



Assessing evaporative cooling from seawater spraying in the marine boundary layer

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Abstract. Increasing frequency and intensity of extreme heat events motivate improved understanding of processes that may modify near-surface thermal conditions. This study investigates seawater spraying as a method for direct atmospheric cooling. Using large-eddy simulations (LES), we quantify plume dynamics, cooling response, and impacts on heat stress across a range of atmospheric conditions. Simulated spray rates of 50 L s^{-1} produce near-surface temperature reductions of approximately 0.5–1 °C within the first few kilometers. Although theoretical analysis suggests that evaporative cooling potential can exceed –20 °C under hot and dry conditions, atmospheric mixing and advection substantially reduce this potential under realistic conditions. Cooling is strongest near the source due to evaporatively driven downdrafts, but decays rapidly downstream. We compare deployment from wind turbines with ship-based platforms. A key finding is that injection height governs plume structure and cooling response. Ship-based spraying produces strong, localized near-surface cooling, whereas wind turbine deployment redistributes cooling more effectively within the lower boundary layer. The turbine wake modifies local mixing, but vertical redistribution is mainly governed by evaporatively driven buoyancy perturbations. Extending the analysis to human thermal comfort reveals that temperature reductions alone do not determine effectiveness. Changes in Heat Index are non-linear and depend on background humidity, with benefits near the source that may diminish or even reverse downstream. Overall, seawater spraying can provide measurable cooling, but its performance is highly sensitive to background atmospheric conditions.

1 Introduction

Extreme heat events are among the deadliest weather-related hazards under ongoing climate change (World Meteorological Organization (WMO), 2026). The years 2015–2025 were the hottest on record, and the combination of high temperature and humidity is pushing environmental conditions toward human physiological limits (Raymond et al., 2020; Pal and Eltahir, 2016). Near life-threatening “feels-like” temperatures have already been reported in vulnerable regions, including values of 55 °C in India, 62 °C in Dubai, and 60 °C in Southern West Africa (Times of India, 2024; Euronews, 2024; World Weather Attribution, 2024; Sojan and Srinivasan, 2024). This contributes to rapidly increasing global health risks, with large fractions of the population exposed to dangerous heat and significant impacts on mortality, productivity, and livelihoods (World Meteorological Organization (WMO), 2026). In Europe as well, extreme summer heat is becoming increasingly hazardous, with



25 heat-related mortality projected to reach 2 million deaths by the end of the century under the SSP3-7.0 scenario (Janoš et al., 2025; Masselot et al., 2025). These trends highlight the need to better understand climate adaptation strategies that interact with atmospheric processes to modify near-surface thermal conditions and human heat exposure.

One mechanism that can locally modify atmospheric temperature is the injection of liquid water into unsaturated air, which induces cooling through droplet evaporation. This process is well understood from basic thermodynamics and is observed in
30 both natural systems, such as waterfalls and sea spray, and engineered applications including evaporative cooling and misting systems in urban environments (Amer et al., 2015; Yan et al., 2021; Nishimura et al., 1998; Jacobs et al., 2020; Huang et al., 2025b). However, while small-scale applications operate at relatively low flow rates and spatial scales, the atmospheric response to larger-scale water injection under realistic boundary layer conditions remains uncertain.

At sufficiently large injection rates, evaporative cooling has the potential to influence temperature and humidity over kilo-
35 meter scales. Figure 1 illustrates an example concept in which seawater is sprayed from offshore wind turbines, enabling continuous injection at elevated heights (TGIP, 2026). Such configurations provide a useful framework to investigate how the marine atmospheric boundary layer responds to localized sources of liquid water, including the role of turbulent mixing, buoyancy, and advection in regulating thermodynamic changes.



Figure 1. Artist impression of a spray of liquid water droplets from the back of the hub of an offshore wind turbine (TGIP, 2026).

A key consideration is that evaporative cooling not only reduces temperature but also increases atmospheric moisture. Be-
40 cause humidity strongly influences human heat stress, the net effect on perceived conditions is not straightforward and depends on the coupled response of temperature and moisture (Sherwood, 2018). Several indices exist to quantify human thermal comfort, including the Physiological Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI) and Hittekracht (an adaptation of the Wet Bulb Globe Temperature; WBGT) (Höppe, 1999; Di Napoli et al., 2021; Pereira Marghidan et al., 2026). In this study, we adopt the Heat Index, which combines air temperature and humidity into a measure of perceived thermal stress



45 and is widely used in operational forecasting and applied in urban heat-exposure studies (Steadman, 1979; Rothfus, 1990; Anderson et al., 2013; NWS, 2025; Perera et al., 2022). This provides a convenient diagnostic to evaluate how thermodynamic changes induced by evaporation translate into variations in heat stress.

The effectiveness of evaporative cooling under atmospheric conditions depends on the interaction between thermodynamic constraints and boundary layer dynamics. Thermodynamics defines the potential temperature response, but the translation of
50 this potential into near-surface cooling depends on plume evolution in a turbulent atmosphere. A process-based understanding is therefore needed to assess whether localized moisture sources can produce kilometer-scale temperature reductions and how such changes affect perceived heat stress.

To address this question, we combine an idealized thermodynamic analysis with large-eddy simulations (LES). First, we estimate the thermodynamic upper bound of evaporative cooling as a function of atmospheric temperature and relative hu-
55 midity. We then use LES to quantify the response of the marine boundary layer to seawater spraying, including plume-scale temperature and humidity transport, turbulent mixing, buoyancy-driven motion, and vertical redistribution. As a novel injection configuration, we compare elevated spraying from wind turbine height with ship-based spraying, allowing us to assess how source height controls plume structure and cooling response. Finally, we evaluate the resulting changes in Heat Index to determine how the coupled temperature and humidity perturbations translate into perceived heat stress. This approach links
60 thermodynamic limits to boundary layer processes and provides a physically based assessment of evaporative cooling in a turbulent atmosphere.

2 Applied atmospheric thermodynamics for maximum evaporative cooling

We consider an idealized air parcel to derive the thermodynamic limits of evaporative cooling. This framework provides an upper bound on temperature reduction against which the LES results can be interpreted. The formulation isolates thermodynamic
65 constraints from dynamical effects such as mixing and advection.

We formulate a set of equations describing the thermodynamic response of an idealized air parcel to the injection and evaporation of liquid water. We consider an air parcel of volume V , characterized by temperature T_{atm} , water vapor specific humidity $q_{\text{v,atm}}$, and pressure p . The total mass of the parcel consists of dry air $m_{\text{d,atm}}$ and water vapor $m_{\text{v,atm}}$. A mass of liquid water m_{l} is introduced into this system.

70 If the initial air is unsaturated, the injected liquid water evaporates, resulting in cooling, as illustrated in Figure 2. The evaporative cooling process continues until saturation is reached. We determine the maximum amount of liquid water $m_{\text{l,max}}$ that can be evaporated before saturation occurs, and the corresponding minimum temperature T_{min} achieved in the parcel. Both quantities depend on the initial atmospheric state T_{atm} and relative humidity RH_{atm} . A summary of thermodynamic definitions and constants is provided in Appendix A.

75 At saturation, the water vapor content reaches its maximum value at T_{min} , and the water vapor specific humidity can be written as

$$q_{\text{v,max}} = q_{\text{sat}}(T_{\text{min}}, p) = \frac{m_{\text{v,atm}} + m_{\text{l,max}}}{m_{\text{d}} + m_{\text{v,atm}} + m_{\text{l,max}}} \quad (1)$$

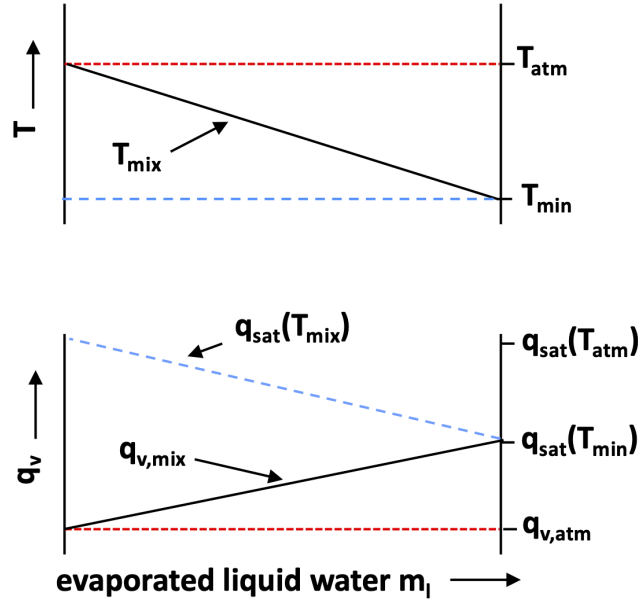


Figure 2. Schematic of evaporative cooling in an air parcel. The upper panel shows the temperature decrease toward T_{mix} , while the lower panel illustrates the evolution of water vapor specific humidity $q_{v,\text{mix}}$ and saturation specific humidity q_{sat} .

This expression assumes that all injected liquid water is available for evaporation and that saturation is reached locally within the parcel. Here, the total water vapor mass at saturation consists of the initial environmental vapor $m_{v,\text{atm}}$ and the evaporated liquid water $m_{l,\text{max}}$.

The corresponding temperature decrease follows from energy conservation, where evaporative cooling removes sensible heat from the air parcel:

$$(c_{p,d}m_d + c_{p,v}m_{v,\text{atm}})(T_{\text{min}} - T_{\text{atm}}) = -L_v m_{l,\text{max}}. \quad (2)$$

Here, $c_{p,d}$ and $c_{p,v}$ denote the specific heat capacities of dry air and water vapor at constant pressure, and L_v is the latent heat of vaporization. This relation expresses conservation of energy, where latent cooling due to evaporation is balanced by a reduction in sensible heat. We neglect the energy required to cool the injected liquid water itself. This contribution scales with $c_l m_{l,\text{max}}$ (liquid phase) or $c_{p,v} m_{l,\text{max}}$ (vapor phase) and is small compared to the latent heat, as $c_{p,v}$ and c_l are on the order of $10^3 \text{ J kg}^{-1} \text{ K}^{-1}$, while L_v is on the order of 10^6 J kg^{-1} .

Combining Eqs. (1) and (2) allows us to determine $m_{l,\text{max}}$ and T_{min} as functions of the initial state. This formulation represents an upper bound, as it assumes complete evaporation and neglects processes such as droplet sedimentation and incomplete mixing, both of which may reduce the achievable cooling under atmospheric conditions.



According to Rogers and Yau (1989), droplets with radius $r < 40 \times 10^{-6}$ m follow a terminal velocity relation $w_T(r) = 1.19 \times 10^8 r^2$, implying that droplets of radius $\sim 3 \mu\text{m}$ settle at approximately 1 mm s^{-1} . Larger droplets or incomplete evaporation would further reduce the effective cooling.

95 The resulting cooling potential depends strongly on the initial thermodynamic state of the atmosphere. As shown in Figure 3, higher temperatures allow for stronger cooling due to the exponential increase of q_{sat} with temperature (governed by the Clausius–Clapeyron relation). Similarly, lower relative humidity increases the available evaporation capacity and thus enhances the cooling potential.

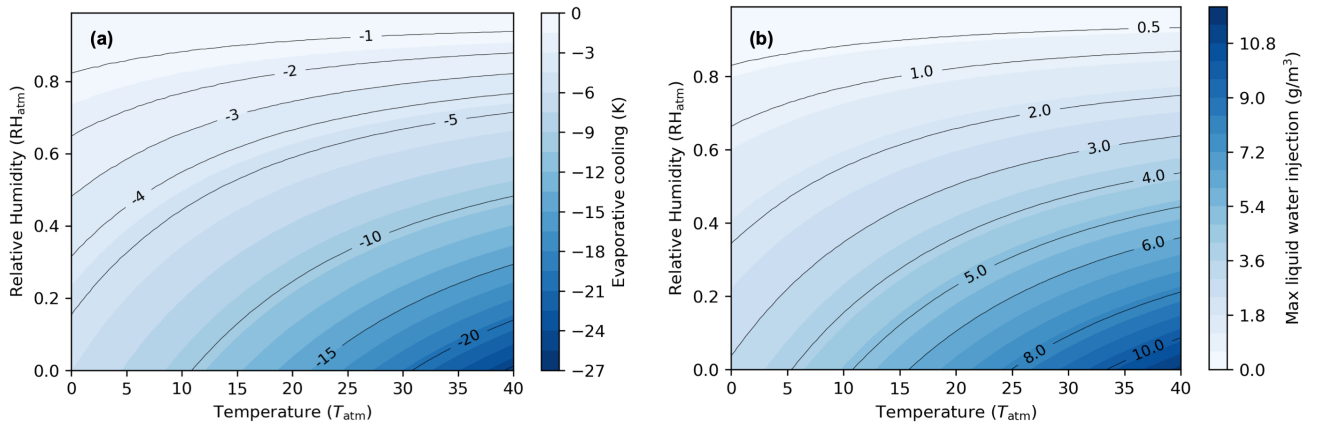


Figure 3. (a) Maximum evaporative cooling as a function of atmospheric temperature and relative humidity. Cooling potential increases with temperature and decreases with RH due to Clausius–Clapeyron scaling. (b) Corresponding maximum liquid water mass $m_{l,\text{max}}$ that can be injected per unit volume before saturation is reached.

To relate these thermodynamic changes to perceived conditions, we translate temperature and humidity variations into changes in Heat Index, following the National Weather Service (NWS) formulation (see Eq. 3) (Rothfus, 1990; NWS, 2025). This approach uses a polynomial approximation following Steadman for moderate conditions and transitions to the Rothfus regression at higher temperatures and humidity, reflecting the strongly nonlinear response of apparent temperature.

$$\text{HI}(T, RH) = \begin{cases} a_0 + a_1 T + a_2 RH + a_3 T RH, & \text{for moderate conditions,} \\ b_0 + b_1 T + b_2 RH + b_3 T RH + b_4 T^2 + b_5 RH^2 + \\ b_6 T^2 RH + b_7 T RH^2 + b_8 T^2 RH^2 + A(T, RH), & \text{otherwise.} \end{cases} \quad (3)$$

The coefficients a_i and b_j follow the NWS implementation of the simplified polynomial and the Rothfus regression (Rothfus, 1990; NWS, 2025). The Rothfus regression is applied when the Heat Index exceeds $\approx 26.6^\circ\text{C}$. Heat Index values are



categorized according to NOAA guidelines, ranging from safe conditions ($< 26.6^{\circ}\text{C}$) to extreme danger ($> 51.1^{\circ}\text{C}$), providing a qualitative framework to interpret changes in heat stress.

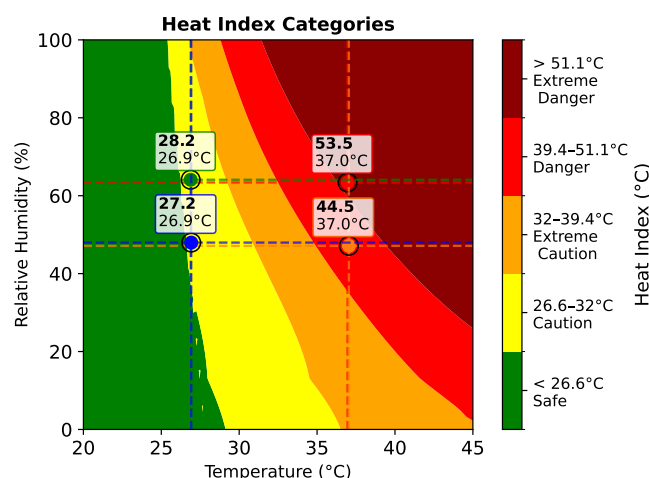


Figure 4. The Heat Index as a function of temperature and relative humidity. Four example atmospheric conditions are highlighted, comparing the temperature (bottom) with the corresponding Heat Index (top, bold).

Figure 4 shows the Heat Index as a function of temperature and relative humidity, illustrating its non-linear behavior. The four dots indicate example atmospheric conditions and demonstrate that, at high temperatures, humidity can increase the Heat Index by up 9°C . In contrast, at lower temperatures this increase is only about 1°C , highlighting the much stronger impact of humidity under hotter conditions. This idealized framework provides a reference against which the impact of boundary layer dynamics can be assessed in the following sections.

3 Set-up of atmospheric modeling

To assess the implications of the theoretical analysis (Section 2), we employ large-eddy simulations to quantify the atmospheric response to seawater spraying. For this, we use an adapted version of the Dutch Atmospheric Large Eddy Simulation Model (DALES) v4.4 described in Heus et al. (2010). DALES is widely used to study atmospheric boundary layer and cloud processes (Siebesma and Cuijpers, 1995). As it explicitly resolves the larger turbulent eddies and associated thermodynamic perturbations, it is well suited to investigate responses to seawater spraying. To investigate the atmospheric response under representative environmental conditions, we define four combinations of atmospheric temperature–humidity based on typical conditions over the Mediterranean Sea and Persian Gulf. Each atmospheric condition is denoted using two letters and its corresponding ambient values (T_T for temperature in $^{\circ}\text{C}$ and RH_{RH} for relative humidity in %). Figure 5a shows the four atmospheric conditions mapped on the maximum evaporative cooling figure (see Fig. 3), to indicate their respective cooling po-



tential. These regimes are also selected to span a range of thermodynamic conditions associated with different buoyancy-driven vertical motions.

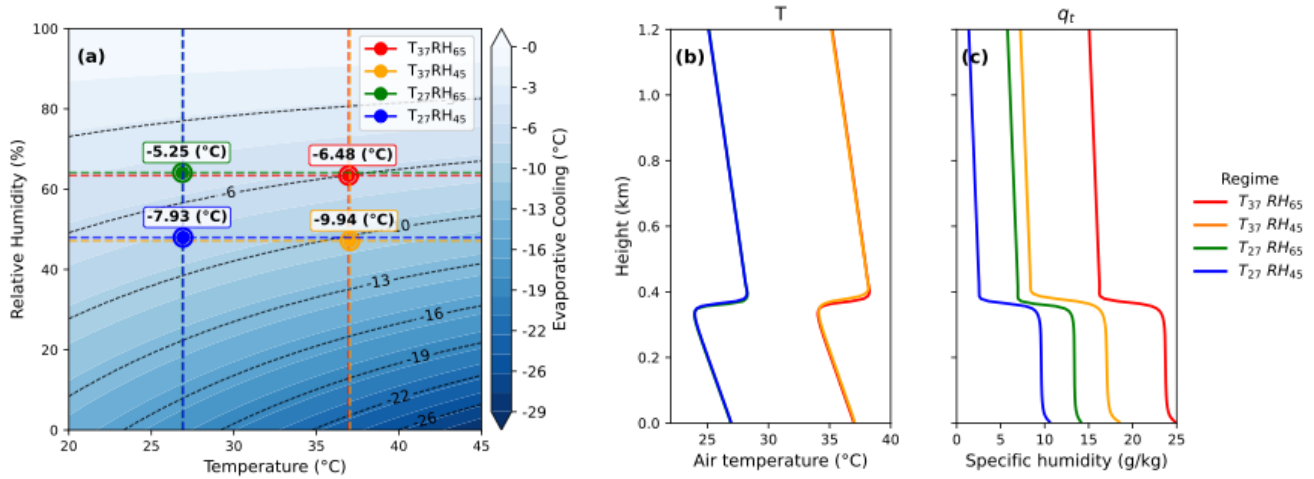


Figure 5. (a) The four atmospheric conditions studied mapped on the Maximum evaporative cooling figure 3, denoted using two letters and its corresponding ambient values (T_T for temperature in °C and RH_{RH} for relative humidity in %). (b) The initial vertical input profiles for each atmospheric case: temperature (°C) and specific humidity (g kg^{-1}).

125 The simulations are performed using the DALES model on a domain of size $25.6 \times 6.4 \times 1.28 \text{ km}^3$ (x, y, z) with a horizontal (vertical) resolution of 25 m (7.5 m) and 170 vertical levels, ensuring sufficient resolution for turbulent structures. The domain size is chosen to capture plume development over kilometer scales while minimizing the influence of periodic boundary conditions. The initial boundary layer height is set to 350 m. An inversion jump is prescribed of +5 K in liquid water potential temperature (θ_l) and -5 g kg^{-1} in total specific humidity (q_t), while free tropospheric gradients are set to 6 K km^{-1} for θ_l and $-1.5 \text{ g kg}^{-1} \text{ km}^{-1}$ for q_t . To maintain computational efficiency and allow for sustained plume development, geostrophic winds are prescribed to match the initial horizontal wind velocity, with $u_g = 5.5 \text{ m s}^{-1}$ and $v_g = 0 \text{ m s}^{-1}$. Surface pressure is set to 1010 hPa. Simulations are initialized with a subgrid turbulent kinetic energy (TKE) of $0.1 \text{ m}^2 \text{ s}^{-2}$ and spun up for 7200 s. Subgrid-scale turbulence is represented using a prognostic turbulent kinetic energy (TKE) scheme, following the standard DALES configuration. After spin-up, θ_{ls} is adjusted such that a mean $\theta_{k=1} - \theta_{ls} = 0.1 \text{ K}$ is maintained. Here, θ_{ls} denotes the surface-layer liquid water potential temperature used in the surface flux calculation. This ensures consistent dynamical structures while preserving the atmospheric state. Simulations are initialized under horizontally homogeneous conditions using prescribed vertical profiles of temperature and specific humidity. After the spin-up period, the resulting atmospheric profiles are used as the initial state for the spray simulations and are shown in Fig. 5b. Surface fluxes are computed interactively using Monin–Obukhov similarity theory. Large-scale subsidence is neglected for simplicity, and no large-scale temperature or moisture tendencies are imposed during the simulations.



Similar to Maalick et al. (2014), seawater spraying is incorporated into DALES by perturbing the prognostic equations for q_t and θ_l (see Appendix B for further details). Simulations are performed with a continuous water spray rate of 50 L s^{-1} . This spray rate represents a moderate forcing magnitude, chosen to assess the atmospheric response to sustained localized moisture input. It is larger than spray rates used in urban misting systems, but remains within the range of industrial-scale water fluxes and is consistent with order-of-magnitude energy constraints for turbine-powered systems.

DALES uses a diagnostic saturation adjustment scheme, so the simulations are not explicitly limited by the saturation constraint derived in Sect. 2. Based on the saturation deficit for each thermodynamic regime and the grid-cell volume, the chosen spray rate leads to strongly localized cooling near the source. Spray perturbations are applied at designated grid points at each model time step, representing a continuous localized source of moisture and latent cooling. Tracer advection is computed using the Kappa scheme (Tatsumi et al., 1995). Cloud droplet processes are represented using a two-moment microphysics scheme (Seifert and Beheng, 2001).

To investigate different injection configurations, seawater spraying is simulated from multiple heights. A wind turbine parameterization is included through momentum sink terms in the Navier–Stokes equations, representing the rotor, tower, and nacelle forces following Meyers and Meneveau (2010) and van Dorp (2016). The turbine corresponds to a Vestas 2 MW system with a hub height of 80 m and a rotor radius of 40 m (Wu and Porte-Agel, 2015). The Concurrent Precursor method is used to generate turbulent inflow conditions (Stevens et al., 2014; Munters et al., 2016). For turbine-based spray cases, the water source is located at hub height. In addition, lower-altitude spraying at $z = 15 \text{ m}$ is included to represent injection from ships or other near-surface infrastructures. Note that no additional parametrization is included to represent a vessel or its exhaust.

For each temperature–humidity regime, five simulations are conducted, representing different configurations of seawater spraying and infrastructure (See Table 1). Each simulation is run for 1.5 hours with continuous spraying, with an initial spin-up period of 2 hours to allow the boundary layer to develop turbulence. The chosen setup represents an idealized marine boundary layer, allowing isolation of the physical processes governing plume evolution and evaporative cooling. While simplified, this configuration captures the key interactions between turbulence, buoyancy, and moisture that control the atmospheric response to localized water injection.

Case name	Seawater spray	Wind turbine	Ship
REF			
Turbine Spray	X	X	
Spray	X		
Turbine		X	
Ship Spray	X		X

Table 1. Overview of simulation settings. REF is the post-spin-up reference case. Turbine Spray includes seawater spraying at wind turbine hub height and the turbine parametrization. Spray uses hub height spraying without the turbine parametrization. Turbine includes only the turbine parametrization. Ship Spray represents low-level spraying at $z = 15 \text{ m}$.



165 4 Results: Atmospheric modeling

We analyze the LES results in terms of anomalies relative to the corresponding reference simulation. We first examine the temperature response and plume structure, focusing on the roles of background thermodynamic state and injection height. We then evaluate how the coupled temperature and humidity perturbations translate into changes in Heat Index.

4.1 Temperature response and plume structure

170 Figure 6 presents the near-surface temperature anomalies induced by seawater spraying for four background thermodynamic conditions, comparing spraying from a turbine or ship.

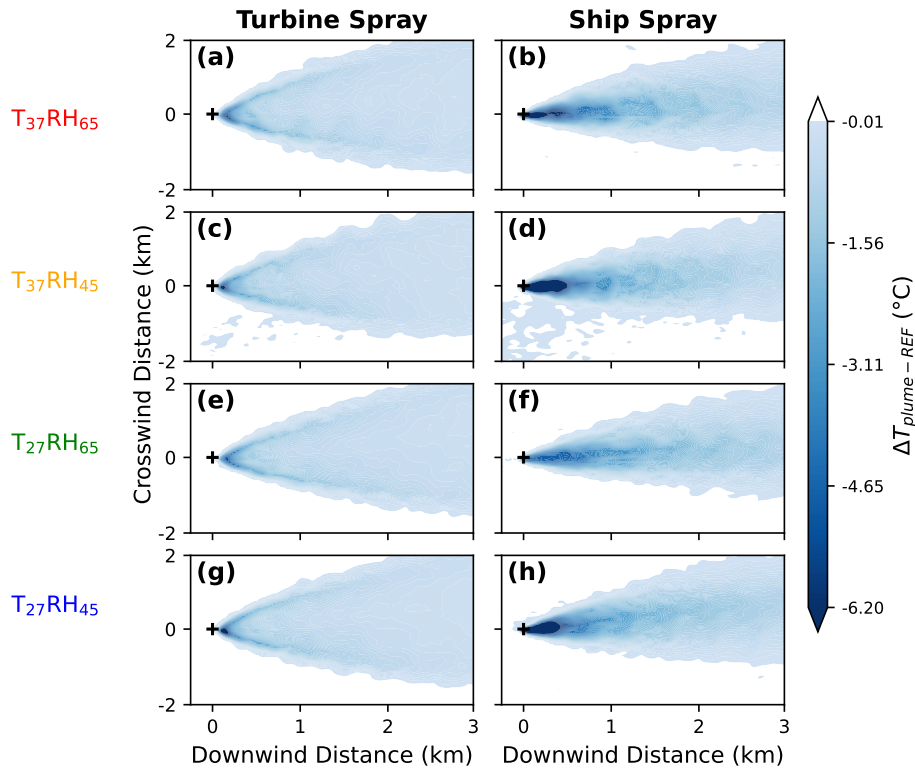


Figure 6. Near-surface horizontal distribution of the temperature anomaly $\Delta T_{\text{plume}-\text{REF}}$, averaged over the final 30 min of the Turbine Spray and Ship Spray simulations. The domain is shown for the first 3 km downwind of the source. Each row represents an atmospheric condition $T_{\text{T}}\text{RH}_{\text{RH}}$, with subscripts indicating the initial near-surface temperature and relative humidity. The color scale uses column-consistent percentile limits. The in-plume region is defined as the coldest 20 % of ΔT .

In all atmospheric conditions, a coherent cooling plume forms at the source and extends several kilometers downwind while widening laterally. Maximum cooling occurs within the first few hundred meters and decays steadily thereafter. Beyond $\sim 1\text{--}2$ km, only weak negative anomalies remain. Atmospheric conditions primarily control cooling magnitude, particularly



for ship-based spraying (right; b,d,f,h). Within the first kilometer, the $T_{27}RH_{65}$ case exhibits a weaker and less concentrated cooling core compared to the warmer regimes, whereas $T_{37}RH_{65}$ and $T_{37}RH_{45}$ show stronger near-source cooling. In contrast, turbine-based spraying (left; a,c,e,g) produces more similar patterns across all regimes, indicating reduced sensitivity to background conditions. Injection height mainly governs plume structure by determining where the evaporative cooling perturbation is introduced relative to the surface layer and lower boundary layer turbulence. Ship-based spraying generates a narrow, elongated cooling core with sharp lateral gradients, while turbine-based spraying produces a broader and more diffuse plume due to enhanced vertical mixing. Overall, background conditions primarily determine the near-source cooling intensity through the available saturation deficit, whereas injection height controls plume geometry, vertical redistribution, and downstream persistence.

To quantify how the cooling signal is vertically redistributed, we compute plume-averaged vertical profiles of the temperature anomaly, distinguishing between the near field (within 3 km downstream) and the far field (beyond 3 km to the end of the model domain). Figure 7 shows the corresponding plume-averaged temperature anomaly profiles for both spray configurations and all four atmospheric regimes. Shading denotes one standard deviation and therefore represents spatial variability within the plume.

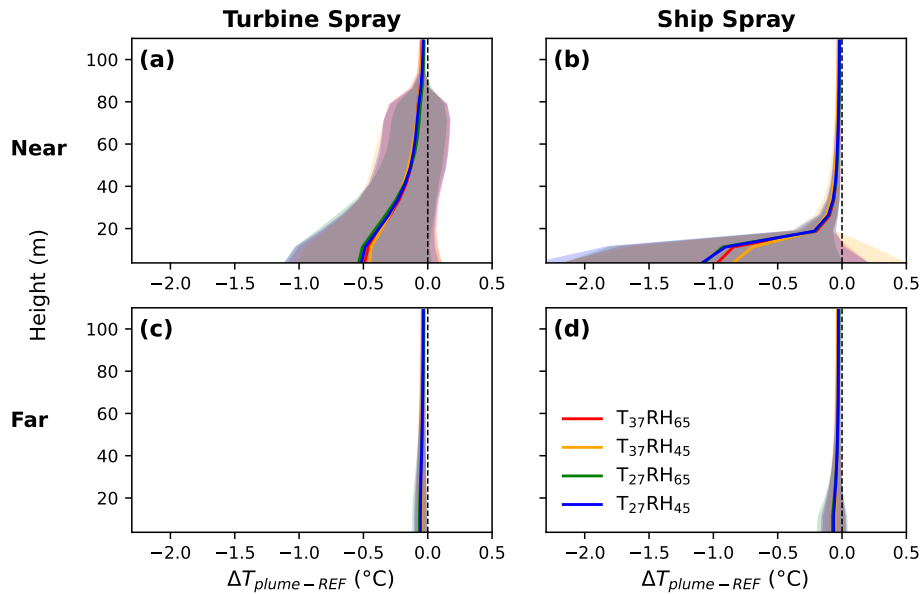


Figure 7. Vertical profile of ΔT averaged over the final 30 minutes for the in-plume region, defined as the coldest 20% of the temperature anomaly, in the near-field (≤ 3 km) and far-field (> 3 km) for both Turbine Spray and Ship Spray. Each color represents an atmospheric condition $T_{TRH_{RH}}$ with the subscripts indicating their initial values at near-surface height. Solid lines denote the mean in-plume cooling, while shaded areas indicate one standard deviation, representing spatial variability within the plume.



Peak plume-averaged cooling ranges from -0.5°C for the wind turbine spraying to -1.0°C for ship-based spraying in the near-field and close to the surface. Wind turbine spraying redistributes cooling over a larger vertical extent. As a result, plume-averaged cooling is enhanced between approximately 20–80 m vertically. Locally, near the surface, ship-based spraying can produce stronger cooling, but this cooling weakens rapidly with height due to the lower injection altitude. Reflected through the shaded areas in Figure 7, spatial variability increases toward the surface, although temperature anomalies remain predominantly negative. In the far field, temperature anomalies are substantially reduced for both configurations to tenths of degrees, and differences between spray types become small. This shows that elevated injection enhances vertical redistribution of the cooling anomaly, whereas low-level injection maximizes the near-surface response but confines it to a shallower layer.

To understand the differences in plume structure caused by turbine- and ship-based spraying, we examine the detailed near-surface and vertical structure of the cooling plume for $T_{37}\text{RH}_{65}$, shown in Fig. 8. This atmospheric regime is chosen because it combines high temperature with high humidity and therefore represents a case in which both evaporative cooling and humidity effects are important. The cross-sections show evaporatively driven downdrafts within the plume, particularly for the turbine configuration, similar to subsiding shells around shallow cumulus clouds (Heus and Jonker, 2008; Huang et al., 2025a). While the wind turbine does not necessarily produce a larger horizontal near-surface footprint, it leads to a more effective vertical redistribution of cooling within the lower part of the boundary layer, in line with Fig 7. This indicates that injection height alters how evaporative cooling is redistributed vertically within the lower boundary layer.

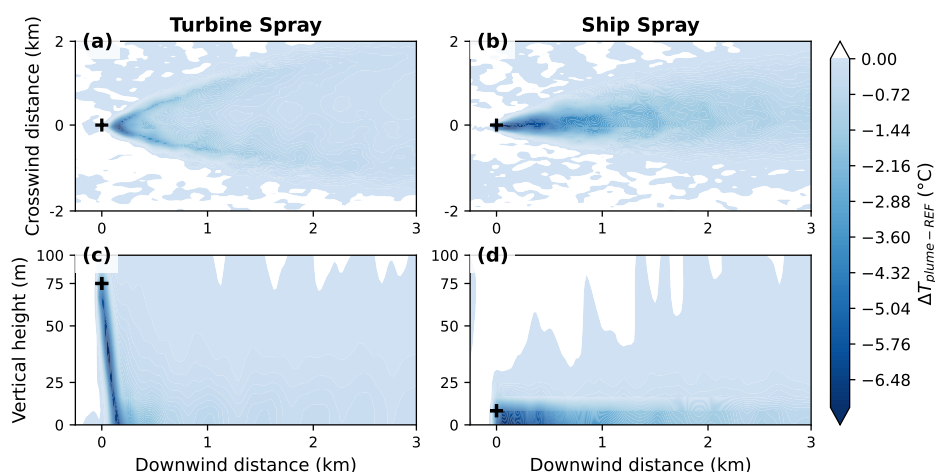


Figure 8. Representative near-surface horizontal and vertical structure of the evaporative cooled plume for the $T_{37}\text{RH}_{65}$ condition. The top row shows near-surface temperature anomalies (ΔT) in the horizontal plane, while the bottom row shows vertical cross-sections through the plume centerline. Results are shown for the Turbine Spray configuration (left column) and the Ship Spray configuration (right column). Temperature anomalies are defined relative to the corresponding reference simulation.

Further downwind, the associated temperature anomalies decay rapidly with distance and diminish to only a few tenths of a degree Celsius for all atmospheric conditions and injection heights (Fig. C1). At these distances, differences in cooling magnitude between atmospheric conditions are reduced, whereas differences in plume width and spatial structure remain



apparent. Overall, this highlights that while water spraying can influence thermodynamics over large distances, its effective cooling impact is primarily confined to the near field.

210 To assess the influence of the wind turbine on plume mixing and cooling, the turbulent kinetic energy anomaly is calculated. The turbine wake enhances the total turbulent kinetic energy within the plume, particularly below ~ 40 m and near the surface (around $+0.04 \text{ m}^2 \text{ s}^{-2}$ for $T_{37}RH_{65}$). However, the overall magnitude and vertical structure of $\Delta TKE_{\text{total}}$ remain comparable across injection heights, as they foremost exhibit substantial turbulence from evaporatively driven downdrafts. This suggests that, in these simulations, plume mixing is only weakly modified by the turbine wake compared with the turbulence generated
215 by evaporatively driven buoyancy perturbations.

4.2 Heat Index response to coupled temperature and humidity perturbations

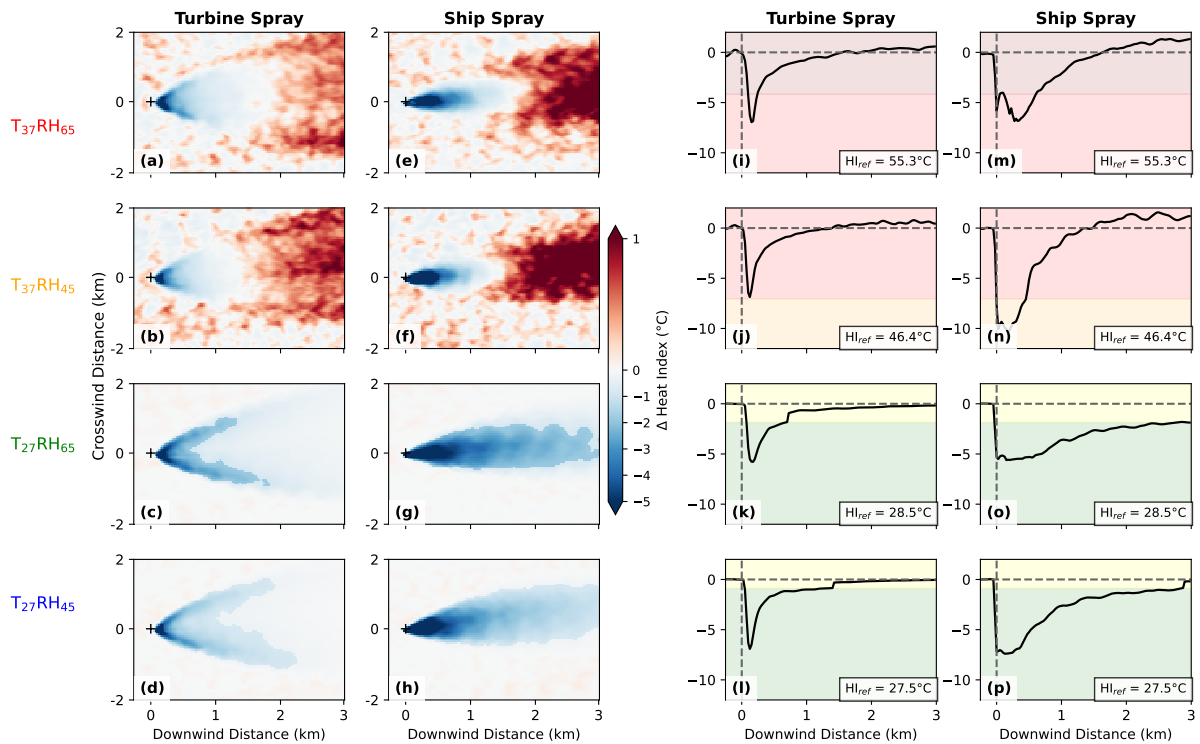


Figure 9. Near-surface horizontal cross-sections and downwind evolution of $\Delta HI_{\text{plume-REF}}$ induced by evaporative spraying under four atmospheric conditions. Left two columns show horizontal cross-sections of ΔHI ($^{\circ}\text{C}$) for the Turbine Spray and Ship Spray, respectively, averaged over the final 30 min of the simulation. The right two columns display corresponding centerline ΔHI profiles along the plume axis. Each row represents an atmospheric condition $T_T RH_{RH}$ with the subscripts indicating their initial values at near-surface height. The domain is zoomed in on 3 km downwind distance. Shaded bands in the profile panels denote absolute National Weather Service (NWS) Heat Index categories mapped into anomaly space relative to the reference state, providing context for potential changes in heat stress exposure. The reference Heat Index (HI_{REF}) for each regime is indicated within the profile panels.



In Section 2, we mapped the four thermodynamic conditions on the Heat Index (HI) (see Fig. 4). To assess how the coupled temperature and humidity perturbations affect perceived heat stress, the simulated anomalies are converted into Heat Index anomalies using Eq. 3. The spatial distributions are shown in Fig. 9a-h, whereas the plume centerline anomalies are presented in Fig. 9i-p.

Compared to the corresponding temperature anomalies (Fig. 6), the ΔHI response exhibits substantially greater spatial variability and a stronger dependence on background atmospheric conditions (see Fig. 9). This behavior is consistently reflected in both the horizontal cross-sections and the centerline profiles, indicating that humidity changes strongly modulate the perceived thermal response. In the warm regimes $T_{37}RH_{45}$ and $T_{37}RH_{65}$, top two rows of Fig. 9a–b,e–f,i–j,m–n, the initial reduction in HI by evaporative cooling near the source is rapidly offset downstream. While all cases show a sharp drop in ΔHI immediately after release, moisture accumulation leads to a recovery toward, and in some cases above, the reference Heat Index. This effect is particularly pronounced for ship-based spraying, where near-surface injection produces strong and persistent humidity anomalies. As seen in both the plume structures (Fig. 9e–f) and centerline profiles (Fig. 9m–n), this results in localized regions of positive ΔHI despite ongoing temperature reductions (see Fig. 6). In contrast, under cooler regimes ($T_{27}RH_{65}$ and $T_{27}RH_{45}$; Fig. 9c–d,g–h,k–l,o–p), reductions in HI remain spatially coherent over the full plume extent. Here, the added moisture is insufficient to offset evaporative cooling, and temperature decreases translate more directly into improved thermal comfort. Although the magnitude of ΔHI decreases with distance, negative anomalies persist throughout the 3 km domain.

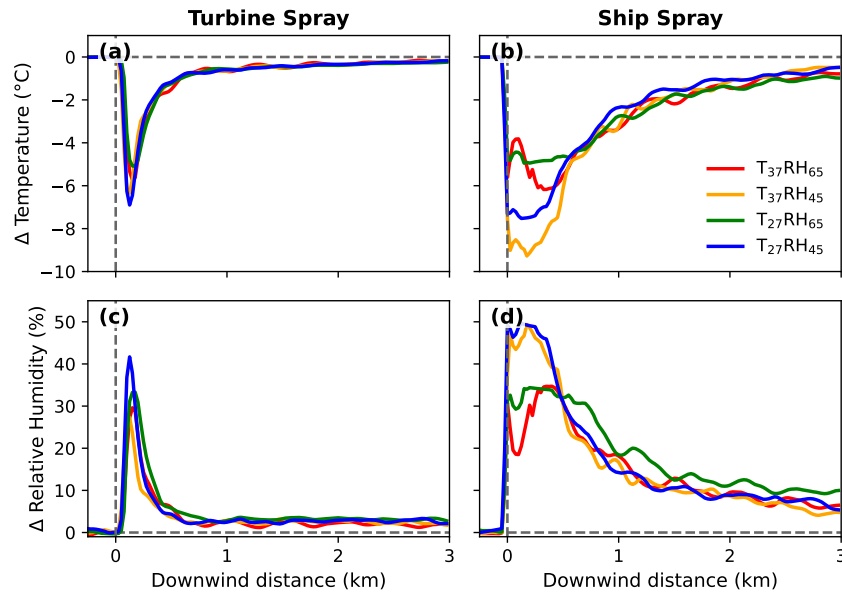


Figure 10. Downwind evolution of $\Delta T_{\text{plume-REF}}$ and $\Delta RH_{\text{plume-REF}}$ induced by evaporative spraying under four atmospheric conditions along the plume axis for the Turbine Spray and Ship Spray, respectively, averaged over the final 30 min. of the simulation. The right two columns display corresponding centerline ΔHI profiles along the plume axis. Each color represents an atmospheric condition $T_{\text{T}}RH_{\text{RH}}$ with the subscripts indicating their initial values at near-surface height. The domain is zoomed in on 3 km downwind distance.



Clear differences also emerge between injection strategies. Ship-based spraying produces stronger near-surface temperature and humidity anomalies, leading to more intense but spatially confined responses (see Fig. 9e-h). In contrast, turbine-based spraying promotes enhanced vertical mixing, resulting in weaker but more diffuse Δ HI reductions. This distinction is evident in the sharper gradients and faster recovery in ship-based centerline profiles compared to the smoother evolution in turbine cases. All configurations exhibit strong near-source HI reductions, with peak decreases of approximately $7 - 10^{\circ}\text{C}$ within the first few hundred meters downstream (see Fig. 9i-p). These reductions are sufficient to temporarily shift conditions across multiple National Weather Service heat stress categories. However, the persistence of this benefit varies strongly by regime and configuration. Beyond approximately 1 km, Δ HI approaches neutral conditions, reaching values between about -2 and $+2^{\circ}\text{C}$ at 3 km, with the fastest recovery occurring in ship-based simulations under humid conditions.

The contrasting Δ HI responses can be directly explained by the coupled evolution of temperature and relative humidity along the plume axis (see Fig. 10). In turbine-based spraying, temperature reductions are accompanied by relatively strong dilution of humidity anomalies, allowing HI reductions to persist over longer distances. In contrast, ship-based spraying injects moisture directly into the near-surface layer, resulting in sustained humidity increases of up to $\sim 40-50\%$ near the source that decay only gradually downstream. This persistent moisture offsets cooling, particularly in the $T_{37}RH_{45}$ regime, where HI recovers to background levels within ~ 1 km and may exceed it further downwind.

Taken together, these results show that the atmospheric response to seawater spraying is governed by the coupled evolution of temperature and humidity rather than by temperature reduction alone. Near the source, evaporative cooling generally dominates and reduces Heat Index. Farther downstream, however, dilution of the temperature anomaly and persistence of humidity perturbations can reduce or reverse this benefit, particularly under hot and humid conditions. The Heat Index response therefore depends strongly on both the background thermodynamic state and the height at which moisture is introduced into the boundary layer.

5 Discussion

5.1 Direct evaporative cooling and comparison with previous work

We first compare the simulated cooling magnitudes with earlier modeling studies that considered direct seawater injection into the marine boundary layer. Maalick et al. (2014) reported a temperature reduction of approximately -1.4°C near the emission source for a seawater flux of 15 kg s^{-1} , corresponding to about two-thirds of their theoretical maximum (-2.1°C). Similarly, Jenkins and Forster (2013) obtained a more modest cooling of -0.4°C for a spray rate of 7.5 kg s^{-1} . In contrast, the present simulations produce very strong local near-source temperature reductions, reaching up to -10°C in individual grid cells close to the spray location. This large local signal mainly reflects the imposed spray rate of 50 L s^{-1} and the bulk saturation adjustment used in the model. It should therefore be interpreted as a localized forcing response rather than as a representative domain-scale cooling magnitude. Downstream of the source, the temperature anomaly rapidly decreases to values that are more comparable to previous studies. Remaining differences can be attributed to environmental and numerical factors. Moreover, both Jenkins and Forster (2013) and Maalick et al. (2014) used atmospheric conditions based on DYCOMS-II with cooler



boundary layer temperatures (~ 292 K), limiting the maximum evaporative cooling in accordance with Clausius–Clapeyron scaling (Stevens et al., 2003). In addition, their coarser model resolutions ($\mathcal{O}(50\text{ m})$ – $\mathcal{O}(300\text{ m})$) likely smoothed the cooling signal, whereas the simulations presented in this study resolve turbulence and plume dynamics at 25 m resolution. It should also be noted that previous studies explicitly included droplet evaporation and coalescence, while the current work adopts a bulk thermodynamic representation. Furthermore, our analysis is based on time-averaged conditions over the final 30 minutes, whereas theoretical maxima refer to initial thermodynamic states. Despite these differences, the studies consistently indicate that the realized cooling response depends strongly on the background thermodynamic state, with larger saturation deficits allowing stronger evaporative cooling.

5.2 Role of injection height and wake-induced turbulence

The comparison between ship- and turbine spray deployment highlights the central role of injection height in controlling plume structure, mixing, and cooling persistence. Ship-based spraying introduces moisture directly into the near-surface layer, producing a shallow and strongly confined cooling plume with large near-surface temperature reductions and sharp horizontal gradients. In contrast, wind turbine deployment injects spray above the surface layer within a mechanically turbulent wake. This enhanced turbulence promotes vertical mixing and dilution, resulting in a broader and more diffuse cooling signal with reduced near-surface intensity. Despite the increased turbulent kinetic energy in the wake, our results indicate that vertical heat transport remains primarily governed by buoyancy-driven downdrafts rather than turbulence intensity itself. As a result, wake effects act mainly to redistribute, rather than amplify, evaporative cooling. As a consequence, a clear trade-off emerges. Ship-based spraying maximizes localized surface cooling and produces strongly confined, horizontally extending plumes, whereas turbine-based spraying yields weaker but more vertically distributed cooling that is less sensitive to background conditions. This indicates that source height controls whether evaporation primarily produces a localized near-surface anomaly or a broader perturbation distributed through the lower boundary layer. An additional implication is the strong spatial confinement of the thermodynamic response. Even in the most effective cases, temperature and Heat Index anomalies decay substantially within 1–2 km downwind. This rapid decay reflects dilution by turbulent mixing and entrainment, and shows that the realized cooling is controlled not only by the imposed water flux but also by the residence time and dispersion of the plume within the boundary layer.

5.3 Heat stress response to coupled temperature and humidity perturbations

The Heat Index response highlights the importance of considering temperature and humidity perturbations jointly (Steadman, 1979; Rothfus, 1990). By resolving plume-scale thermodynamic responses, we show that the relationship between temperature reduction and perceived cooling is strongly non-linear and dependent on atmospheric conditions. A key outcome is that temperature reduction and Heat Index reduction are not directly proportional. Although temperature decreases are largest near the source, the corresponding Heat Index response is strongly modulated by humidity and may recover rapidly downstream or even become positive under humid conditions. As a result, temperature-based assessments alone may overestimate actual reductions in heat stress. In cooler regimes, similar temperature reductions lead to smaller changes in heat stress, reflecting the



reduced sensitivity of Heat Index to humidity. These results show that the sign and magnitude of the Heat Index response depend on the background thermodynamic state. Under hot and humid conditions, added moisture can offset or even reverse the apparent benefit of temperature reductions. This is particularly relevant for hot and humid coastal regions, such as the Persian Gulf, coastal West Africa, and South Asia, where heat stress is strongly controlled by humidity and where additional moisture may therefore reduce the effectiveness of direct evaporative cooling (Pal and Eltahir, 2016; Parkes et al., 2022; Sojan and Srinivasan, 2024). This behavior is consistent with urban-scale studies, where temperature reductions are intrinsically coupled to humidity increases, leading to non-linear and often reduced improvements in thermal comfort (Farnham et al., 2015). Recent work on urban misting systems shows that while substantial local cooling can be achieved, the net benefit to thermal comfort depends strongly on background humidity and ventilation, with reduced effectiveness in humid climates (Ulpiani et al., 2019; Huang et al., 2025b). This highlights that the limitations identified here at plume scale reflect a more general constraint of evaporative cooling strategies across spatial scales. Future work should extend this analysis to more complete exposure metrics and realistic human environments, including urban geometry, radiation, ventilation, and additional thermal comfort indices such as PET, UTCI, or Hittekracht (Höppe, 1999; Bröde et al., 2012; Pereira Marghidan et al., 2026).

5.4 Atmospheric and energetic constraints

A first-order constraint on the magnitude of evaporative cooling follows from energy and mass balance considerations. Evaporation of 1 kg of water can cool on the order of 10^3 m^3 of air by approximately 1 K, indicating that substantial cooling requires large water fluxes. In the present simulations, the imposed spray rate represents an upper-bound scenario, producing strong near-source cooling that relaxes rapidly downstream. From an energetic perspective, the latent heat associated with evaporation dominates the cooling budget, while the mechanical energy required for pumping and atomization depends strongly on spray design and droplet size. The present simulations therefore primarily address the atmospheric response to a prescribed water flux, rather than optimizing the engineering design of a spray system. For turbine-based deployment, the available mechanical power is unlikely to be the dominant constraint at the spray rate considered here, although this depends on the specific atomization technology and operating conditions. However, the realized cooling is primarily constrained by atmospheric transport and thermodynamic adjustment rather than by the imposed water flux alone. These constraints imply that increasing the water flux does not necessarily lead to proportional increases in useful near-surface cooling. Stronger forcing may enhance local evaporation, but turbulent dilution, plume displacement, and humidity accumulation can limit the persistence and apparent benefit of the cooling signal. Mixing therefore redistributes the thermodynamic perturbation over a larger volume, reducing the local temperature deficit while extending the spatial footprint of the plume. Practical relevance depends on the coupling between spray characteristics, boundary layer structure, and meteorological variability. In particular, temporal variability in wind speed and direction is expected to influence energy availability, plume transport, and whether cooling anomalies remain aligned with coastal target areas during periods of high heat exposure.



330 5.5 Relation to other seawater spraying applications

The results are also relevant for other seawater spraying applications, particularly Marine Cloud Brightening (MCB), where the atmospheric transport of injected salt is a key uncertainty (Latham et al., 2012; Wood, 2021). MCB aims to generate sub micron aerosols that perturb cloud microphysics and enhance the reflectivity of low clouds. For this application, seawater spraying typically occurs at relatively low flow rates ($\mathcal{O}(10^{-1}) \text{ L s}^{-1}$), but with high atomization energy requirements ($\mathcal{O}(10^2\text{--}10^3) \text{ kW}$) (Harrison et al., 2025; Hernandez Jaramillo et al., 2025; Reardon et al., 2026). Direct evaporative cooling differs from MCB in that it prioritizes rapid evaporation and sensible heat reduction, whereas MCB is optimized for aerosol production and cloud interactions. These different objectives also imply different sensitivities to injection height. Elevated injection, such as from wind turbines, may increase salt-to-cloud delivery when vertical transport limits aerosol entrainment into clouds, particularly in stable or weakly coupled marine boundary layers (Feingold et al., 2024; Hernandez-Jaramillo et al., 2025; Zhang et al., 2026). In contrast, lower-level injection may be more effective when near-surface effects or direct interaction with the ocean surface are desired, such as for shading vulnerable marine ecosystems (Butcherine et al., 2023). The present results emphasize that, for both applications, source height and boundary layer coupling strongly influence where injected water or aerosol perturbations are transported. Elevated injection may enhance vertical redistribution, but it also reduces control over the near-surface footprint and couples the perturbation more strongly to boundary layer transport.

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Overall, the simulations show that seawater spraying produces a strongly localized thermodynamic perturbation whose evolution is governed by boundary layer dynamics. While the thermodynamic potential for evaporative cooling can be large under warm and dry conditions, the realized near-surface response is limited by turbulent dilution, vertical redistribution, and humidity accumulation. Injection height controls the partitioning between localized surface cooling and broader boundary layer modification, whereas the Heat Index response depends on the non-linear coupling between temperature and humidity. These constraints suggest that the atmospheric effectiveness of seawater spraying cannot be inferred from water flux or theoretical cooling potential alone.

350

6 Conclusion

In response to the increasing frequency and severity of extreme heat events and associated global health risks, this study assessed the atmospheric response to seawater spraying as a direct evaporative cooling mechanism in the marine boundary layer. By combining an idealized thermodynamic framework with large eddy simulations, we evaluated how background thermodynamic conditions, injection height, and boundary layer transport control the realized cooling and associated Heat Index response.

The thermodynamic analysis shows that evaporative cooling potential can be substantial under hot and dry conditions, with theoretical temperature reductions exceeding -20°C . However, the LES results demonstrate that turbulent mixing, advection, and dilution strongly limit the realized cooling under atmospheric conditions. For a spray rate of 50 L s^{-1} , near-surface cooling of approximately $0.5\text{--}1^\circ\text{C}$ is obtained within the first few kilometers downstream, while temperature anomalies decrease

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rapidly farther from the source. The strongest cooling occurs near the surface due to evaporatively driven downdrafts, making such systems directly relevant for near-surface human exposure.

365 Injection height is a key control on plume structure and vertical redistribution. Low-level spraying produces stronger but more localized near-surface cooling, whereas elevated injection from a wind turbine results in a broader and more vertically distributed temperature perturbation. The turbine wake modifies the local flow, but the main control on vertical redistribution is the height of injection and the buoyancy response to evaporation.

370 The Heat Index response shows that temperature reductions alone are insufficient to assess the effectiveness of evaporative cooling. Added moisture can offset or even reverse the apparent benefit of cooling under hot and humid conditions, whereas under more moderate conditions the temperature reduction dominates and produces sustained negative Heat Index anomalies. This highlights the importance of considering coupled temperature-humidity changes when evaluating spray-induced cooling.

Overall, our modeling results demonstrate that seawater spraying can provide measurable atmospheric cooling under suitable conditions, but its effectiveness for reducing heat stress is constrained by both thermodynamic and boundary layer processes. 375 Under moderate conditions, evaporative cooling can reduce the Heat Index, whereas under hot and humid conditions, heat stress is strongly controlled by humidity and added moisture can offset or even outweigh the benefit of temperature reductions beyond the near-source region.

Standard thermal comfort metrics may also provide an incomplete assessment of spray-based cooling, because they do not explicitly account for droplet-skin interactions and direct evaporative heat loss from the body (Oh et al., 2021). Future 380 work should therefore couple atmospheric dynamics with more complete human heat-exposure metrics, including radiation, ventilation, exposure duration, and physiological responses.

Together, these findings show that direct evaporative cooling belongs to a broader class of spray-based atmospheric interventions, including shading and Marine Cloud Brightening, but that its effectiveness cannot be inferred from water flux alone. Instead, cooling depends on the combined effects of saturation deficit, injection height, plume transport, turbulent dilution, 385 and humidity accumulation. The main implication is therefore that seawater spraying has the potential to provide targeted near-surface cooling, but only when meteorological conditions allow evaporative temperature reductions to outweigh added humidity.

Code and data availability. The full DALES source code and example input files for the simulations can be found here: <https://doi.org/10.5281/zenodo.21239333> The fundamental description of DALES is given by Heus et al. (2010). Ongoing updates of DALES are provided 390 through <https://github.com/dalessteam/dales>. Further details and output files used for analysis can be provided upon request to the corresponding author.



Author contributions. AB: Conceptualization, Methodology, Software, Formal analysis, Data curation, Visualization, Writing – Original draft. SdR: Conceptualization, Methodology, Software, Visualization, Supervision, Writing – Review & Editing. HR: Conceptualization, Funding acquisition, Supervision, Writing – Review & Editing.

395 *Competing interests.* No competing interests

Acknowledgements. We thank the Refreeze the Arctic Foundation for funding this research. We are grateful to the team of The Global Irrigation Project, whose inquiry into the potential for cloud formation through water spraying from wind turbines inspired this work. We also thank Indall for kindly providing Figure 1. We acknowledge Caspar Jungbacker and Fredrik Jansson for their assistance with DALES, Pim van Dorp for developing the turbine set-up and Dion Hoeksema for implementing the turbine in DALES v4. We further thank Niels Janssen
400 for his support with VRLab and access to its resources, as well as the Snellius supercomputer team for providing computational resources. Finally, we acknowledge the contributions of students involved in this project, in particular Mark van der Gun and Maelys Bruneau. During the preparation of this work the author(s) used Microsoft Copilot in order to rewrite and optimize structure for parts of the article. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

405 **Appendix A: Summary of applied atmospheric thermodynamical relations**

R_d	287.04	$\text{J kg}^{-1} \text{K}^{-1}$	gas constant for dry air
R_v	461.5	$\text{J kg}^{-1} \text{K}^{-1}$	gas constant for water vapor
L_v	2.53×10^6	J kg^{-1}	latent heat for vaporization
$c_{p,d}$	1004	$\text{J kg}^{-1} \text{K}^{-1}$	specific heat for dry air at constant pressure
$c_{p,v}$	1870	$\text{J kg}^{-1} \text{K}^{-1}$	specific heat for water vapor at constant pressure
c_l	4186	$\text{J kg}^{-1} \text{K}^{-1}$	specific heat for liquid water

Table A1. Summary of thermodynamic constants used in this study (Emanuel, 1994).

The saturation water vapor specific humidity $q_{\text{sat}}(p, T)$ for an air parcel with absolute temperature T at atmospheric pressure p can be computed following the Clausius Clapeyron relation (Stull, 1988),

$$q_{\text{sat}}(T, p) = \frac{e_{\text{sat}}}{\frac{R_v}{R_d}(p - e_{\text{sat}}) + e_{\text{sat}}} = \frac{\epsilon e_{\text{sat}}}{p + e_{\text{sat}}(\epsilon - 1)}, \quad (\text{A.1})$$

with

$$410 \quad \epsilon \equiv \frac{R_d}{R_v}, \quad (\text{A.2})$$



and R_d and R_v the gas constants for dry air and water vapor, respectively. Table A1 shows a summary of the used thermodynamic constants. For typical temperatures in the marine atmospheric boundary layer we will use the following approximate form for the saturated water vapor pressure e_{sat} (Stull, 1988),

$$e_{\text{sat}}(T) = 610.78 \exp \left[\frac{17.2694(T - 273.16)}{T - 35.86} \right]. \quad (\text{A.3})$$

415 The water vapor pressure e_v , given by

$$e_v = \rho_v R_v T \quad (\text{A.4})$$

is needed to assess the relative humidity,

$$\text{RH} = \frac{e_v}{e_{\text{sat}}}. \quad (\text{A.5})$$

420 The gas law involves the density of air ρ , pressure p , temperature T , water vapor and liquid water specific humidity, q_v and q_l , respectively,

$$p = \rho R_d T (1 + \epsilon_I q_v - q_l), \quad (\text{A.6})$$

with $\epsilon_I = R_v/R_d - 1 \approx 0.608$. Note that the water vapor specific humidity q_v is defined as the ratio of the densities of water vapor $\rho_v = m_v/V$ to that of the density of air including water,

$$q_v = \frac{\rho_v}{\rho} = \frac{m_v}{m_{\text{tot}}}, \quad (\text{A.7})$$

425 with

$$\rho = \frac{m_{\text{tot}}}{V} = \frac{m_d + m_v + m_l}{V}, \quad (\text{A.8})$$

and the total mass of an air parcel m_{tot} containing dry air m_d and water in both the gas m_v and liquid phase m_l .

Appendix B: The Add-On to Implement Seawater Spraying

430 Here we describe the add-on in DALES to represent seawater spraying. This section describes the development and performance of this add-on.

The add-on introduces a source for a mass of water (m_{liq}), or salt, into the simulation at a spray rate (S_{spray}) in a certain location (i, j, k) :

$$S_{\text{spray}} \equiv \frac{\partial m_{liq}}{\partial t}, \quad (\text{B.1})$$

where S_{spray} is expressed in $kg\ s^{-1}$. This spray rate was added to budgets for heat and moisture ($\frac{\partial \theta_l}{\partial t}$ and $\frac{\partial q_t}{\partial t}$).



435 In DALES, the following definitions are used for the specific humidities:

$$q_v = \frac{m_{vap}}{m_{dry} + m_{vap} + m_{liq}}, q_l = \frac{m_{liq}}{m_{dry} + m_{vap} + m_{liq}}, q_t = \frac{m_{vap} + m_{liq}}{m_{dry} + m_{vap} + m_{liq}}. \quad (B.2)$$

The liquid potential temperature is defined as

$$\theta_l = \theta - \frac{L_v}{c_p \Pi} q_l, \quad (B.3)$$

where θ is the potential temperature, L_v and c_p are constants representing respectively the latent heat of vaporization and
440 specific heat of dry air at constant pressure. Finally, Π is the Exner function as defined as:

$$\Pi = \left(\frac{p_f}{p_0} \right)^{R_d/c_p} \quad (B.4)$$

Finally, we need the expression for the density of air. The mesh-volume, ΔV , equals $\Delta x \Delta y \Delta z$. The density of air reads:

$$\rho = \frac{m_{dry} + m_{vap} + m_{liq}}{\Delta V}. \quad (B.5)$$

To formulate the source terms, we take the time derivative through the quotient rule of the expression for q_t and substitute
445 $\frac{\partial m_{liq}}{\partial t}$ with S_{spray} :

$$\frac{\partial q_t}{\partial t} = \frac{\frac{\partial m_{liq}}{\partial t} (m_{dry} + m_{vap} + m_{liq}) - (m_{vap} + m_{liq}) \frac{\partial m_{liq}}{\partial t}}{(m_{dry} + m_{vap} + m_{liq})^2} = \frac{(1 - q_t) S_{spray}}{m_{dry} + m_{vap} + m_{liq}}. \quad (B.6)$$

Now, we substitute the density and volume where possible. This results in:

$$\frac{\partial q_t}{\partial t} = \frac{(1 - q_t) S_{spray}}{\rho \Delta V}. \quad (B.7)$$

The same steps used to obtain $\frac{\partial q_t}{\partial t}$ in Equation B.6 and Equation B.7 were applied to retrieve $\frac{\partial q_l}{\partial t}$. Now take the time
450 derivative of Equation B.3, and substitute $\frac{\partial q_l}{\partial t}$ to end with

$$\frac{\partial \theta_l}{\partial t} = - \frac{L_v}{c_p \Pi} \frac{(1 - q_l) S_{spray}}{\rho \Delta V}. \quad (B.8)$$

These expressions were implemented in the model to account for the effects of spraying on the moistening and subsequent evaporative cooling of air.



Appendix C: Additional Figures

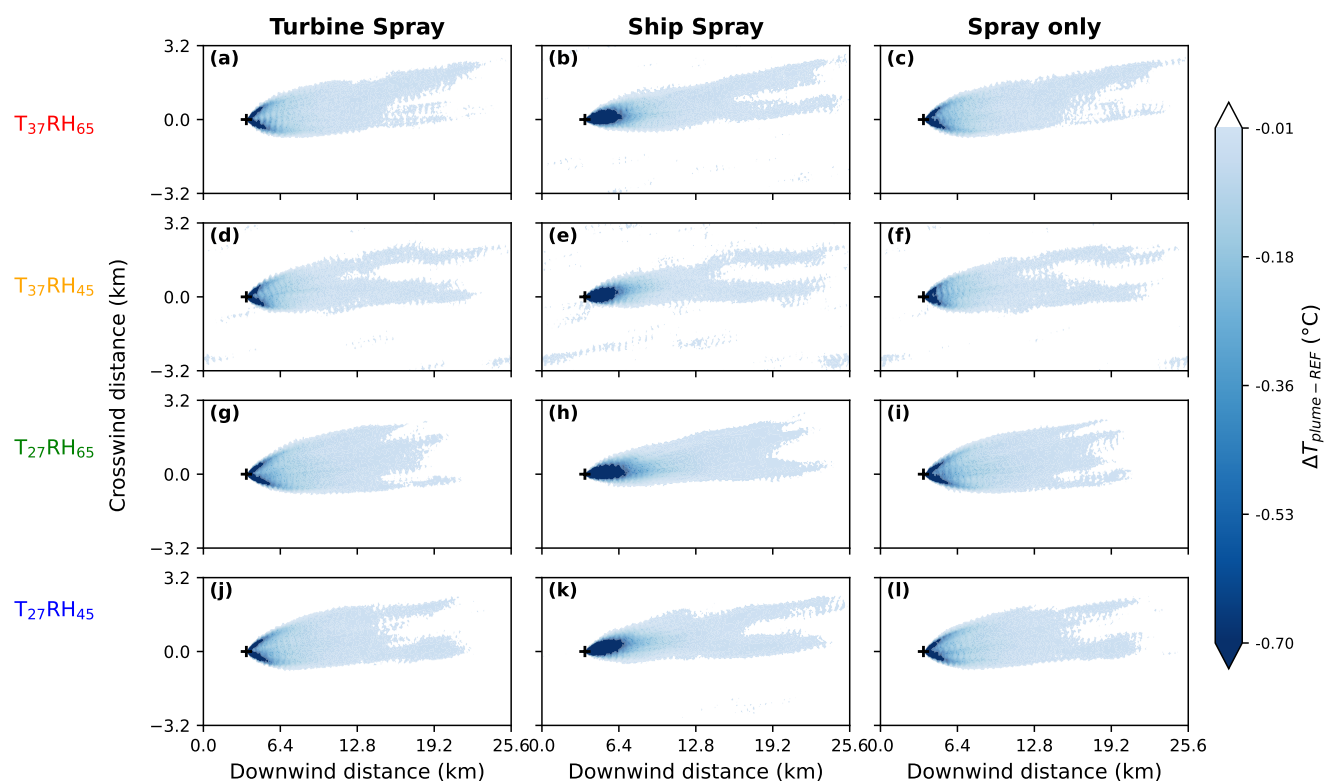


Figure C1. Horizontal cross-sections (XY) of the temperature anomaly $\Delta T_{\text{plume}} - \text{REF}$ averaged over the final 30 minutes of the WT Spray (param.), Spray only, and Ship Spray simulations for all four atmospheric cases at near-surface level $z=3.75$ m. The color scale is based on column-consistent percentile limits, and regions outside the plume (defined by the coldest 20% of ΔT).



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