humidity ratio that could be used is calculated from the wet-bulb saturation limit. The rate of vapor injection is limited by evaporation and how much water is in

the air so that the area didn't get too saturated. The seawater flow is regulated by a widespread spray network according to the wind and humidity. This control also influences the formation of residual aerosols, salt concentration, hygroscopic growth of particles and their transport. This contributes to the particle-size resolved environmental assessment of the marine spray systems.

3.2. Salt deposition risk framework

As seawater evaporates, nonvolatile salts become more concentrated and solid particles form that can remain in the atmosphere or deposit on nearby surfaces. These particles have been associated with salinization, plant damage and corrosion [12,13]. The theoretical salt load and dry-particle diameter are determined based on the salinity, seawater density, pumping rate, extent of evaporation and conservation of volumetric mass.

$$d_{dry} = d_o \left(\frac{S_n \rho_w}{\rho_{salt}} \right)^{\frac{1}{3}} \quad (4)$$

where d_{dry} is diameter of residual dry salt particles, d_o diameter of initial seawater droplets, S_n is salinity of seawater in the form of a mass fraction, and ρ_w and ρ_{salt} are densities of seawater and crystalline salt, respectively. At a seawater salinity of 3.5 wt.% and a halite density of 2160 kg/m³, droplets of 200–500 μm thickness leave salt residues of about 50–130 μm thickness. Depending on the type of salt, how it crystallizes, the shape of the particles, and the weather conditions that determine how much evaporates and how much residue is left behind, these idealized values can vary. The salt particles left behind are usually on the order of micrometers, but they can fragment into smaller aerosols. Their movement is dependent on the size, density, wind and stability of the atmosphere. The formation at the nanoscale is not clearly modeled and must be experimentally characterized. Spraying should be minimized when conditions are such that salt may move toward ecosystems or sensitive areas.

4. OPERATIONAL OPTIMIZATION AND THE STRUCTURE OF THE MOI INDEX

4.1 multi-criteria optimization index

The Moisture Opportunity Index (MOI) is a parameter that allows the control of various spray areas without the need for dimensions. It considers atmospheric, thermodynamic, aerodynamic and environmental factors to identify the best conditions for seawater evaporation and moisture transport, as well as the risks of marine aerosol and salt deposition. The MOI is set for each sector using the governing relationship.

$$MOI_i = F_{evap,i} F_{aircap,i} F_{wind,i} F_{dir,i} F_{lift,i} F_{sink,i} F_{safety,i} \quad (5)$$

MOI_i is Moisture Opportunity Index for spray sector i . Each factor is scored from 0 to 1, with higher scores indicating more favorable conditions for the operational criterion. The multiplicative formulation guaranties that the index is zero if any of the factors is zero, so that the sector is not activated if a specific atmospheric or environmental condition is absent.

The evaporation factor (F_{evap}) is a measure of the efficiency with which water is thought to be transferred from seawater droplets to the surrounding air. The atmospheric moisture-capacity factor (F_{aircap}) is a measure of the additional amount of water vapor that can be stored in the incoming airflow. The wind-speed factor (F_{wind}) describes the conditions in which sufficient air can flow through the atmosphere but not too many droplets and residual salt particles can be blown away by the wind. The wind-direction factor (F_{dir}) evaluates the degree of alignment between atmospheric airflow and the intended moisture-transport course to the Mesopotamian Valley.

The atmospheric lifting factor (F_{lift}) is a measure of the probability of vertical moisture transport by analyzing the boundary layer dynamics and the atmospheric stability. The moisture transport factor (F_{sink}) relies on Lagrangian atmospheric trajectory analysis data and quantifies the probability for air masses from coastal spray sectors to reach the selected inland regions. Finally, the environmental safety factor (F_{safety}) is a safety operational constraint that permits to reduce or stop spray activities when wind forecasts predict a high-risk of deposition of saline particles in agricultural areas, populated areas or sensitive coastal environments. Geographic information systems (GIS) and space observations might be helpful for locating and monitoring such environmentally sensitive areas [14,15].

Particle-size-resolved aerosol monitoring could improve assessment of fine and nanoscale salt transport and deposition. The MOI-based controller regulates sector pumping according to evaporation, atmospheric moisture capacity, and wind conditions. Pumping is reduced near saturation or during unfavorable conditions, while environmentally unsafe sectors are deactivated to minimize saline aerosol impacts.

5. SIMULATION METHODOLOGY

Throughout this research, Python has been utilized to build the models that mathematically describe how the climate will change, to manipulate climate datasets, to perform complex and advanced numerical calculations, and to solve the complex differential equations describing the rate of evaporation. Additionally, Python has been employed to create graphical representations of the data and to evaluate the spatial variability of ERA5.

5.1. Interpolating the ERA5 atmospheric reanalysis

In order to determine whether it is possible for the framework to be feasible in terms of seasonality, a variety of historical atmospheric parameters have been used from the ERA5 hourly reanalysis databases [15]. These databases are accessed through the Copernicus Climate Change Service (CDS). Large areas of the upper Tigris and Euphrates River systems' major source water basins are examined. Specifically, the areas included the northwestern Arabian Gulf, the Red Sea, the Gulf of Oman, and the eastern Mediterranean. Variables that are collected included temperature at 2 m, dew point, wind components at 10 m, PBLH (Boundary Layer Height), and CAPE (Convective Available Potential Energy).

5.2. Dispersion and transport of atmospheric moisture via Lagrangian models

The operation of the model can be confirmed that the injection of coastal vapors into the atmosphere has been successfully transported into the defined target coordinates of Iraq (30°-37°N, 43°-48°E) by an integrated transport line that ties the WAM2 layers v3 model [17] as a means to determine the mass of water vapor injected into the atmosphere and the HYSPLIT and FLEXPART models [18], which use the projected paths of the winds to locate the potential deposition areas.

In order to verify the effectiveness of the Lagrange models in transporting moisture, a forward trajectory simulation is conducted using the HYSPLIT model [19],[20] under favorable conditions for transporting moisture southeastward (on April 11, 2023). Results (see Figure 1) show perfectly matched spatial locations where the air mass originated at the coastal location (29.5°N, 48.8°E), penetrated the region of interest in Iraq, and demonstrated that there are large amounts of atmospheric lifting occurring during the course of the simulation. Additionally, both the horizontal cross-sections and vertical cross-sections indicate a high degree of effective atmospheric lift activity, which supports the operation of the stability factor (F_{lift}) as part of the MOI Index and demonstrates the capacity of

the atmospheric system to effectively transport and deposit the vapor introduced into the atmosphere onto its continental targets.

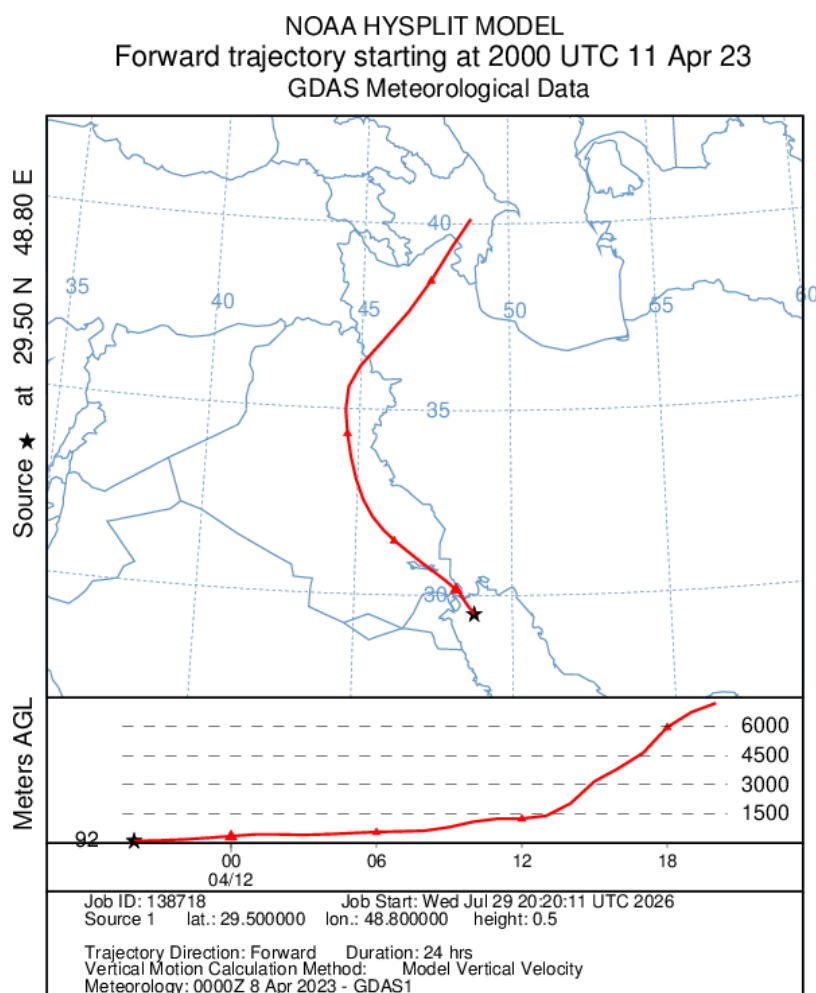


Figure 1 24-hour forward trajectory simulation in Iraq on April 11, 2023.

5.3. Nanotechnology-relevant aerosol assessment

Residual marine aerosols are theoretically assessed using droplet size, salinity, evaporation fraction, and mass conservation. The model estimates salt-particle size but does not resolve nanoscale nucleation or fragmentation. Future SMPS, SEM, TEM, and EDS measurements could determine nanoparticle distributions, morphology, dimensions, and composition, enabling experimental validation of marine aerosol formation.

6. RESULTS AND DISCUSSION

6.1 Droplet dynamics and evaporation efficiency

Beginning with the addition of hydrodynamic drag physics as well as terminal velocity, this leads to a difference between the calculated atmospheric residence time and net evaporation fraction when comparing those results to a simple model of the trajectory of a projectile. Numerically, it can be shown that, at the lower end of the size range (droplet diameter = 200 μm), a much higher level of evaporation that exceeds 80% is experienced by these droplets using the reference weather conditions ($T=35^\circ\text{C}$, $\text{RH}=40\%$, $S=5$ m/s) from an altitude of 50 m. The increased evaporation efficiency can be

attributed to the drag forces acting on the smaller-diameter drops that slow down the vertical fall rate, allowing for additional time to interact with the surrounding air.

By contrast, large droplets (500 μm) will evaporate at a much lower rate of approximately 21.4%. Droplets fall to their terminal velocities so quickly and spend such little time being affected by the atmosphere.

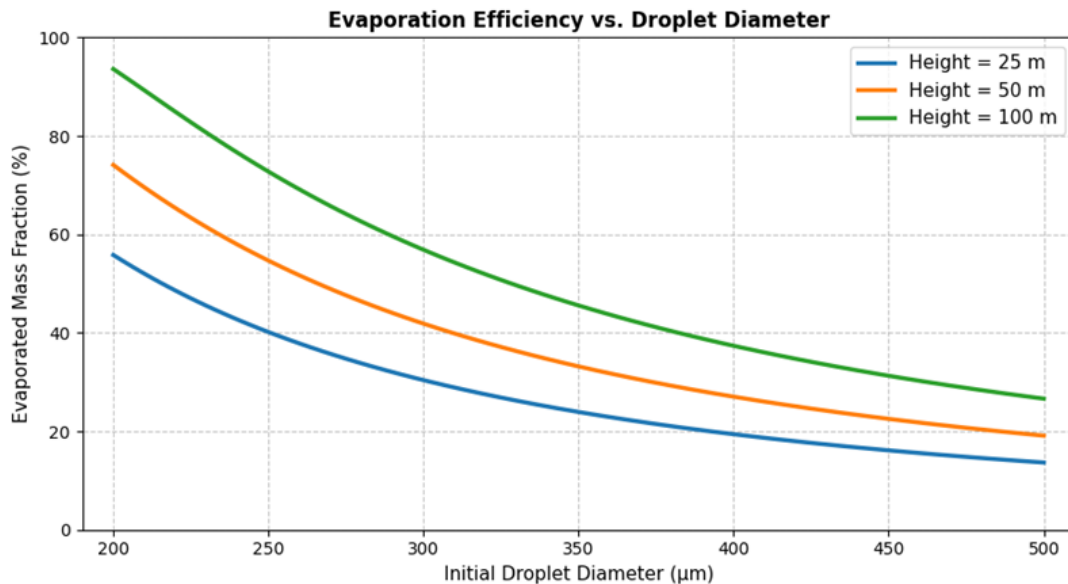


Figure 2 Efficiency of evaporation of the droplet and actual atmospheric survival time taking drag forces into account at altitudes of 25, 50, and 100 meters.

Figure (2) represents a non-linear, inverse relation between the ratio of evaporated mass with respect to the initial diameter of the seawater droplets injected and the ratio of the initial diameter of the droplets at three operating altitudes (25, 50, and 100 m) under the same reference atmospheric conditions (temperature = 35° C; relative humidity = 40%; wind speed = 5 m/s). In studying these curves, the following important things have been brought to light:

1. Effect of size (mechanical and thermodynamic): From Fig. 2, it can be seen that the evaporation efficiency decreases sharply with increasing size of the droplets. For instance, at 50 m altitude (orange curve), there is an approximate evaporation of 75% of the fine droplets (200 μm) compared to a loss of approximately 20% for larger droplets (500 μm). This phenomenon may be explained by two major effects:
2. Specific Surface Area: The smaller size of the drops gives them an increased surface area for volume ratio. The greater surface area for volume ratio will increase the rate of heat exchange through the law of d^2 .
3. Terminal Velocity: The terminal velocity of the larger droplet is much higher than that of the smaller droplet. As such, the large droplets (about 500 μm) become heavy enough to overcome hydrodynamic drag (C_d), fall faster toward the surface, and be removed sooner than they can be totally vaporized.
4. Effect of Injection Height (Air Exposure Time): The diagram indicates that the spray tower height has a significant impact on overall performance. Evaporation increased significantly when doubling the height of the tower from 25 meters (blue line) to 100 meters (green line). While an average 300 μm droplet will evaporate approximately 30% at a height of 25 meters, it evaporates to almost 55% at a height of 100 meters. The reason for such large differences in rate of evaporation is due to the fact that

the larger distance allows the drops to have additional air exposure, which provides longer times for convective forces to act upon the droplets.

5. Geometric and Operational Projection: The 100-meter elevation produces nearly complete evaporation (95% evaporation) of small droplets. However, this is environmentally unrecommended and also unpalatable in terms of its engineering implications. In addition to producing very small salt particles that could travel long distances through the air, total evaporation requires a large amount of energy to lift the water. This is directly related to the operating height as described by the hydraulic power equation:

$$P = \frac{\rho_w \times g \times h \times Q}{\eta} \quad (6)$$

An operating height near 50 m with 300–350 μm droplets balances energy use and evaporation efficiency (30–45%) while limiting airborne salt transport.

6.2 Air carrying capacity and cloud choke

Simulation showed strong gate effect of atmospheric moisture capacity. In the example, a flow of 5 m/s through a cross section of 1000 m^2 could have taken up about 7,300 m^3/day before it is saturated in the area. If you go beyond that limit, the vapor gets stifled, the droplets evaporate slower and you can apply distributed modular spraying instead of centralized operation.

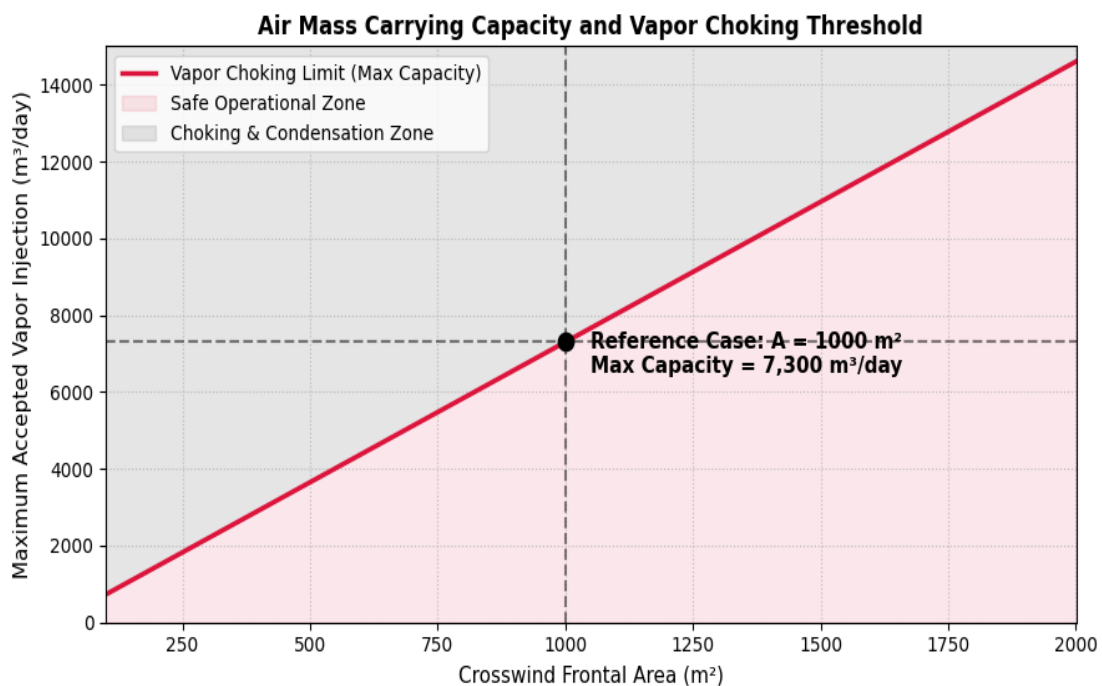


Figure 3 Correlation between the leading edge of a moisture cloud and the maximum amount of vapor that can be released in a day.

6.3 Environmental trade-offs: salt deposition barrier

At ($Q=1$) m^3/s and 35% evaporation efficiency, the amount of salt carried through the air is 12.25 kg/s or about 1,058 tons/day. The size of the salt particles left behind is 50–130 μm . Figure 4 shows the salt flux, which increases linearly with the increasing pumping rate and evaporation efficiency. Separate experiments are needed to confirm nanoscale aerosol formation.

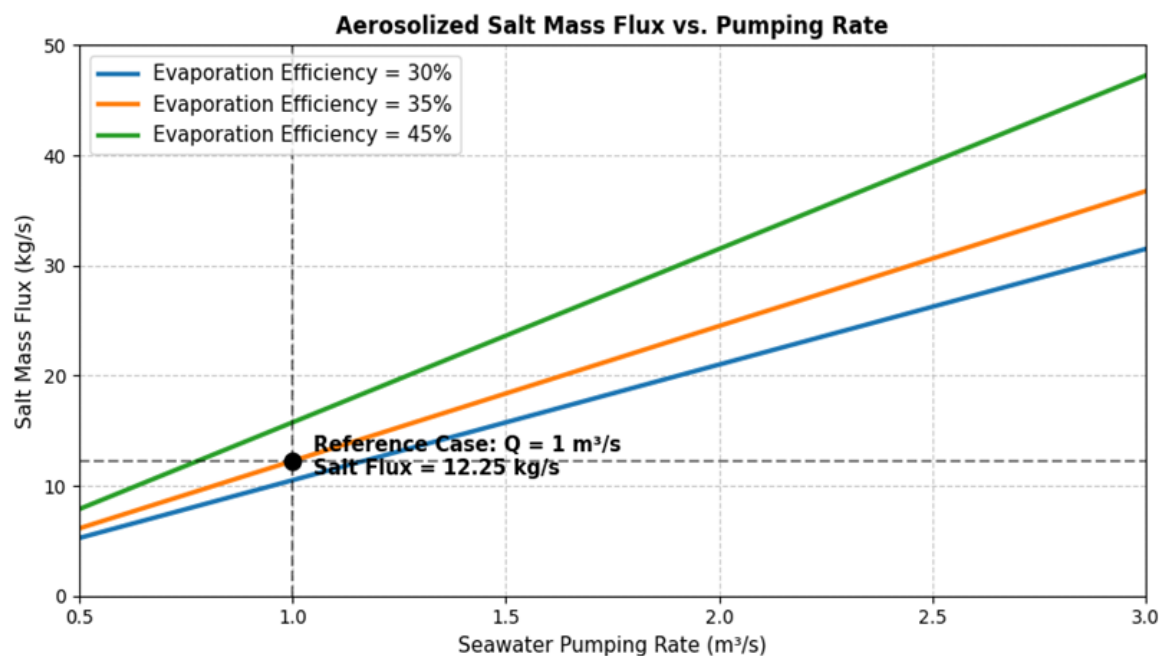


Figure 4 Theoretical dependence of the amount of salt retained in seawater at various evaporation rates on the rate of pumping seawater.

6.4. Nanotechnology-related implications of marine aerosol formation

Theory predicts primary salt residues will be 50-130 micron with possible formation of nanoscale aerosols from secondary fragmentation under some conditions. The way they land and move depends on their size, composition and the atmosphere. Table 1 shows the main operating parameters. This demonstrates the importance of particle-size-resolved monitoring and experimental nanoparticle characterization in future studies.

Table 1 Theorized parameters of seawater evaporation and their link to marine aerosol formation and environmental monitoring.

Parameter	Theoretical result or reference value	Nanotechnology-related implications
Initial seawater droplet diameter	200–500 μm	Influences evaporation rate and residual aerosol dimensions.
Proposed operating droplet diameter	300–350 μm	Provides a preliminary balance between evaporation performance and salt-residue considerations.
Reference injection height	50 m	Influences droplet residence time and potential aerosol transport.
Estimated evaporation efficiency	30–45% for the proposed operating range	Influences the concentration of residual salts within evaporating droplets.
Estimated dry salt-particle diameter	50–130 μm	Indicates micrometer-scale salt residues rather than demonstrated nanoparticles.
Illustrative salt-residue burden	Approximately 1,058 metric tons/day	Conditional mass-balance estimate at 1 m^3/s flow and 35% evaporation; indicates the potential particulate burden.
Potential nanoscale aerosol fraction	Below 100 nm	Requires experimental determination; not quantified in the current simulation.
Proposed nanoparticle characterization	SMPS, SEM, TEM, and EDS	Enables future characterization of particle-size distributions, morphology, and composition.

4. CONCLUSIONS

The current research explored the theoretical feasibility of a smart distributed marine spray network to enhance the humidity of the air in dry and semi-dry areas. It examined droplet evaporation dynamics, atmospheric moisture limitations, salt residue formation, and aerosol issues concerning nanotechnology. The computer results show that the droplet size and injection height were very important factors for evaporation efficiency. Because they had a greater surface area to volume ratio, the smaller droplets evaporated more easily, and stayed in the air longer. The optimal operating conditions were found to be an initial droplet diameter of about 300–350 μm and an injection height of 50 m, with 30–45 % evaporation efficiency in the conditions studied. The atmosphere was estimated to be able to store about 7,300 m^3 of water per day for a reference frontal area of 1,000 m^2 . This illustrates the importance of spreading seawater injection over a few operating sectors to avoid over-saturating areas of the atmosphere. Theoretical calculations of salt residue also showed that spraying large amounts of seawater could produce large numbers of particles, so it was important to take a close look at the motion of these particles through the air and into the environment. The estimated dry residues of the droplet sizes investigated were mainly in the micrometer range. Thus, their sizes do not provide evidence for the formation of nanoparticles. In any case, investigation and characterization of aerosols with the help of nanotechnology could provide us with useful additional information on how smaller particles could be fabricated, transported and influence the environment. The proposed Moisture Opportunity Index presents a framework to think about how to take advantage of weather conditions and environmental constraints to improve performance of distributed spray networks. In the future, experiments should be conducted to verify the efficiency of evaporation, to quantify the amount of salt deposition and aerosols of various sizes, and to determine the energy and space requirement for

the suggested system. In general, this study establishes the computer framework for the study of distributed atmospheric humidification and determines the additional measurements necessary to assess its feasibility for aerosol monitoring and environmental protection strategies based on nanotechnology.

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