Mist cooling in urban spaces: Understanding the key factors behind the mitigation potential

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Abstract:	Mist cooling is a widely known and applied heat mitigation technology, especially in urban settings. Despite this, conceiving the right installation is no trivial matter as scattered and unstandardized is the knowledge on the multiple interrelations with the local microclimate. This paper investigates how the cooling efficiency of a dry mist system depends on the local meteorological trends. An experimental system of 24 overhead nozzles constantly operating at 0.7 MPa, was installed in Italy and monitored for a week in summertime. Temperature and relative humidity underneath the mist were mapped in five locations with a time step of 10 s, together with the main meteorological parameters, measured at an undisturbed location, for reference. Cooling and humidification capacity were characterized as probability density, key summary statistics and relevant confidence intervals with minimal redundancy and minimal distortion. A supervised learning algorithm was used to disclose the sensitivity of the recorded temperature drop to the contextual microclimatic evolution. It was demonstrated that the cooling capacity of the tested system was largely a function of the local wet bulb depression, as instantaneous reading as well as short-term trend. Additionally, solar irradiation and wind speed were found to be negatively and positively correlated, respectively.
Suggested Reviewers:	Emmanuel Bozonnet Emmanuel.Bozonnet@univ-lr.fr Professor Emmanuel Bozonnet conducts his research in building physics and building interactions with urban microclimate, from urban canyon to district scale. This modeling work has been corroborated by various scale experiments from the building envelope component to the development of a reduced scale mockup for urban canyons and in situ buildings. These studies focus on the development of cooling strategies for the mitigation of building energy demand and urban heat islands.
	Carlos Bartesaghi-Koc carlos.bartesaghikoc@adelaide.edu.au Lecturer in Landscape Architecture, his focus is on performance-based analysis of cities, neighbourhoods, urban precincts, streets and buildings from ecological and holistic point of views. His second research focus is on climate-sensitive and generative+responsive design supported by computational and sensing technologies such as AI, machine learning, IoT and smart sensors.
	Dionysia Kolokotsa dkolokotsa@enveng.tuc.gr Denia (Dionysia) Kolokotsa is Associate Professor at the School of Environmental Engineering of the Technical University of Crete, Greece. Her research interests include energy management for the built environment, energy efficiency and renewables, integration of advanced energy technologies, indoor environmental quality, energy efficiency in buildings, cool materials, distributed energy management systems, artificial intelligence.

Response to Reviewers:	

Dear reviewers,
we carefully addressed the raised issues and highly appreciated your observations to improve our work. Each change we made is outlined below.

Reviewer #1: The manuscript entitled "Mist cooling in urban spaces: Understating the key factors behind the mitigation potential" deals with an urban evaporative cooling system namely mist cooling by using spray nozzles at high pressure (0.7 MPa). After setting an experimental prototype, it is found that the solar radiation and the wind speed are the most influencing values upon a certain temperature drop. It was also found that the relative humidity increase is small, making thus this approach suitable for hot humid conditions.

Although the topic is interesting and very important, some concerns have to be addressed before the document can be considered as suitable for publication:

1. My main concern is regarding the time of temperature drop. The results shown in the document are considered as instantaneous. Nevertheless the temperature drop has a limit of time, after the outdoor air temperature and the solar radiation increase it again. Moreover, as you mention on the manuscript, the system has an on/off mechanism. If the temperature drop occurs only for a few seconds, the mist cooling has to be turned on almost all the time when is necessary, making a greater water consumption. An analysis of what would be the time of "recuperation" of the outdoor temperature must be included in the study.

The authors thank Reviewer#1 for this observation, as this is a critical question. The results shown are instantaneous, but the evolutionary algorithm (used to investigate the role of key environmental factors) included the so called historical-operators, in the specific case, the simple moving average operator. In this way the analysis was able to track time-lagged dependencies. About the smart on/off mechanism, it is utterly true what the Reviewer highlights. Indeed the injection was on almost all the time during the monitoring campaign, due to the high temperatures in the considered period of observation. Nonetheless, this is the reason why we selected that time window to investigate the relation between water-mist-assisted cooling and boundary conditions. A significant intervention of the smart logic would have biased the analysis towards environmental conditions conducive to stronger evaporation and would have made it complicated to discern the effect under prolonged and “pulsed” operations. The following explanatory lines have been incorporated in the text to stress this important point:

“Against this climatic context, the fuzzy logic switched on the misting at around 10 am LST and switched it off at around 6:30 pm LST with only minor interruptions of maximum 2 minutes in between, due to the simultaneous occurrence of high wind speed and low local temperature. This provides optimal grounds to investigate the cooling capacity in relation to different boundary conditions.”

As a final remark, it is actually positive that the logic maintains continuous injection if necessary to maintain comfort conditions. Whenever unneeded (cooler days or different climatic context) the logic succeeded at managing the pump activation with significant energy saving compared to environmentally-non-responsive on/off logics. This is described in our previous publication for both Ancona's climate (Cfa) and Rome's climate (Csa): G. Ulpiani, C. Di Perna, M. Zinzi, Water nebulization to counteract urban overheating : Development and experimental test of a smart logic to maximize energy efficiency and outdoor environmental quality, Appl. Energy. 239 (2019) 1091–1113. doi:10.1016/j.apenergy.2019.01.231

An analysis of what would be the time of "recuperation" of the outdoor temperature would be extremely interesting, but it is envisioned to be strongly related to the climatic context. The data used in this paper appear to be insufficient to uncover potential relationships. Further data will be collected in the future to investigate this pivotal point. This is now stressed in the conclusions. We very much thank the Reviewer for the observation.

2. You are studying the cooling potential onto the urban space. Nonetheless, you are forgetting that an evaporative-cooling approach is more effective if it's oriented towards the users. For this case, you have to apply a thermal comfort index considering the mist cooling upon the person. Please do so; otherwise, your work could be considered as incomplete.

Many thanks for raising this point. A dedicated analysis on comfort improvement via smart-controlled mist cooling was carried out in a previous paper on the same experimental rig:

G. Ulpiani, E. Di Giuseppe, C. Di Perna, M. D'Orazio, M. Zinzi, Thermal comfort improvement in urban spaces with water spray systems: Field measurements and survey, Build. Environ. 156 (2019) 46–61. doi:https://doi.org/10.1016/j.buildenv.2019.04.007

There we investigated the impacts on PET, SET* and UTCI through a variety of statistical metrics (including non-parametric Spearman correlation test, non-parametric Kruskal-Wallis H, test correlation matrices, Frequent Pattern (FP)-Growth algorithms) on the basis of comfort questionnaires released to passersby both in Ancona and Rome.

The following lines have been added in the text to help the reader navigate the different aspects covered in the related publications:

"For further details about the fuzzy logic, the reader is referred to previous research [16], where the efficiency in terms of energy saving was demonstrated, compared to on-off operation. Comfort enhancement was also investigated in [21] where PET, SET* and UTCI differences between misted and undisturbed locations were analyzed through a variety of statistical metrics(including non-parametric Spearman correlation test, non-parametric Kruskal-Wallis H test, correlation matrices, Frequent Pattern (FP)-Growth algorithms) based on comfort questionnaires."

We would like to stress that the control logic was especially devised to track users' comfort, hence the inclusion of i) a temperature threshold set to be equal to the neutral temperature in Mediterranean contexts (extracted from the work by Salata et al.[1]); ii) the Humidex and the

[1] F. Salata, I. Golasi, R. de Lieto Vollaro, A. de Lieto Vollaro, Outdoor thermal comfort in the Mediterranean area. A transversal study in Rome, Italy, Build. Environ. 96 (2016) 46–61. doi:10.1016/j.buildenv.2015.11.02

Cooling Power index that have been proposed and used as thermal comfort indices[2]. Hence a user-oriented approach was incorporated directly in the control logic.

3. In my opinion, a description of the approach's application has to be stated in detail. Even though the system works in a proper manner in a small-scale case, what are the challenges of applying the mist cooling system upon a city scale? The economic and technical issues have to be discussed. Otherwise, the manuscript describes a conventional evaporative cooling system which is already in the market, and that is used elsewhere.

Many thanks for the suggestion. The following lines were added to the discussion to address both points 3 and 4.

"Overall, mist cooling is a high-impact local-scale urban overheating countermeasure. It is not meant to be used on large areas not to introduce excessive humidity in the air, adversely impact on water management during droughts and not to jeopardize passersby's right to decide whether or not to be directly exposed to the mist. A city-scale application would be achieved by spreading several small-scale installations in appropriate locations (city hot spots with low, steady wind speed, no canyon effect, no excessive urban shading and close to vulnerable population, e.g. elderly, low-income groups). Notably, urban canyons and shading should be carefully evaluated prior to any installations due to the local acceleration of the wind flow [36] and the enhanced wetting risk associated with lower heat absorption by the water droplets [5], respectively. Microscale urban simulations and experimentally substantiated artificial-intelligence-assisted analyses like the evolutionary algorithm proposed in this study, would be especially valuable in defining the most appropriate installation sites. From a technical and economical perspective, the use of smart logics, able to weigh the injection of water upon a variety of drivers as the one hereby presented, is expected to be a major enabler in urban-scale deployment."

4. If the results show that the wind speed and the solar radiation are influencing variables upon the outdoor temperature, urban approaches such as urban canyons and urban shading have to be mentioned.

Refer to point 3.

Specific comments:

Line 197: In what city of Italy the study was carried out?

Corrected.

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[2] S. Ghani, E.M. Bialy, F. Bakochristou, S.M.A. Gamaledin, M.M. Rashwan, B. Hughes, Thermal comfort investigation of an outdoor air-conditioned area in a hot and arid environment, Sci. Technol. Built Environ. 23 (2017) 1113–1131

Line 202: The unit is %, not °C.

Many thanks for spotting the typo. Corrected.

Line 205: Fig. 2 lacks of quality and resolution.

Fig. 2 has been redesigned to improve quality and aesthetics.

Line 247: In Fig. 2, what does the y-axis stand for?

Raincloud plots have on the y-axis the group they refer to. In this case it’s the location of the probe, which was represented in the manuscript with the same symbol used in Fig. 1 for reference.

Line 309: Please include in Fig. 5 the comparison of temperatures considering also solar radiation alone.

Irradiation plots were not included because the evolutionary algorithm found no significant relation by considering irradiation only. Thanks for highlighting this point. Few lines were added for clarity: “On the other side, knowing irradiation only led to no significant prediction of the temperature drop.”

Line 421: Reference (28) is not correctly written, please correct.

Many thanks for spotting it. Corrected.

The authors warmly thank Reviewer 1 for all the suggestions that considerably helped enhancing the contents and the clarity of the manuscript. We trust the manuscript covers now all critical points within its scope and better stresses its connection with previously published results.

Reviewer #2: The work provides concise, thoughtfully justified results that can be of use in future research. Limitations are clearly stated. Extending the study to further climate, as proposed for future work, would have add much more scientific value.
I nonetheless think the manuscript would be suitable for publication, after some minor clarifications:

1) It would be necessary that authors clearly state its novelty compared to their own previous research (references [13] and [28]. This could be done, for example, in the last paragraph of the introduction.

Many thanks for the observation. We included the following lines in the last paragraph of the introduction, as suggested:

“This study adds to the body of knowledge collected in the afore-mentioned studies and complements the energy and comfort analyses in [16,19,20] by investigating the sensitivity of dry misters to air temperature, relative humidity, wind speed and solar radiation, to help delineate appropriate design guidelines and site criteria”.

Additionally, the contents of the previous publications are now described in more detail throughout the manuscript.

2) A reference should be given to justify information given in lines 67 to 70, on the increasing interest of the system in countries such as UK and Germany.

Many thanks. References have been added.

3) Please develop the idea in line 183: "the effect of the logic is"… Has this been compared to other control strategies in current or previous studies?

It was compared with on-off logics in G. Ulpiani, C. Di Perna, M. Zinzi, Water nebulization to counteract urban overheating : Development and experimental test of a smart logic to maximize energy efficiency and outdoor environmental quality, Appl. Energy. 239 (2019) 1091–1113. doi:10.1016/j.apenergy.2019.01.231.

Few additional lines have been included to better relate the proposed control logic to its proved benefits. The reader is referred to the above publication for an in-depth description of the logic and the explanation on how fuzzification combines different drivers:

“For further details about the fuzzy logic, the reader is referred to previous research [16], where the efficiency in terms of energy saving was demonstrated, compared to on-off operation. Comfort enhancement was also investigated in [21] where PET, SET* and UTCI differences between misted and undisturbed locations were analyzed through a variety of statistical metrics(including non-parametric Spearman correlation test, non-parametric Kruskal-Wallis H test, correlation matrices, Frequent Pattern (FP)-Growth algorithms) based on comfort questionnaires.”

4) In lines 140-141 it is said that "sensor network should be placed in the proximity of the injection". Later, the particular position for the experimental setup is presented in figure 1 and lines 187 to 191. Clearly specifying "proximity" would justify the selected position for the sensors.

The authors thank the reviewer for raising this important methodological point. Explanatory lines were added both to specify what we meant with “promixity” and to justify the height of the probes, as follows:

“Specifically, since the vertical cooling and humidification profiles obey to a Lorentzian distribution, hitting the peak at approximately 0.5 m of the injection [20], temperature and/or humidity detectors should be placed at no more than few meters away from the nozzles.”

“Five thermohygrometers were located within the ground-projected perimeter of the misting matrix at a height of 1.1 m, which represents the suggested breast level of a standing person and head level of a sitting person in ISO 7726 [28].”

Also, the height of the probes was included in Fig. 1 for the sake of completeness.

Although information is clearly presented and well structured, addressing the following minor comments could improve the work in this sense.

- There are two "figure 2". Please revise figure numbering.

Many thanks for spotting it. Corrected.

- Maybe information given in lines 160 to 182 (or even until line 186) would be better placed in subsection 2.1 or in its own subsection, as it describes general issues concerning configurations and not the particular one in the experimental setup.

The authors agree with the Reviewer. On the other side, we trust that removing those lines from their current location would make it harder for the reader to interpret the proposed experimental design. These general issues justify the particular setup.

- Consider specifying in the caption of current figure 3 if the wind rose corresponds to data during the one-week measuring period, as well as the particular location.

Corrected.

- Line 118: consider saying "subsections" instead of "subparagraphs".

Corrected.

- Consider expanding text in line 181 from "The reader is referred to [13]" into "The reader is referred to previous research [13]" (for example). The same happens in line 339: "in line with [28]".

Corrected.

- There is a typographical error in line 132.

Many thanks for spotting it. Corrected.

The authors thank Reviewer #2 for all the suggestions and the careful revision of the manuscript.

Reviewer #4: I really appreciated this paper. The topic of evaporative cooling of outdoor spaces is very well addressed. A convincing theoretical approach is coupled with an experimental setup. Data from monitoring campaign is correctly handled, and their interpretation provides very interesting hints to understand the influence of environmental factors on the efficiency of the process. In general, the manuscript is well written and organised. I suggest publishing the paper as it is.

The authors warmly thank Reviewer #4 for the kind words and the support. Much appreciated.

Title

Mist cooling in urban spaces: Understanding the key factors behind the mitigation potential

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Abstract

Mist cooling is a widely known and applied heat mitigation technology, especially in urban settings. Despite this, conceiving the right installation is no trivial matter as scattered and unstandardized is the knowledge on the multiple interrelations with the local microclimate. This paper investigates how the cooling efficiency of a dry mist system depends on the local meteorological trends. An experimental system of 24 overhead nozzles constantly operating at 0.7 MPa, was installed in Italy and monitored for a week in summertime. Temperature and relative humidity underneath the mist were mapped in five locations with a time step of 10 s, together with the main meteorological parameters, measured at an undisturbed location, for reference. Cooling and humidification capacity were characterized as probability density, key summary statistics and relevant confidence intervals with minimal redundancy and minimal distortion. A supervised learning algorithm was used to disclose the sensitivity of the recorded temperature drop to the contextual microclimatic evolution. It was demonstrated that the cooling capacity of the tested system was largely a function of the local wet bulb depression, as instantaneous reading as well as short-term trend. Additionally, solar irradiation and wind speed were found to be negatively and positively correlated, respectively.

Keywords: water misting; experimental monitoring; urban climate; evaporative cooling; sensitivity analysis; artificial intelligence

Acronyms and symbols (alphabetical order)

ANOVA	Analysis of variance	Oh	Ohnesorge number
μ	Dynamic viscosity of the fluid [Ns/m^2]	PE	Cooling power index [$mcal/cm^2s$]
av	Subscript for average value	PV	Photovoltaic
C	Centre (position)	r	Water droplet radius [m]
CD	Drag coefficient	Re	Reynolds number
d	Droplet diameter [m]	RH	Relative humidity [%]
d_n	Nozzle diameter [m]	S	South (position)
E	East (position)	sma	Simple moving average
F	Resulting force [N]	T_{db}	Dry-bulb temperature [°C]
g	Gravitational acceleration [m/s^2]	T_{wb}	Wet-bulb temperature [°C]
Ioh	Horizontal global solar irradiance [W/m^2]	UHI	Urban heat island
IQR	Interquartile range	v	Characteristic velocity of the flow [m/s]
k_a	Thermal conductivity of air [W/(mK)]	vr,av	Mean relative velocity between droplet and surrounding air [m/s]
l	Characteristic length scale of flow [m]	W	West (position)
L	Latent heat of evaporation [J/kg]	ws	Wind speed [m/s]
m	Water droplet mass [kg]	γ	Surface tension [N/m]

MAE	Mean absolute error	ΔT_c	Temperature drop in the middle of the mist [°C]
MSE	Mean squared error	$\Delta T_{wb,c}$	Wet-bulb depression in the middle of the mist [°C]
N	North (position)	ρ	Density of water [kg/m^3]
n	Number of 10 s lasting injections in a minute time	σ	Standard deviation

1. Introduction

Water-based features have always been key in the cooling strategies for urban spaces. In most studies, devoted to the mitigation of urban heat islands (UHIs), the blue mitigator is represented by water bodies having high thermal mass (e.g. sea, lake, river). Such large natural formations are the preserve of a limited number of densely inhabited cityscapes in the world. Besides their cooling effect is nor controllable nor tunable, thus affecting the heating consumptions in a year-round evaluation. Several researches concur that multiple, strategically positioned artificial installations, even small-scale ones, tend to have a pronounced cooling impact, locally more intense and spatially more distributed than a lone, large source [1–4]. These micro-features can be designed with due consideration to prevailing winds and synergies with other evaporative processes (e.g. local evapotranspiration) so as to maximize the efficiency and optimize the usefulness on the territory and the comfort of typical users.

Among the technological alternatives (e.g. cooling towers, sprinklers, fountains, ponds), dry misters are gaining popularity as, beyond being a very locally impactful cooling technique, their working principle well responds to growing concerns about energy consumption, water usage and climate-anxiety. By pulverizing water into micrometric particles, dry misters attain flash and complete evaporation of the injected droplets, drawing the necessary heat from the surrounding air. The resulting water consumption is extremely modest and the risk of skin wettedness can be easily averted by appropriate layouts. Furthermore, dry misters lend themselves to a variety of applications, targeting the whole sphere of comfort. Their action is not merely thermohygrometric, but affects all the major environmental parameters, by attenuating solar radiation [5], scavenging dust [6], breaking the wind force while engendering a local turbulent flow of cooled air, all factors contributing to an efficient heat removal and to the generation of pleasant spaces in the urban realm, especially where overheating and pollution risks are prominent. As discussed in recent review papers [7,8], this technology is especially valuable in dry and warm climates, although good performance has been demonstrated also in humid locations like Singapore [8]. Increasing interest has also been expressed by heating-dominated countries, such as UK and Germany, to cope with the unprecedented escalation of heat-stress events in recent years [9,10]. These countries are less armored against urban overheating, thus increasing the heat resistance of their infrastructure has become a priority target. Compared to passive and natural mitigators, misters and other artificial water features are especially desirable in such contexts where intense outdoor cooling is a sporadic necessity, given their adjustability, controllability and scalability.

Experimental evidence suggests that misting systems can induce a local temperature drop from few degrees Celsius (1-2 °C), up to over 15 °C [8]. On average, the reduction falls in the 7-8 °C range, with major deviations due to the selected technology (in terms of nozzle geometry, operating pressure and layout), the local microclimate and the typology of cooled area (open outdoor, semi-enclosed, indoor) [11]. The humidification is in the order of 20%. Beyond technological considerations, the cooling capacity of misting systems depends on the contextual microclimate. In [12] Yoon and Yamada demonstrated that relative humidity is the governing parameter, even more than temperature, in the considered range. Humid conditions depreciated the extent and completeness of the evaporation process. The authors suggested potentially optimal thermohygrometric boundary conditions: 70% and 30-34 °C as for relative humidity and ambient temperature, respectively. During the 2010 Shanghai Expo [13], Huang et al. monitored an extensive misting system of about 136 nozzle and reported temperature drops of 6-12 °C within 1 m of the injections, when the ambient temperature was 34-40 °C and the relative humidity was 32-55 %. Considering the wet bulb depression (ΔT_{wb}, difference between wet bulb and dry bulb temperatures) as theoretical limit, the authors computed the cooling efficiency by dividing the actual temperature drop to the ideal wet bulb depression: it reached 90 % in the Expo Pavilion. The same authors [14] developed a mathematical model to parameterize the thermohygrometric conditions in the misted area as a function of several environmental and technological parameters. They concluded that lower relative humidity and lower wind speeds were precursors to accentuated performances. Speaking of wind, a 2009 experimental and numerical study [15] investigated its role when misters were used in open outdoors. It was found that, on average, the cooling was higher downwind (nearly 4 °C difference). Wind's impact was also highlighted in a recent publication by Ulpiani et al. [16]. The authors monitored a 24-nozzle overhead system in Mediterranean urban contexts (open areas), capable of temperature reductions up to 7.5 °C, and found that the local cooling was largely a function of the temperature and the wind speed. Generally, a light steady breeze of about 1 m/s is regarded as optimal operating condition, while under winds blowing at more than 3 m/s, it is suggested to shut off the injection [8]. Finally, Kim et al. [17] analyzed the role of solar radiation on the cooling capacity of a cross-shaped system of overhead blast sprayers, by performing Duncan multiple range test and one-way ANOVA. Statistically, the temperature drop was higher during hot and sunny days. Other factors, such as water temperature (7 %), were found to play a minor role and were thus examined to a lesser extent [18].

This study adds to the body of knowledge collected in the afore-mentioned studies and complements the energy and comfort analyses in [16,19,20] by investigating the sensitivity of dry misters to air temperature, relative humidity, wind speed and solar radiation, to help delineate appropriate design guidelines and site criteria. Indeed, while installing a misting system is a fairly easy task, planning its installation is no trivial matter if high efficiencies are to be guaranteed. Experimental data was collected and analyzed through statistical tools and evolutionary algorithms to spot interlinks and casual effects. In the next paragraphs methods, materials and results are illustrated.

2. Materials and methods

To investigate key causes and key consequences around the heat mitigation potential of mist cooling, potential drivers were first identified on a proper theoretical basis and later correlated to experimental data, collected out of a bespoke monitoring setup. These steps are discussed in the following sub-sections.

2.1 Theoretical background

Mist sprays for urban cooling typically form by direct droplet creation right after the pressurized and turbulent water jet leaves the nozzle. The degree of atomization mostly depends on the water speed and the discharge diameter. The governing variables can be lumped into the Reynolds (Re) and the Ohnesorge number (Oh), ratios of inertial forces to viscous forces and of viscous forces to surface tension, respectively [21]:

$$\mathrm{Re} = \frac{\rho\, v\, l}{\mu} \quad (1)$$

$$Oh = \frac{\mu}{\sqrt{\rho\,\gamma\,d_n}} \tag{2}$$

Atomized droplets are spherical with very good approximation, thus they can be accurately described by their diameter, or more precisely, by their statistical diameter distribution. The most common metric is the Sauter Mean Diameter, given by the average ratio of volume to surface area. Micron-sized droplets decelerate very fast. The deceleration is the result of a number of forces that act on the water droplet moving in the air, each with its own velocity. Beyond Magnus, Saffman and Faxen forces that play a minor role, the dominant drivers are gravity and friction [22]. This can be expressed by:

$$F_{av} = \frac{d}{dt}(m_{av} \cdot v_{av}) = \rho \cdot \frac{\pi \cdot d_{av}^3}{6} \cdot g - C_D \cdot \frac{\pi \cdot d_{av}^2 \cdot \rho}{8} \cdot (v_{r,av}) \cdot |v_{r,av}| \tag{3}$$

where the subscript "av" stands for average values for the mist cloud, F is the resulting force [N], m is the droplet mass [kg], g is the gravitational acceleration [m/s^2], $v_{r,av}$ is the mean relative velocity between droplet and surrounding air [m/s] and C_D is drag coefficient, which for small droplets can be assumed equal to 24/Re (or other empirical relationships [18]). When the droplet diameter is in the order of few microns (as in the case of dry misters) the resulting throw length is extremely short, even if the flow is initially very pressurized (1-2 MPa). This explains why overhead misting lines can be safely and efficiently placed close to passersby. This also suggests that, when characterizing the cooling capacity of a real installation, the sensor network should be placed in the proximity of the injection. Specifically, since the vertical cooling and humidification profiles obey to a Lorentzian distribution, hitting the peak at approximately 0.5 m of the injection [20], temperature and/or humidity detectors should be placed at no more than few meters away from the nozzles. While decelerating, the droplets evaporate. The rate depends on the size (exposed surface-to-volume ratio), the relative humidity and temperature of the surroundings (dictating the vapor partial pressure) and the wind speed (stimulating convective heat loss and promoting air mix). Pruppacher and Klett demonstrated that, in typical outdoor air conditions, the evaporation rate (expressed in terms of change in radius, r) is a function of the wet bulb depression [23]:

$$\frac{\mathrm{dr}}{\mathrm{dt}} \approx -\frac{\Delta T_{wb} \cdot k_a}{L \cdot \rho \cdot r} \tag{4}$$

where k_a is the thermal conductivity of air [W/(mK)] and L is the latent heat of evaporation [J/kg]. This relationship, however, does not contemplate the effect of wind speed on break-up mechanisms into child particles, on particle dilution, on convective heat transfer, and on local turbulence.

To gain more insight into the effects of the environmental context on the cooling and the humidification that come with the evaporative process inside the mist layer, an experimental rig was conceived, based on the above considerations.

2.2 Experimental setup

The test rig consisted of 24 hollow cone nozzles connected to a high-pressure, self-compensating pump (0.7 MPa). As a result of the nozzles' geometry and the operating pressure, the injected droplets' diameter obeyed to a Rosin-Rammler distribution with a Mean Sauter Diameter around 10 μm. The high surface-to-volume ratio ensured flash evaporation within few centimeters of the orifice. The water flow rate was 0.09 m^3/h. The nozzles were hanged at a height of 3.3 m (in line with typical settings [8]) and distributed in 4 parallel lines as depicted in Fig. 1. Extensive details of the experimental setup can be found in [16,20].

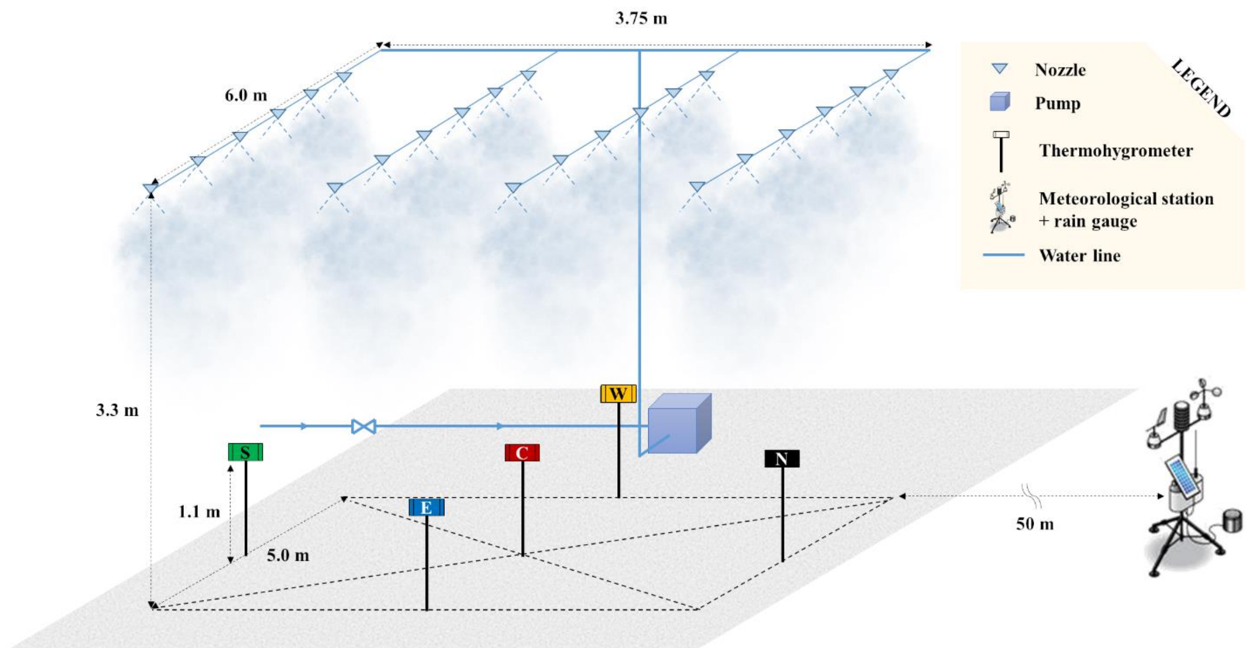

Fig. 1 Schematics of the experimental setup: mechanical components and sensor network

The distinctive feature of the misting system in object lies in the control of the injection. Misting systems are typically operated in a continuous or on-off mode. The latter is beneficial in terms of comfort as it helps containing the humidification, without congesting the air with overabundant evaporating droplets [24,25]. On the other side, given the risk of Legionella contamination, the water circulating in the hydraulic circuit must be discharged at any switch off, thus causing higher water wastage. Also, no guidelines or well-established procedures support the selection of on-off timing for intermittent operations: generally, the injection time varies from seconds to tens of minutes and its setting is left to the user [8]. Smart logics could be especially beneficial i) in optimizing the injection on the basis of the concomitant ambient conditions and comfort enhancement potential and ii) in rationalizing the amount of energy needed to operate the system thus making self-sustained solutions (e.g. PV-powered ones) more practical [16,26]. Against this backdrop, the experimental system in object was devised so that the duration of the injection could be responsive to the measured changed in air temperature, relative humidity, wind speed and solar irradiation. Approximate reasoning, in the form of fuzzy logic, was adopted to chase optimal comfort conditions. The duration of the misting action was proportional to the offset from the target neutral temperature (defined from previous comfort-oriented studies [27]) and to the level of irradiation and was adjusted on the basis of two lumped indexes: the Humidex which accounts for the combined action of temperature and humidity and the cooling power index (PE) which accounts for temperature and wind speed. These indexes weight the capability of ambient air in a given thermodynamic state to accommodate extra humidity and to be cooled by evaporative processes without imperiling the latent mechanisms of heat transfer. For further details about the fuzzy logic, the reader is referred to previous research [16], where the efficiency in terms of energy saving was demonstrated, compared to on-off operation. Comfort enhancement was also investigated in [20] where PET, SET* and UTCI differences between misted and undisturbed locations were analyzed through a variety of statistical metrics (including non-parametric Spearman correlation test, non-parametric Kruskal-Wallis H test, correlation matrices, Frequent Pattern (FP)-Growth algorithms) based on comfort questionnaires. Under hot Mediterranean summers (as in this study), the effect of the logic is to i) switch on/off autonomously depending on morning and evening conditions, ii) maintain a continuous injection around peak hours, iii) allow for interruptions under cold and humid or windy conditions (precursor to undesired humidification).

The perturbing action of the misting system was characterized by recording the temperature and relative humidity underneath the lines. Five thermohygrometers were located within the ground-projected perimeter of the misting matrix at a height of 1.1 m, which represents the suggested breast level of a standing person and head level of a sitting person in ISO 7726 [28] . One probe was placed in central position (denoted with “C” in Fig. 1) and the other four were distributed towards the cardinal directions (denoted with “N” , “S”, “E” and “W” in Fig. 1). The accuracy was ± 0.2 °C in the −20 °C ÷ 80 °C temperature range, and ± 2 % in the 10 ÷ 90 % relative humidity range. A monitoring station, placed approximately 50 m away from the misted area, recorded the meteorological parameters (temperature, relative humidity, solar radiation, wind speed and direction) representative of concomitant undisturbed conditions. The corresponding accuracies were 0.2 °C, 1.5 %, < 5 %, 1.5 % and 1°. The sampling rate was 10 s, the averaging time was 1 min.

The monitoring campaign took place in Ancona, Italy (see Fig. 2), under Cfa climatic conditions according to the updated Köppen and Geiger classification [29], namely temperate marine climate with warm and humid summer extending from June to September. The analyzed data refer to a week time in August (13-19 August 2018), over which the temperature ranged between 20.2 °C and 36.3 °C, with a median of 25.7 °C. The relative humidity varied from a minimum of 44.8 % up to 87.1 % maintaining a median of about 62.4 %, while the global horizontal irradiance reached a maximum of 1202 W/m^2 with a median of 547 W/m^2. Against this climatic context, the fuzzy logic switched on the misting at around 10 am LST and switched it off at around 6:30 pm LST with only minor interruptions of maximum 2 minutes in between, due to the simultaneous occurrence of high wind speed and low local temperature. This provides optimal grounds to investigate the cooling capacity in relation to different boundary conditions.

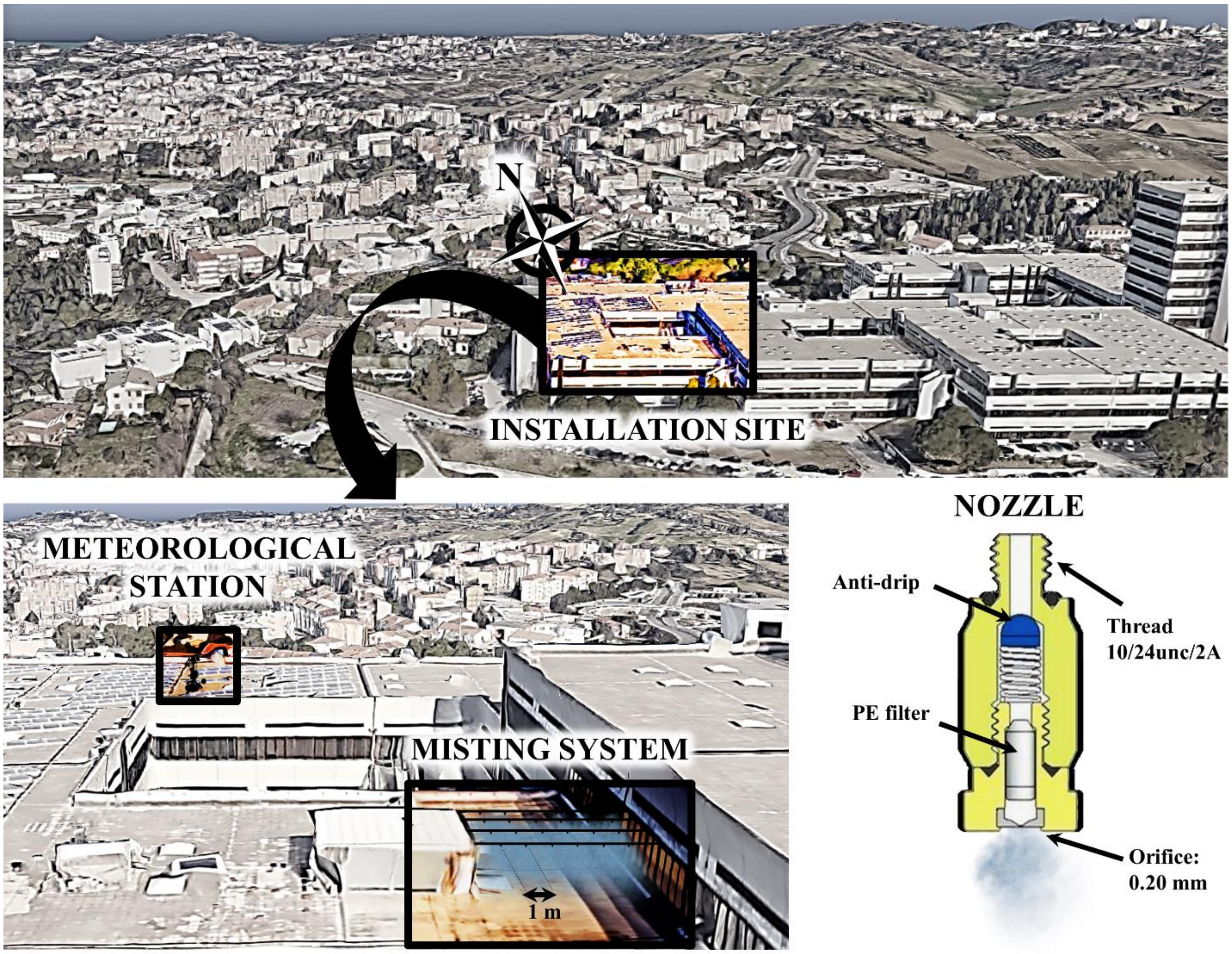

Fig. 2 Installation site, close-up on the misting system and the meteorological station, and exploded-view of the adopted hollow cone nozzle.

3. Results

3.1 Cooling performance and humidification

Fig. 3 displays temperature drop and relative humidity gain at the different locations in the form of raincloud plots. Raincloud plots combine a split-half violin plot, raw jittered data points and a boxplot. This representation is especially powerful and intuitive as it accurately and transparently visualizes raw data, probability density, key summary statistics and relevant confidence intervals with minimal redundancy and minimal distortion [30].

By looking at the probability density of the temperature drop at different values (half violin plots), it is apparent how the central and the northern locations were the only ones with a pronounced characteristic response to evaporative cooling: the former showed a sharp peak around 1.0 °C, while the second around 2.5 °C and a very narrow variability. This can be explained by considering that southern winds were the strongest (refer to the wind rose in Fig. 4), thus progressively entraining the droplets and concentrating them along the travel to the north. The central location was also the only one with a considerable skewness of the first and third quartile with respect to the median and towards higher values, implying that the temperature drop varied more when above the median. Data related to eastern, southern and western locations were much more dispersed and stretched along a much wider span of values, including absolute maxima (7.4 °C recorded at the east-located probe) and minima. This was likely due to the complex turbulent motions happening in proximity of the bordering walls, which suggests that misting systems can produce a quite stable cooling action only if local winds are light breezes and if no canyon/tunnel effect occurs due to bordering landscape and roughness.

The relative humidity increased by maximum 12.6 % in the middle of the mist layer, while tended to stay lower downwind, at the southern point of measurement. Considering that the average relative humidity at the undisturbed location was 57.67 %, it was proved that under smart controlled operation the maximum humidity could be reasonably maintained below 70 %, which is the proposed threshold by Ishii et al. for misting systems [24]. By looking at the probability density, every location showed a pronounced peak, but for different RH values: the central location peaked at the highest level (around 5.0 %), followed by the eastern location (around 3.5 %) and the western/northern locations (both around 2.0 %). Unexpectedly, the peak of the bell at the southern location fell into the negative side of the x-axis, meaning that the probability of having a drier environment than at the reference location was high. This, again, can be explained by looking at Fig. 4: strong southern winds tended to effectively remove the droplets, thus impeding the local rise in relative humidity. Additionally, compared to the reference location, the southern probe was inside the wind channel created by the walls onto which the misting lines were secured, thus being locally affected by an accelerated airflow.

All distributions were rather symmetric around the median, but at the northern location, where a higher chance of lower humidity gains than the median was recorded.

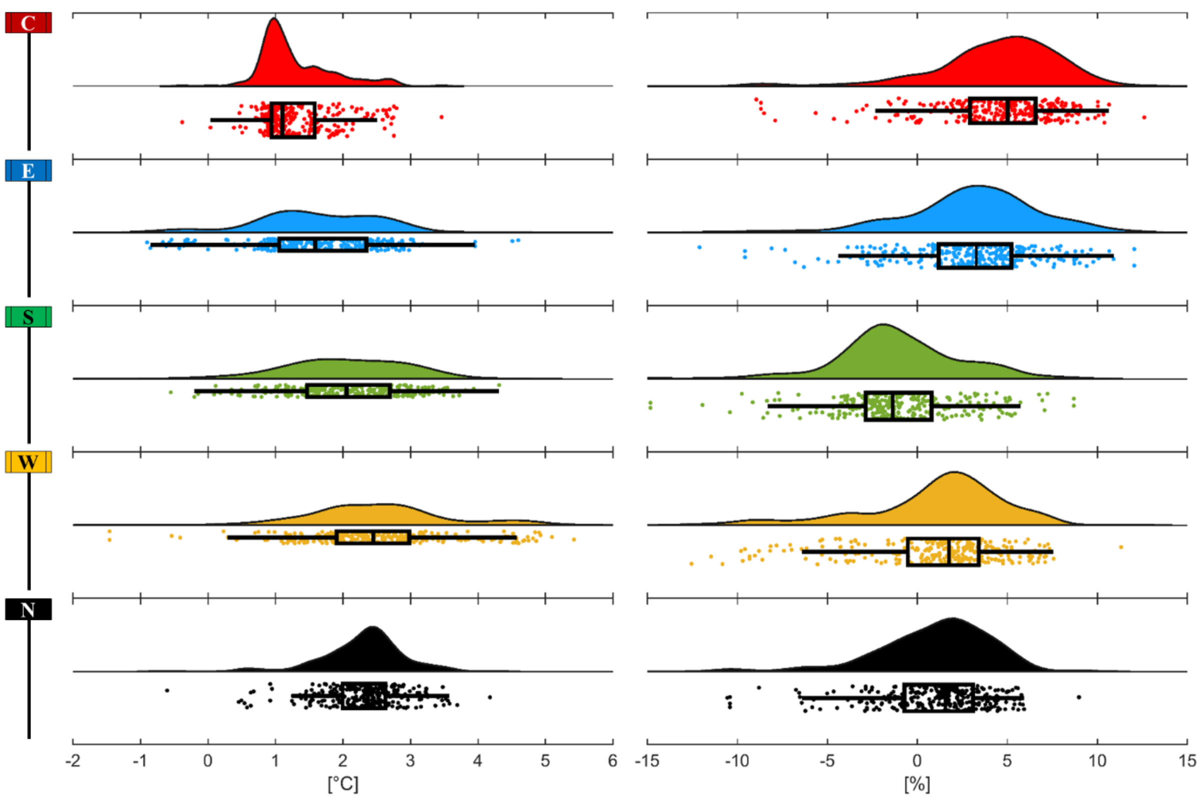

Fig. 3 Raincloud plots of temperature drop (left side) and relative humidity gain (right side) at the five considered locations.

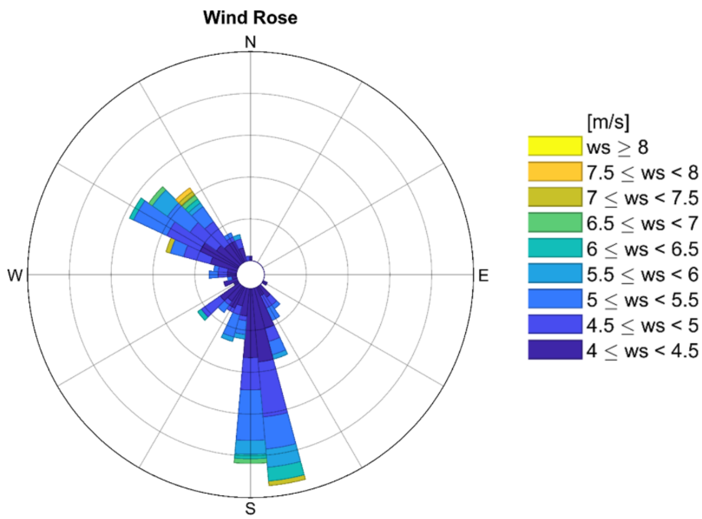

Fig. 4 Wind rose, representing wind direction and intensity during the monitoring campaign at the undisturbed location.

3.2 Driving forces

Finely sprayed mists tend to evaporate in proportion to the wet bulb depression, as remarked in previous studies [31]. Here, the wet bulb depression ranged between 2.2 °C and 10.3 °C in the misted area and between 3.2 °C and 9 °C in the undisturbed location.

The wet bulb temperature (T_{wb}) was calculated, based on the measured dry-bulb temperature T_{db} and relative humidity RH, according to the empirical fit by Stull [32]:

$$T_{wb} = T_{db} \cdot tan^{-1}\left[0.151977 \cdot (RH + 8.313659)^{\frac{1}{2}}\right] + tan^{-1}(T_{db} + RH) - tan^{-1}(RH - 1.676331) + 0.00391838 \cdot RH^{\frac{3}{2}} \cdot tan^{-1}(0.023101 \cdot RH) - 4.686035 \quad (5)$$

which well fits for dry-bulb temperatures between -20 °C and 50 °C and RH in the 5-99 % range (absolute error between -1 °C and 0.65 °C).

The wet bulb depression in the middle of the mist layer ($\Delta T_{wb,c}$) was used as representative parameter of the thermo-hygrometric conditions in the misted area. To further investigate how other potential drivers (solar irradiation, wind …) related to the temperature drop achieved by the misting system in the central portion of the conditioned area (ΔT_c), an artificial intelligence approach, based on evolutionary algorithms, was deployed.

The input dataset comprised the wet-bulb depression, all the outputs of the meteorological station and the duration of the misting, represented by the parameter n, namely the number of 10 minute lasting operations in a minute time ($0 \leq n \leq 6$). The training and testing datasets were equally apportioned (50 % and 50 %).

Through a supervised gene-programming, different candidate functions evolved through mutation and competed until the fittest candidate was obtained (max R^2). An 8-coefficient equation was eventually proposed:

$$\Delta T_c = 0.5 \cdot sma(\Delta T_{wb,c}, 3) + 1.5 \cdot 10^{-2} \cdot ws \cdot \Delta T_{wb,c} + 6.1 \cdot 10^{-4} \cdot Ioh \cdot sma(\Delta T_{wb,c}, 3) + 2.2 \cdot 10^{-6} \cdot Ioh^2 - 0.75 - 8.1 \cdot 10^{-3} \cdot Ioh - 3.1 \cdot n - 5.3 \cdot 10^{-2} \cdot sma(\Delta T_{wb,c}, 3)^2 \quad (6)$$

where ws is the wind speed in [m/s], Ioh is the horizontal global irradiance in [W/m^2] and sma is the simple moving average operator. The comparison between modeled and measured data is displayed in Fig. 5.

The R^2 approached 0.86 with a maximum absolute error of 0.83 °C, a mean absolute error of 0.09 °C and a mean squared error of 0.02 °C.

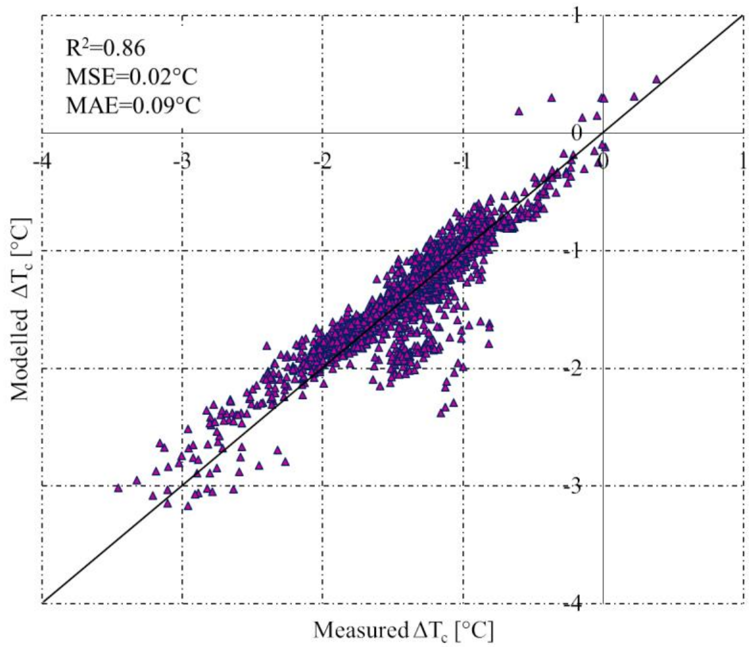

Fig. 5 Plot of modelled versus measured temperature drop in the middle of the mist. Goodness of fit displayed in terms of R^2, mean squared error (MSE) and mean absolute error (MAE)

Hence, further evidence was collected about how the cooling capacity of misting systems is largely a function of the local wet bulb depression even in complex outdoor contexts. Interestingly, both the instantaneous and the previous 30 s average were driving factors. A sensitivity analysis on the data (see Table 1) showed that the relative impact of wet-bulb depression on the target variable was the highest, followed by solar radiation, wind speed and duration of the injection. A negative correlation was identified between solar irradiation and temperature drop, which could be the result of the preponderance of increased heat over peak hours compared to the enhanced cooling capacity of the misting system. Conversely, a positive correlation could be established between wind speed and temperature drop, meaning that by increasing the dilution of the droplet cloud, higher evaporation rates could be achieved. However, it should be stressed that the greatest misalignment between measured and modelled ΔT_c occurred right at higher wind speeds, meaning that the beneficial effect of wind speed on cooling capacity is limited to low velocities.

Table 1. Sensitivity analysis

Sensitivity	Magnitude	Positive Likelihood	Negative Likelihood
$\left\lvert\frac{\partial \Delta T_c}{\partial \Delta T_{wb,c}}\right\rvert \cdot \frac{\sigma(\Delta T_{wb,c})}{\sigma(\Delta T_c)}$	0.77	100 %	0 %
$\left\lvert\frac{\partial \Delta T_c}{\partial Ioh}\right\rvert \cdot \frac{\sigma(Ioh)}{\sigma(\Delta T_c)}$	0.68	7 %	93 %
$\left\lvert\frac{\partial \Delta T_c}{\partial ws}\right\rvert \cdot \frac{\sigma(ws)}{\sigma(\Delta T_c)}$	0.29	100 %	0 %
$\left\lvert\frac{\partial \Delta T_c}{\partial n}\right\rvert \cdot \frac{\sigma(n)}{\sigma(\Delta T_c)}$	0.16	0 %	100 %

The same evolutionary algorithm was later applied only considering the availability of data from the reference station (without any measurement underneath the mist) which is likely to be the case in real installations. The penalty in the predicting capacity is demonstrated in Fig. 6. Fig 6a represents the results obtained when wind speed was the only environmental parameter retained in the final optimized equation and Fig 6b when both wind speed and solar irradiation were contemplated. The importance of knowing the wet bulb depression in the area emerges clearly, although it is quite interesting to observe that wind speed and solar radiation are good estimators of the overall trend. On the other side, knowing irradiation only led to no significant prediction of the temperature drop.

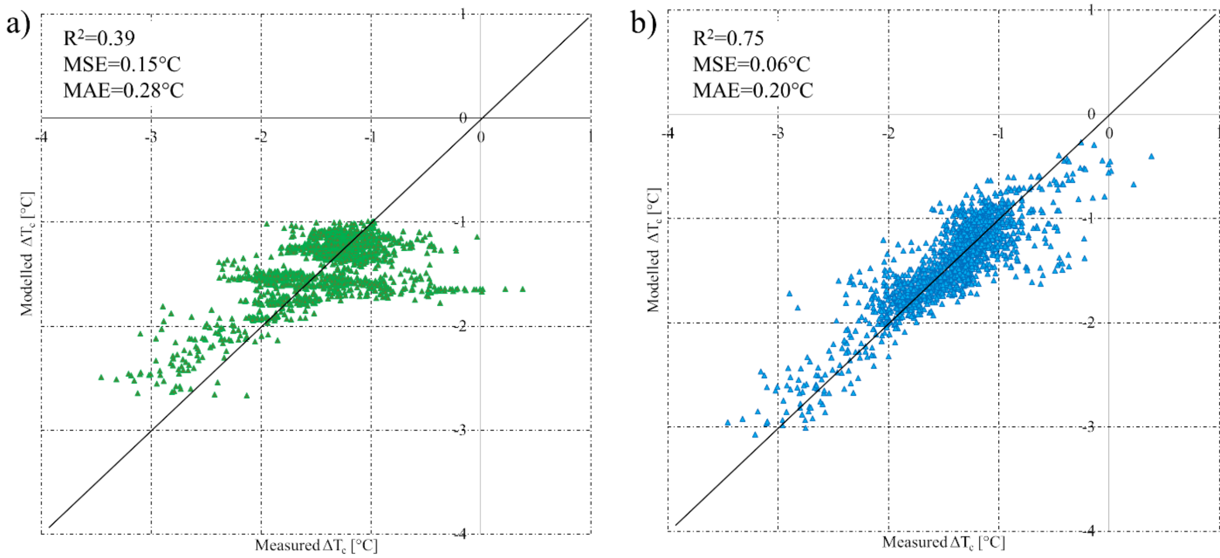

Fig. 6 Plot of modelled versus measured temperature drop in the middle of the mist, when considering the following environmental parameters: a) only wind speed, b) wind speed and solar irradiation. Goodness of fit displayed in terms of R^2, mean squared error (MSE) and mean absolute error (MAE)

4 Discussion and conclusions

Dry misters are efficient heat mitigators, yet their cooling capacity heavily depends on the microclimatic context. An experimental system of 24 overhead nozzles was monitored for one week in summertime and Mediterranean climate to establish potential links between the measured temperature drop and the environmental parameters in the misted area as well as in a near undisturbed location.

During the campaign, the temperature in the undisturbed location peaked at 36.3 °C with a median of 25.7 °C, while the relative humidity reached 87.1 % maintaining a median of about 62.4 °C, with the highest values recorded overnight when the misting was inactive. In the misted area, the temperature at about 2.2 m of the injection and 1.1 m above the ground could be reduced by up to 7.4 °C by injecting pulverized water droplets, while maintaining the humidity gain below 13 %. By means of evolutionary algorithms, the temperature drop in the misted area could be expressed as a function of only 4 parameters with good accuracy (R^2 = 0.86): wet-bulb depression, solar irradiation, wind speed and injection duration, in order of decreasing sensitivity. A strong positive correlation was established between the achieved cooling effect and the potential capacity of the air volume to accommodate extra moisture, represented by the wet bulb depression. The temperature drop was emphasized when the wet bulb depression stayed higher in the previous 30 s. A negative correlation emerged between global horizontal irradiation and temperature drop, which entails that the solar-induced temperature increase outweighed the solar-induced enhancement of the evaporative rate. Another positive correlation was identified between wind speed and temperature drop, although the sensitivity was much reduced. Faster winds engendered efficient heat removal mechanisms and helped spread the droplets, thus reducing the risk of coalescence and augmenting the changes of break-ups into child particles. On the other side, the predictability of the temperature drop drastically declined at high wind speeds suggesting the existence of a threshold over which the positive impact of wind-driven dilution reverses, in line with previous research [19]. Further investigation will be devoted to determining these thresholds in different climatic contexts, to quantifying the time needed for outdoor temperatures to fall back into uncomfortable limits after injection cessation and to defining bespoke strategies against future escalation of urban heat islands [33–35]. Overall, mist cooling is a high-impact local-scale urban overheating countermeasure. It is not meant to be used on large areas not to introduce excessive humidity in the air, adversely impact on water management during droughts and not to jeopardize passersby's right to decide whether or not to be directly exposed to the mist. A city-scale application would be achieved by spreading several small-scale installations in appropriate locations (city hot spots with low, steady wind speed, no canyon effect, no excessive urban shading and close to vulnerable population, e.g. elderly, low-income groups). Notably, urban canyons and shading should be carefully evaluated prior to any installations due to the local acceleration of the wind flow [36] and the enhanced wetting risk associated with lower heat absorption by the water droplets [5], respectively. Microscale urban simulations and experimentally substantiated artificial-intelligence-assisted analyses like the evolutionary algorithm proposed in this study, would be especially valuable in defining the most appropriate installation sites. From a technical and economical perspective, the use of smart logics, able to weigh the injection of water upon a variety of drivers as the one hereby presented, is expected to be a major enabler in urban-scale deployment.

Acknowledgments

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References

[1] K.R. Gunawardena, M.J. Wells, T. Kershaw, Utilising green and bluespace to mitigate urban heat island intensity, Sci. Total Environ. 584–585 (2017) 1040–1055. doi:10.1016/j.scitotenv.2017.01.158.

[2] M. Santamouris, L. Ding, F. Fiorito, P. Oldfield, P. Osmond, R. Paolini, D. Prasad, A. Synnefa, Passive and active cooling for the outdoor built environment – Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects, Sol. Energy. 154 (2017) 14–33. doi:10.1016/j.solener.2016.12.006.

[3] M. Taleghani, U. Berardi, The effect of pavement characteristics on pedestrians' thermal comfort in Toronto, Urban Clim. 24 (2018) 449–459. doi:10.1016/j.uclim.2017.05.007.

[4] S. Haddad, G. Ulpiani, R. Paolini, A. Synnefa, M. Santamouris, Experimental and Theoretical analysis of the urban overheating and its mitigation potential in a hot arid city – Alice Springs, Archit. Sci. Rev. (2019) 1–16. doi:10.1080/00038628.2019.1674128.

[5] L.A. Dombrovsky, V.P. Solovjov, B.W. Webb, Attenuation of solar radiation by a water mist from the ultraviolet to the infrared range, J. Quant. Spectrosc. Radiat. Transf. 112 (2011) 1182–1190. doi:10.1016/j.jqsrt.2010.08.018.

[6] S. Yu, Water spray geoengineering to clean air pollution for mitigating haze in China's cities, Environ. Chem. Lett. 12 (2014) 109–116. doi:10.1007/s10311-013-0444-0.

[7] A.S. Nouri, J.P. Costa, M. Santamouris, A. Matzarakis, Approaches to outdoor thermal comfort thresholds through public space design: A review, Atmosphere (Basel). 9 (2018). doi:10.3390/atmos9030108.

[8] G. Ulpiani, Water mist spray for outdoor cooling: A systematic review of technologies, methods and impacts, Appl. Energy. 254 (2019) 113647. doi:10.1016/j.apenergy.2019.113647.

[9] H. Barrow, C.W. Pope, Droplet evaporation with reference to the effectiveness of water-mist cooling, Appl. Energy. 84 (2007) 404–412. doi:10.1016/j.apenergy.2006.09.007.

[10] M. Beermann, B.; Berchtold, M.; Baumüller, J.; Gross, G.; Kratz, Städtebaulicher Rahmenplan Klimaanpassung für Die Stadt Karlsruhe (Teil II), Karlsruhe, Germany, 2014. https://fachdokumente.lubw.baden-wuerttemberg.de/servlet/is/109723/U83-W03-N11.pdf?command=downloadContent&filename=U83-W03-N11.pdf.

[11] J. Wang, X. Tu, Z. Wang, J. Huang, Application and Numerical Simulation on Water Mist Cooling for Urban Environment Regulation, in: Lect. Notes Comput. Sci., 2010. doi:10.1007/978-3-642-15859-9.

[12] G. Yoon, H. Yamada, M. Okumiya, Study on a cooling system using water mist sprayers; system control considering outdoor environment., Korea-Japan Jt. Symp. Human-Environment Syst. Cheju, Korea, p. 4. (2008).

[13] C. Huang, D. Ye, H. Zhao, T. Liang, Z. Lin, H. Yin, Y. Yang, The research and application of spray cooling technology in Shanghai Expo, Appl. Therm. Eng. 31 (2011) 3726–3735. doi:10.1016/j.applthermaleng.2011.03.039.

[14] C. Huang, J. Cai, Z. Lin, Q. Zhang, Y. Cui, Solving model of temperature and humidity profiles in spray cooling zone, Build. Environ. 123 (2017) 189–199. doi:10.1016/j.buildenv.2017.06.043.

[15] W. Jun-feng, T. Xin-cheng, Experimental Study and Numerical Simulation on Evaporative Cooling of Fine Water Mist in Outdoor Environment, 2009 Int. Conf. Energy

Environ. Technol. (2009) 156–159. doi:10.1109/ICEET.2009.44.

[16] G. Ulpiani, C. Di Perna, M. Zinzi, Water nebulization to counteract urban overheating : Development and experimental test of a smart logic to maximize energy efficiency and outdoor environmental quality, Appl. Energy. 239 (2019) 1091–1113. doi:10.1016/j.apenergy.2019.01.231.

[17] J.-H. Kim, M.-H. Lee, Y.-H. Yoon, A Verification Study on the Temperature reduction Effect of Water Mist Injection, Int. J. Korea Inst. Ecol. Archit. Environ. 15 (2015) 5–14.

[18] C. Farnham, M. Nakao, M. Nishioka, M. Nabeshima, T. Mizuno, Effect of Water Temperature on Evaporation of Mist Sprayed From a Nozzle, J. Heat Isl. Inst. Int. 10 (2015) 35–44.

[19] G. Ulpiani, E. Di Giuseppe, C. Di Perna, M.D. Orazio, M. Zinzi, Design optimization of mist cooling for Urban Heat Island mitigation: experimental study on the role of injection density, (2019). doi:10.1088/1755-1315/296/1/012025.

[20] G. Ulpiani, E. Di Giuseppe, C. Di Perna, M. D'Orazio, M. Zinzi, Thermal comfort improvement in urban spaces with water spray systems: Field measurements and survey, Build. Environ. 156 (2019) 46–61. doi:https://doi.org/10.1016/j.buildenv.2019.04.007.

[21] B.M. Schneider, Experimental studies on the spray structure in transient, evaporating and non-evaporating fuel jets under high pressure, ETH Zurich, 2003.

[22] B.P. Husted, G. Homstedt, T. Hertzberg, The physics behind water mist systems, IWMA Conf. (2004) 6–8. https://iwma.net/publications/conference-papers/.

[23] H.R. Pruppacher, J.D. Klett, Microphysics of Clouds and Precipitation, 1997.

[24] T. Ishii, M. Tsujimoto, G. Yoon, M. Okumiya, Cooling System with Water Mist Sprayers for Mitigation of Heat-island Drymist system : Uchimizu, Seventh Int. Conf. Urban Clim.

(2009) 2–3.

[25] S.A. Domínguez, F.J. Sánchez, The effect of evaporative cooling techniques on reducing urban heat, in: Urban Clim. Mitig. Tech., Routledge, 2016: pp. 127–144.

[26] A. Atieh, S. Al Shariff, Solar energy powering up aerial misting systems for cooling surroundings in Saudi Arabia, Energy Convers. Manag. 65 (2013) 670–674. doi:10.1016/j.enconman.2011.10.031.

[27] F. Salata, I. Golasi, R. de Lieto Vollaro, A. de Lieto Vollaro, Outdoor thermal comfort in the Mediterranean area. A transversal study in Rome, Italy, Build. Environ. 96 (2016) 46–61. doi:10.1016/j.buildenv.2015.11.023.

[28] ISO, ISO 7726:1998 Ergonomics of the thermal environment -- Instruments for measuring physical quantities, (1998).

[29] M.C. Peel, B.L. Finlayson, T.A. McMahon, Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci. Discuss. 4 (2007) 439–473.

[30] M. Allen, D. Poggiali, K. Whitaker, T.R. Marshall, R.A. Kievit, Raincloud plots: A multi-platform tool for robust data visualization [version 1; peer review: 2 approved], Wellcome Open Res. 4 (2019) 1–41. doi:10.12688/wellcomeopenres.15191.1.

[31] C. Farnham, M. Nakao, M. Nishioka, M. Nabeshima, Quantification of the Effect of Cooling Mists on Individual Thermal Comfort, in: Seventh Int. Conf. Urban Clim., 2009.

[32] R. Stull, Wet-bulb temperature from relative humidity and air temperature, J. Appl. Meteorol. Climatol. 50 (2011) 2267–2269.

[33] G.Y. Yun, J. Ngarambe, P.N. Duhirwe, G. Ulpiani, R. Paolini, S. Haddad, K. Vasilakopoulou, M. Santamouris, Predicting the magnitude and the characteristics of the urban heat island in coastal cities in the proximity of desert landforms. The case of

Sydney, Sci. Total Environ. 709 (2020) 136068. doi:10.1016/j.scitotenv.2019.136068.

[34] C. Rosenzweig, W.D. Solecki, L. Parshall, M. Chopping, G. Pope, R. Goldberg, Characterizing the urban heat island in current and future climates in New Jersey, Environ. Hazards. 6 (2005) 51–62. doi:10.1016/j.hazards.2004.12.001.

[35] J. Wang, B. Huang, D. Fu, P.M. Atkinson, X. Zhang, Response of urban heat island to future urban expansion over the Beijing-Tianjin-Hebei metropolitan area, Appl. Geogr. 70 (2016) 26–36. doi:10.1016/j.apgeog.2016.02.010.

[36] P. Kastner-Klein, E. Fedorovich, M.W. Rotach, A wind tunnel study of organised and turbulent air motions in urban street canyons, J. Wind Eng. Ind. Aerodyn. 89 (2001) 849–861. doi:10.1016/S0167-6105(01)00074-5.

Highlights

- A water mist cooling system was monitored in summertime in an urban location.
- The efficiency of heat mitigation was linked to the local meteorological trends.
- Collected data were processed by statistical analyses and evolutionary algorithms.
- Wet-bulb depression, solar irradiation and wind speed proved to be key drivers.
- Wind speed was found to arbitrate the predictability of the temperature drop.

Title

Mist cooling in urban spaces: Understanding the key factors behind the mitigation potential

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Abstract

Mist cooling is a widely known and applied heat mitigation technology, especially in urban settings. Despite this, conceiving the right installation is no trivial matter as scattered and unstandardized is the knowledge on the multiple interrelations with the local microclimate. This paper investigates how the cooling efficiency of a dry mist system depends on the local meteorological trends. An experimental system of 24 overhead nozzles constantly operating at 0.7 MPa, was installed in Italy and monitored for a week in summertime. Temperature and relative humidity underneath the mist were mapped in five locations with a time step of 10 s, together with the main meteorological parameters, measured at an undisturbed location, for reference. Cooling and humidification capacity were characterized as probability density, key summary statistics and relevant confidence intervals with minimal redundancy and minimal distortion. A supervised learning algorithm was used to disclose the sensitivity of the recorded temperature drop to the contextual microclimatic evolution. It was demonstrated that the cooling capacity of the tested system was largely a function of the local wet bulb depression, as instantaneous reading as well as short-term trend. Additionally, solar irradiation and wind speed were found to be negatively and positively correlated, respectively.

Keywords: water misting; experimental monitoring; urban climate; evaporative cooling; sensitivity analysis; artificial intelligence

Acronyms and symbols (alphabetical order)

ANOVA	Analysis of variance	Oh	Ohnesorge number
μ	Dynamic viscosity of the fluid [Ns/m^2]	PE	Cooling power index [$mcal/cm^2s$]
av	Subscript for average value	PV	Photovoltaic
C	Centre (position)	r	Water droplet radius [m]
CD	Drag coefficient	Re	Reynolds number
d	Droplet diameter [m]	RH	Relative humidity [%]
d_n	Nozzle diameter [m]	S	South (position)
E	East (position)	sma	Simple moving average
F	Resulting force [N]	T_{db}	Dry-bulb temperature [°C]
g	Gravitational acceleration [m/s^2]	T_{wb}	Wet-bulb temperature [°C]
Ioh	Horizontal global solar irradiance [W/m^2]	UHI	Urban heat island
IQR	Interquartile range	v	Characteristic velocity of the flow [m/s]
k_a	Thermal conductivity of air [W/(mK)]	vr,av	Mean relative velocity between droplet and surrounding air [m/s]
l	Characteristic length scale of flow [m]	W	West (position)
L	Latent heat of evaporation [J/kg]	ws	Wind speed [m/s]
m	Water droplet mass [kg]	γ	Surface tension [N/m]

MAE	Mean absolute error	ΔT_c	Temperature drop in the middle of the mist [°C]
MSE	Mean squared error	$\Delta T_{wb,c}$	Wet-bulb depression in the middle of the mist [°C]
N	North (position)	ρ	Density of water [kg/m^3]
n	Number of 10 s lasting injections in a minute time	σ	Standard deviation

1. Introduction

Water-based features have always been key in the cooling strategies for urban spaces. In most studies, devoted to the mitigation of urban heat islands (UHIs), the blue mitigator is represented by water bodies having high thermal mass (e.g. sea, lake, river). Such large natural formations are the preserve of a limited number of densely inhabited cityscapes in the world. Besides their cooling effect is nor controllable nor tunable, thus affecting the heating consumptions in a year-round evaluation. Several researches concur that multiple, strategically positioned artificial installations, even small-scale ones, tend to have a pronounced cooling impact, locally more intense and spatially more distributed than a lone, large source [1–4]. These micro-features can be designed with due consideration to prevailing winds and synergies with other evaporative processes (e.g. local evapotranspiration) so as to maximize the efficiency and optimize the usefulness on the territory and the comfort of typical users.

Among the technological alternatives (e.g. cooling towers, sprinklers, fountains, ponds), dry misters are gaining popularity as, beyond being a very locally impactful cooling technique, their working principle well responds to growing concerns about energy consumption, water usage and climate-anxiety. By pulverizing water into micrometric particles, dry misters attain flash and complete evaporation of the injected droplets, drawing the necessary heat from the surrounding air. The resulting water consumption is extremely modest and the risk of skin wettedness can be easily averted by appropriate layouts. Furthermore, dry misters lend themselves to a variety of applications, targeting the whole sphere of comfort. Their action is not merely thermohygrometric, but affects all the major environmental parameters, by attenuating solar radiation [5], scavenging dust [6], breaking the wind force while engendering a local turbulent flow of cooled air, all factors contributing to an efficient heat removal and to the generation of pleasant spaces in the urban realm, especially where overheating and pollution risks are prominent. As discussed in recent review papers [7,8], this technology is especially valuable in dry and warm climates, although good performance has been demonstrated also in humid locations like Singapore [8]. Increasing interest has also been expressed by heating-dominated countries, such as UK and Germany, to cope with the unprecedented escalation of heat-stress events in recent years [9,10]. These countries are less armored against urban overheating, thus increasing the heat resistance of their infrastructure has become a priority target. Compared to passive and natural mitigators, misters and other artificial water features are especially desirable in such contexts where intense outdoor cooling is a sporadic necessity, given their adjustability, controllability and scalability.

Experimental evidence suggests that misting systems can induce a local temperature drop from few degrees Celsius (1-2 °C), up to over 15 °C [8]. On average, the reduction falls in the 7-8 °C range, with major deviations due to the selected technology (in terms of nozzle geometry, operating pressure and layout), the local microclimate and the typology of cooled area (open outdoor, semi-enclosed, indoor) [11]. The humidification is in the order of 20%. Beyond technological considerations, the cooling capacity of misting systems depends on the contextual microclimate. In [12] Yoon and Yamada demonstrated that relative humidity is the governing parameter, even more than temperature, in the considered range. Humid conditions depreciated the extent and completeness of the evaporation process. The authors suggested potentially optimal thermohygrometric boundary conditions: 70% and 30-34 °C as for relative humidity and ambient temperature, respectively. During the 2010 Shanghai Expo [13], Huang et al. monitored an extensive misting system of about 136 nozzle and reported temperature drops of 6-12 °C within 1 m of the injections, when the ambient temperature was 34-40 °C and the relative humidity was 32-55 %. Considering the wet bulb depression (ΔT_{wb}, difference between wet bulb and dry bulb temperatures) as theoretical limit, the authors computed the cooling efficiency by dividing the actual temperature drop to the ideal wet bulb depression: it reached 90 % in the Expo Pavilion. The same authors [14] developed a mathematical model to parameterize the thermohygrometric conditions in the misted area as a function of several environmental and technological parameters. They concluded that lower relative humidity and lower wind speeds were precursors to accentuated performances. Speaking of wind, a 2009 experimental and numerical study [15] investigated its role when misters were used in open outdoors. It was found that, on average, the cooling was higher downwind (nearly 4 °C difference). Wind's impact was also highlighted in a recent publication by Ulpiani et al. [16]. The authors monitored a 24-nozzle overhead system in Mediterranean urban contexts (open areas), capable of temperature reductions up to 7.5 °C, and found that the local cooling was largely a function of the temperature and the wind speed. Generally, a light steady breeze of about 1 m/s is regarded as optimal operating condition, while under winds blowing at more than 3 m/s, it is suggested to shut off the injection [8]. Finally, Kim et al. [17] analyzed the role of solar radiation on the cooling capacity of a cross-shaped system of overhead blast sprayers, by performing Duncan multiple range test and one-way ANOVA. Statistically, the temperature drop was higher during hot and sunny days. Other factors, such as water temperature (7 %), were found to play a minor role and were thus examined to a lesser extent [18].

This study adds to the body of knowledge collected in the afore-mentioned studies and complements the energy and comfort analyses in [16,19,20] by investigating the sensitivity of dry misters to air temperature, relative humidity, wind speed and solar radiation, to help delineate appropriate design guidelines and site criteria. Indeed, while installing a misting system is a fairly easy task, planning its installation is no trivial matter if high efficiencies are to be guaranteed. Experimental data was collected and analyzed through statistical tools and evolutionary algorithms to spot interlinks and casual effects. In the next paragraphs methods, materials and results are illustrated.

2. Materials and methods

To investigate key causes and key consequences around the heat mitigation potential of mist cooling, potential drivers were first identified on a proper theoretical basis and later correlated to experimental data, collected out of a bespoke monitoring setup. These steps are discussed in the following sub-sections.

2.1 Theoretical background

Mist sprays for urban cooling typically form by direct droplet creation right after the pressurized and turbulent water jet leaves the nozzle. The degree of atomization mostly depends on the water speed and the discharge diameter. The governing variables can be lumped into the Reynolds (Re) and the Ohnesorge number (Oh), ratios of inertial forces to viscous forces and of viscous forces to surface tension, respectively [21]:

$$\mathrm{Re} = \frac{\rho \, v \, l}{\mu} \tag{1}$$

$$\mathrm{Oh} = \frac{\mu}{\sqrt{\rho\,\gamma\,\mathrm{d_n}}} \tag{2}$$

Atomized droplets are spherical with very good approximation, thus they can be accurately described by their diameter, or more precisely, by their statistical diameter distribution. The most common metric is the Sauter Mean Diameter, given by the average ratio of volume to surface area. Micron-sized droplets decelerate very fast. The deceleration is the result of a number of forces that act on the water droplet moving in the air, each with its own velocity. Beyond Magnus, Saffman and Faxen forces that play a minor role, the dominant drivers are gravity and friction [22]. This can be expressed by:

$$\mathrm{F_{av}} = \frac{\mathrm{d}}{\mathrm{dt}}(m_{av} \cdot v_{av}) = \rho \cdot \frac{\pi \cdot d_{av}^3}{6} \cdot g - C_D \cdot \frac{\pi \cdot d_{av}^2 \cdot \rho}{8} \cdot \left(v_{r,av}\right) \cdot \left|v_{r,av}\right| \tag{3}$$

where the subscript "av" stands for average values for the mist cloud, F is the resulting force [N], m is the droplet mass [kg], g is the gravitational acceleration [m/s^2], $v_{r,av}$ is the mean relative velocity between droplet and surrounding air [m/s] and C_D is drag coefficient, which for small droplets can be assumed equal to 24/Re (or other empirical relationships [18]). When the droplet diameter is in the order of few microns (as in the case of dry misters) the resulting throw length is extremely short, even if the flow is initially very pressurized (1-2 MPa). This explains why overhead misting lines can be safely and efficiently placed close to passersby. This also suggests that, when characterizing the cooling capacity of a real installation, the sensor network should be placed in the proximity of the injection. Specifically, since the vertical cooling and humidification profiles obey to a Lorentzian distribution, hitting the peak at approximately 0.5 m of the injection [20], temperature and/or humidity detectors should be placed at no more than few meters away from the nozzles. While decelerating, the droplets evaporate. The rate depends on the size (exposed surface-to-volume ratio), the relative humidity and temperature of the surroundings (dictating the vapor partial pressure) and the wind speed (stimulating convective heat loss and promoting air mix). Pruppacher and Klett demonstrated that, in typical outdoor air conditions, the evaporation rate (expressed in terms of change in radius, r) is a function of the wet bulb depression [23]:

$$\frac{\mathrm{dr}}{\mathrm{dt}} \approx -\frac{\Delta T_{wb} \cdot k_a}{L \cdot \rho \cdot r} \tag{4}$$

where k_a is the thermal conductivity of air [W/(mK)] and L is the latent heat of evaporation [J/kg]. This relationship, however, does not contemplate the effect of wind speed on break-up mechanisms into child particles, on particle dilution, on convective heat transfer, and on local turbulence.

To gain more insight into the effects of the environmental context on the cooling and the humidification that come with the evaporative process inside the mist layer, an experimental rig was conceived, based on the above considerations.

2.2 Experimental setup

The test rig consisted of 24 hollow cone nozzles connected to a high-pressure, self-compensating pump (0.7 MPa). As a result of the nozzles' geometry and the operating pressure, the injected droplets' diameter obeyed to a Rosin-Rammler distribution with a Mean Sauter Diameter around 10 μm. The high surface-to-volume ratio ensured flash evaporation within few centimeters of the orifice. The water flow rate was 0.09 m^3/h. The nozzles were hanged at a height of 3.3 m (in line with typical settings [8]) and distributed in 4 parallel lines as depicted in Fig. 1. Extensive details of the experimental setup can be found in [16,20].

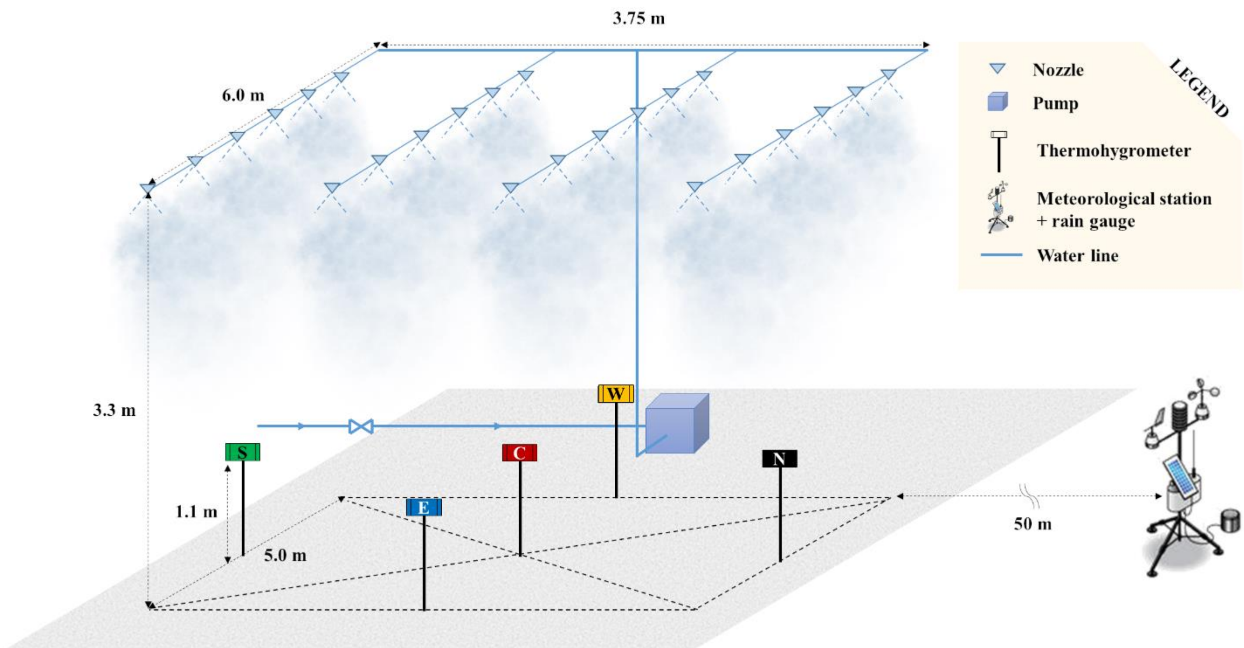

Fig. 1 Schematics of the experimental setup: mechanical components and sensor network

The distinctive feature of the misting system in object lies in the control of the injection. Misting systems are typically operated in a continuous or on-off mode. The latter is beneficial in terms of comfort as it helps containing the humidification, without congesting the air with overabundant evaporating droplets [24,25]. On the other side, given the risk of Legionella contamination, the water circulating in the hydraulic circuit must be discharged at any switch off, thus causing higher water wastage. Also, no guidelines or well-established procedures support the selection of on-off timing for intermittent operations: generally, the injection time varies from seconds to tens of minutes and its setting is left to the user [8]. Smart logics could be especially beneficial i) in optimizing the injection on the basis of the concomitant ambient conditions and comfort enhancement potential and ii) in rationalizing the amount of energy needed to operate the system thus making self-sustained solutions (e.g. PV-powered ones) more practical [16,26]. Against this backdrop, the experimental system in object was devised so that the duration of the injection could be responsive to the measured changed in air temperature, relative humidity, wind speed and solar irradiation. Approximate reasoning, in the form of fuzzy logic, was adopted to chase optimal comfort conditions. The duration of the misting action was proportional to the offset from the target neutral temperature (defined from previous comfort-oriented studies [27]) and to the level of irradiation and was adjusted on the basis of two lumped indexes: the Humidex which accounts for the combined action of temperature and humidity and the cooling power index (PE) which accounts for temperature and wind speed. These indexes weight the capability of ambient air in a given thermodynamic state to accommodate extra humidity and to be cooled by evaporative processes without imperiling the latent mechanisms of heat transfer. For further details about the fuzzy logic, the reader is referred to previous research [16], where the efficiency in terms of energy saving was demonstrated, compared to on-off operation. Comfort enhancement was also investigated in [20] where PET, SET* and UTCI differences between misted and undisturbed locations were analyzed through a variety of statistical metrics (including non-parametric Spearman correlation test, non-parametric Kruskal-Wallis H test, correlation matrices, Frequent Pattern (FP)-Growth algorithms) based on comfort questionnaires. Under hot Mediterranean summers (as in this study), the effect of the logic is to i) switch on/off autonomously depending on morning and evening conditions, ii) maintain a continuous injection around peak hours, iii) allow for interruptions under cold and humid or windy conditions (precursor to undesired humidification).

The perturbing action of the misting system was characterized by recording the temperature and relative humidity underneath the lines. Five thermohygrometers were located within the ground-projected perimeter of the misting matrix at a height of 1.1 m, which represents the suggested breast level of a standing person and head level of a sitting person in ISO 7726 [28] . One probe was placed in central position (denoted with "C" in Fig. 1) and the other four were distributed towards the cardinal directions (denoted with "N" , "S", "E" and "W" in Fig. 1). The accuracy was ± 0.2 °C in the −20 °C ÷ 80 °C temperature range, and ± 2 % in the 10 ÷ 90 % relative humidity range. A monitoring station, placed approximately 50 m away from the misted area, recorded the meteorological parameters (temperature, relative humidity, solar radiation, wind speed and direction) representative of concomitant undisturbed conditions. The corresponding accuracies were 0.2 °C, 1.5 %, < 5 %, 1.5 % and 1°. The sampling rate was 10 s, the averaging time was 1 min.

The monitoring campaign took place in Ancona, Italy (see Fig. 2), under Cfa climatic conditions according to the updated Köppen and Geiger classification [29], namely temperate marine climate with warm and humid summer extending from June to September. The analyzed data refer to a week time in August (13-19 August 2018), over which the temperature ranged between 20.2 °C and 36.3 °C, with a median of 25.7 °C. The relative humidity varied from a minimum of 44.8 % up to 87.1 % maintaining a median of about 62.4 %, while the global horizontal irradiance reached a maximum of 1202 W/m^2 with a median of 547 W/m^2. Against this climatic context, the fuzzy logic switched on the misting at around 10 am LST and switched it off at around 6:30 pm LST with only minor interruptions of maximum 2 minutes in between, due to the simultaneous occurrence of high wind speed and low local temperature. This provides optimal grounds to investigate the cooling capacity in relation to different boundary conditions.

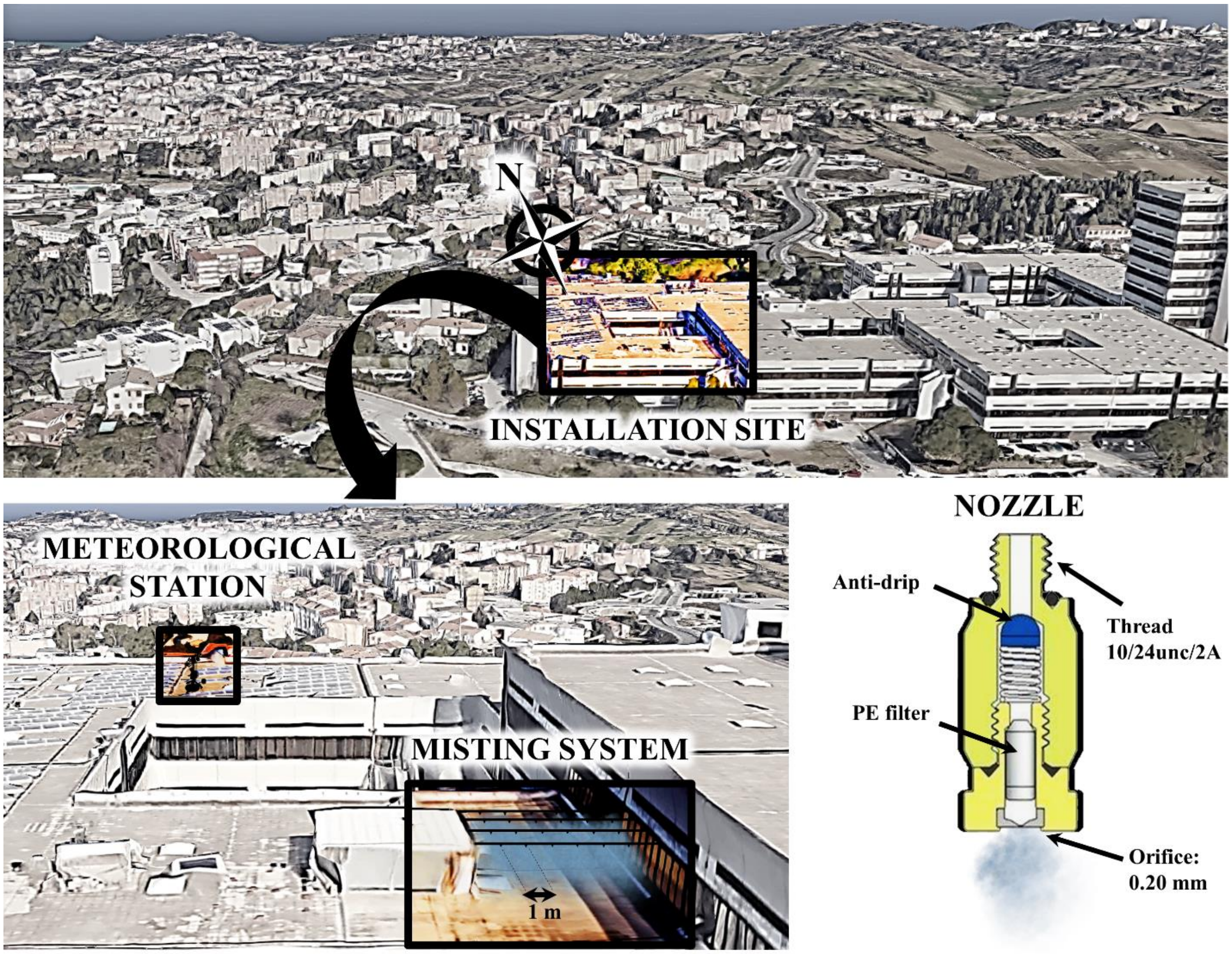

Fig. 2 Installation site, close-up on the misting system and the meteorological station, and exploded-view of the adopted hollow cone nozzle.

3. Results

3.1 Cooling performance and humidification

Fig. 3 displays temperature drop and relative humidity gain at the different locations in the form of raincloud plots. Raincloud plots combine a split-half violin plot, raw jittered data points and a boxplot. This representation is especially powerful and intuitive as it accurately and transparently visualizes raw data, probability density, key summary statistics and relevant confidence intervals with minimal redundancy and minimal distortion [30].

By looking at the probability density of the temperature drop at different values (half violin plots), it is apparent how the central and the northern locations were the only ones with a pronounced characteristic response to evaporative cooling: the former showed a sharp peak around 1.0 °C, while the second around 2.5 °C and a very narrow variability. This can be explained by considering that southern winds were the strongest (refer to the wind rose in Fig. 4), thus progressively entraining the droplets and concentrating them along the travel to the north. The central location was also the only one with a considerable skewness of the first and third quartile with respect to the median and towards higher values, implying that the temperature drop varied more when above the median. Data related to eastern, southern and western locations were much more dispersed and stretched along a much wider span of values, including absolute maxima (7.4 °C recorded at the east-located probe) and minima. This was likely due to the complex turbulent motions happening in proximity of the bordering walls, which suggests that misting systems can produce a quite stable cooling action only if local winds are light breezes and if no canyon/tunnel effect occurs due to bordering landscape and roughness.

The relative humidity increased by maximum 12.6 % in the middle of the mist layer, while tended to stay lower downwind, at the southern point of measurement. Considering that the average relative humidity at the undisturbed location was 57.67 %, it was proved that under smart controlled operation the maximum humidity could be reasonably maintained below 70 %, which is the proposed threshold by Ishii et al. for misting systems [24]. By looking at the probability density, every location showed a pronounced peak, but for different RH values: the central location peaked at the highest level (around 5.0 %), followed by the eastern location (around 3.5 %) and the western/northern locations (both around 2.0 %). Unexpectedly, the peak of the bell at the southern location fell into the negative side of the x-axis, meaning that the probability of having a drier environment than at the reference location was high. This, again, can be explained by looking at Fig. 4: strong southern winds tended to effectively remove the droplets, thus impeding the local rise in relative humidity. Additionally, compared to the reference location, the southern probe was inside the wind channel created by the walls onto which the misting lines were secured, thus being locally affected by an accelerated airflow.

All distributions were rather symmetric around the median, but at the northern location, where a higher chance of lower humidity gains than the median was recorded.

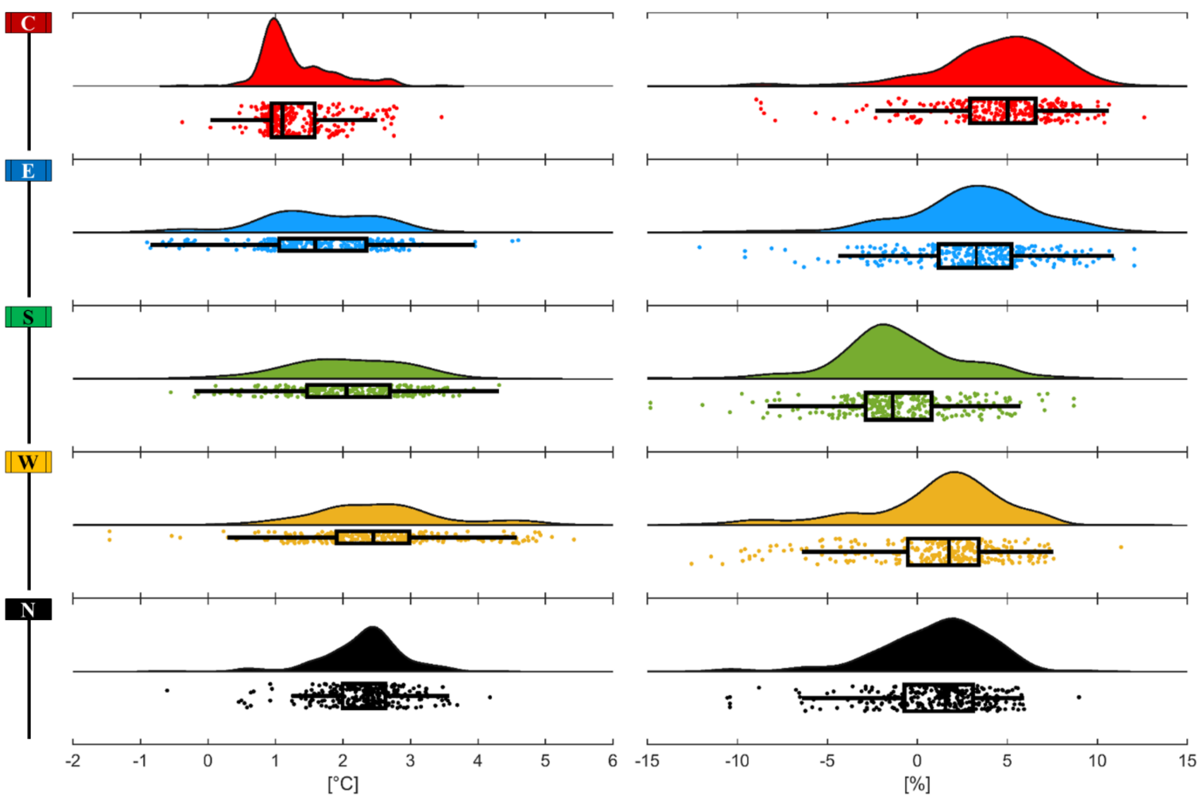

Fig. 3 Raincloud plots of temperature drop (left side) and relative humidity gain (right side) at the five considered locations.

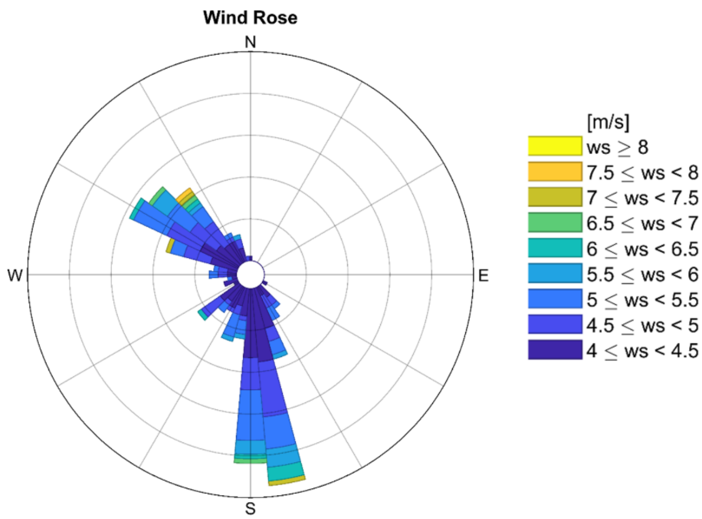

Fig. 4 Wind rose, representing wind direction and intensity during the monitoring campaign at the undisturbed location.

3.2 Driving forces

Finely sprayed mists tend to evaporate in proportion to the wet bulb depression, as remarked in previous studies [31]. Here, the wet bulb depression ranged between 2.2 °C and 10.3 °C in the misted area and between 3.2 °C and 9 °C in the undisturbed location.

The wet bulb temperature (T_{wb}) was calculated, based on the measured dry-bulb temperature T_{db} and relative humidity RH, according to the empirical fit by Stull [32]:

$$T_{wb} = T_{db} \cdot tan^{-1}\left[0.151977 \cdot (RH + 8.313659)^{\frac{1}{2}}\right] + tan^{-1}(T_{db} + RH) - tan^{-1}(RH - 1.676331) + 0.00391838 \cdot RH^{\frac{3}{2}} \cdot tan^{-1}(0.023101 \cdot RH) - 4.686035 \quad (5)$$

which well fits for dry-bulb temperatures between -20 °C and 50 °C and RH in the 5-99 % range (absolute error between -1 °C and 0.65 °C).

The wet bulb depression in the middle of the mist layer ($\Delta T_{wb,c}$) was used as representative parameter of the thermo-hygrometric conditions in the misted area. To further investigate how other potential drivers (solar irradiation, wind …) related to the temperature drop achieved by the misting system in the central portion of the conditioned area (ΔT_c), an artificial intelligence approach, based on evolutionary algorithms, was deployed.

The input dataset comprised the wet-bulb depression, all the outputs of the meteorological station and the duration of the misting, represented by the parameter n, namely the number of 10 minute lasting operations in a minute time ($0 \leq n \leq 6$). The training and testing datasets were equally apportioned (50 % and 50 %).

Through a supervised gene-programming, different candidate functions evolved through mutation and competed until the fittest candidate was obtained (max R^2). An 8-coefficient equation was eventually proposed:

$$\Delta T_c = 0.5 \cdot sma(\Delta T_{wb,c}, 3) + 1.5 \cdot 10^{-2} \cdot ws \cdot \Delta T_{wb,c} + 6.1 \cdot 10^{-4} \cdot Ioh \cdot sma(\Delta T_{wb,c}, 3) + 2.2 \cdot 10^{-6} \cdot Ioh^2 - 0.75 - 8.1 \cdot 10^{-3} \cdot Ioh - 3.1 \cdot n - 5.3 \cdot 10^{-2} \cdot sma(\Delta T_{wb,c}, 3)^2 \quad (6)$$

where ws is the wind speed in [m/s], Ioh is the horizontal global irradiance in [W/m^2] and sma is the simple moving average operator. The comparison between modeled and measured data is displayed in Fig. 5.

The R^2 approached 0.86 with a maximum absolute error of 0.83 °C, a mean absolute error of 0.09 °C and a mean squared error of 0.02 °C.

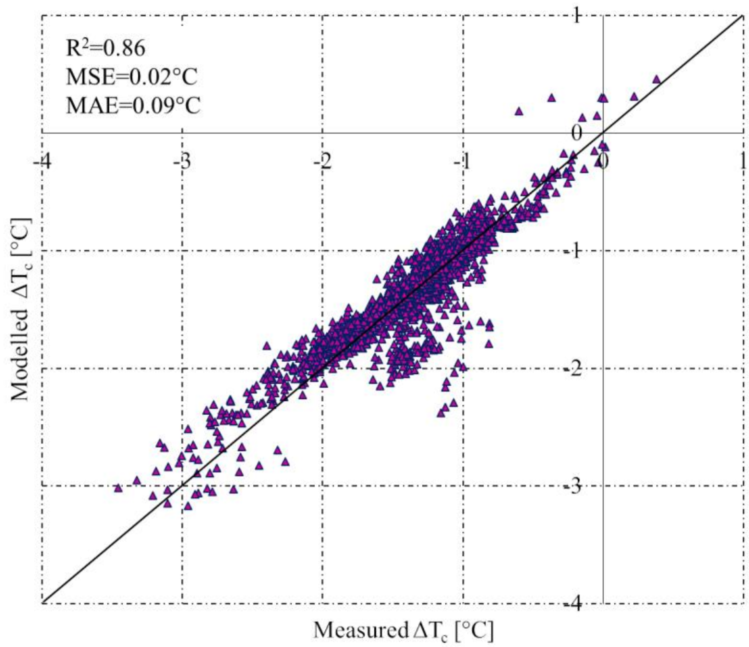

Fig. 5 Plot of modelled versus measured temperature drop in the middle of the mist. Goodness of fit displayed in terms of R^2, mean squared error (MSE) and mean absolute error (MAE)

Hence, further evidence was collected about how the cooling capacity of misting systems is largely a function of the local wet bulb depression even in complex outdoor contexts. Interestingly, both the instantaneous and the previous 30 s average were driving factors. A sensitivity analysis on the data (see Table 1) showed that the relative impact of wet-bulb depression on the target variable was the highest, followed by solar radiation, wind speed and duration of the injection. A negative correlation was identified between solar irradiation and temperature drop, which could be the result of the preponderance of increased heat over peak hours compared to the enhanced cooling capacity of the misting system. Conversely, a positive correlation could be established between wind speed and temperature drop, meaning that by increasing the dilution of the droplet cloud, higher evaporation rates could be achieved. However, it should be stressed that the greatest misalignment between measured and modelled ΔT_c occurred right at higher wind speeds, meaning that the beneficial effect of wind speed on cooling capacity is limited to low velocities.

Table 1. Sensitivity analysis

Sensitivity	Magnitude	Positive Likelihood	Negative Likelihood
$\overline{\left\lvert\frac{\partial \Delta T_c}{\partial \Delta T_{wb,c}}\right\rvert}\cdot\frac{\sigma(\Delta T_{wb,c})}{\sigma(\Delta T_c)}$	0.77	100 %	0 %
$\overline{\left\lvert\frac{\partial \Delta T_c}{\partial Ioh}\right\rvert}\cdot\frac{\sigma(Ioh)}{\sigma(\Delta T_c)}$	0.68	7 %	93 %
$\overline{\left\lvert\frac{\partial \Delta T_c}{\partial ws}\right\rvert}\cdot\frac{\sigma(ws)}{\sigma(\Delta T_c)}$	0.29	100 %	0 %
$\overline{\left\lvert\frac{\partial \Delta T_c}{\partial n}\right\rvert}\cdot\frac{\sigma(n)}{\sigma(\Delta T_c)}$	0.16	0 %	100 %

The same evolutionary algorithm was later applied only considering the availability of data from the reference station (without any measurement underneath the mist) which is likely to be the case in real installations. The penalty in the predicting capacity is demonstrated in Fig. 6. Fig 6a represents the results obtained when wind speed was the only environmental parameter retained in the final optimized equation and Fig 6b when both wind speed and solar irradiation were contemplated. The importance of knowing the wet bulb depression in the area emerges clearly, although it is quite interesting to observe that wind speed and solar radiation are good estimators of the overall trend. On the other side, knowing irradiation only led to no significant prediction of the temperature drop.

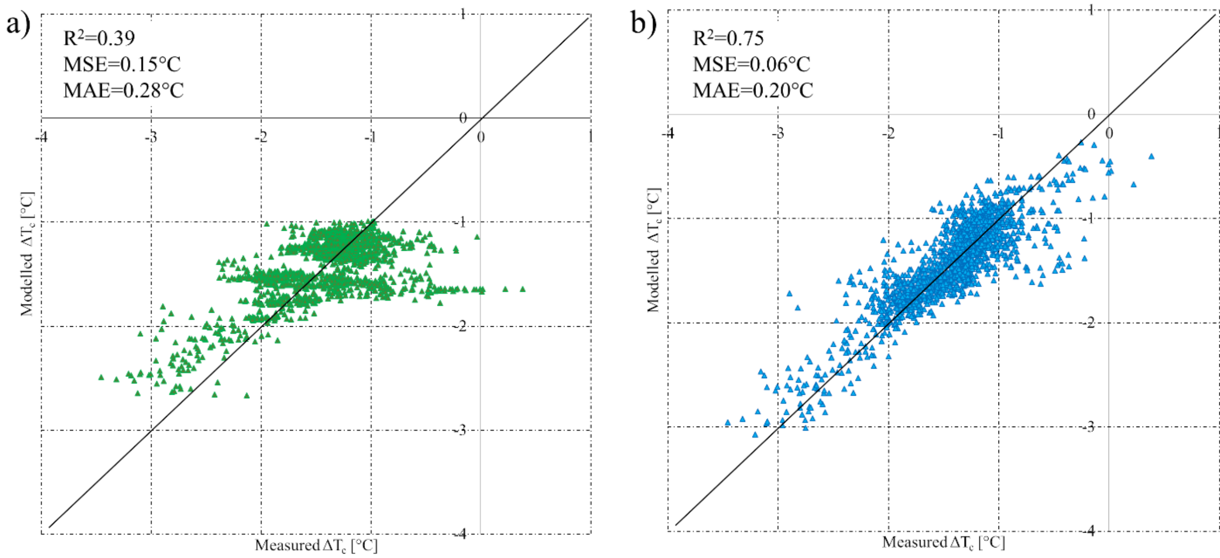

Fig. 6 Plot of modelled versus measured temperature drop in the middle of the mist, when considering the following environmental parameters: a) only wind speed, b) wind speed and solar irradiation. Goodness of fit displayed in terms of R^2, mean squared error (MSE) and mean absolute error (MAE)

4 Discussion and conclusions

Dry misters are efficient heat mitigators, yet their cooling capacity heavily depends on the microclimatic context. An experimental system of 24 overhead nozzles was monitored for one week in summertime and Mediterranean climate to establish potential links between the measured temperature drop and the environmental parameters in the misted area as well as in a near undisturbed location.

During the campaign, the temperature in the undisturbed location peaked at 36.3 °C with a median of 25.7 °C, while the relative humidity reached 87.1 % maintaining a median of about 62.4 °C, with the highest values recorded overnight when the misting was inactive. In the misted area, the temperature at about 2.2 m of the injection and 1.1 m above the ground could be reduced by up to 7.4 °C by injecting pulverized water droplets, while maintaining the humidity gain below 13 %. By means of evolutionary algorithms, the temperature drop in the misted area could be expressed as a function of only 4 parameters with good accuracy (R^2 = 0.86): wet-bulb depression, solar irradiation, wind speed and injection duration, in order of decreasing sensitivity. A strong positive correlation was established between the achieved cooling effect and the potential capacity of the air volume to accommodate extra moisture, represented by the wet bulb depression. The temperature drop was emphasized when the wet bulb depression stayed higher in the previous 30 s. A negative correlation emerged between global horizontal irradiation and temperature drop, which entails that the solar-induced temperature increase outweighed the solar-induced enhancement of the evaporative rate. Another positive correlation was identified between wind speed and temperature drop, although the sensitivity was much reduced. Faster winds engendered efficient heat removal mechanisms and helped spread the droplets, thus reducing the risk of coalescence and augmenting the changes of break-ups into child particles. On the other side, the predictability of the temperature drop drastically declined at high wind speeds suggesting the existence of a threshold over which the positive impact of wind-driven dilution reverses, in line with previous research [19]. Further investigation will be devoted to determining these thresholds in different climatic contexts, to quantifying the time needed for outdoor temperatures to fall back into uncomfortable limits after injection cessation and to defining bespoke strategies against future escalation of urban heat islands [33–35]. Overall, mist cooling is a high-impact local-scale urban overheating countermeasure. It is not meant to be used on large areas not to introduce excessive humidity in the air, adversely impact on water management during droughts and not to jeopardize passersby's right to decide whether or not to be directly exposed to the mist. A city-scale application would be achieved by spreading several small-scale installations in appropriate locations (city hot spots with low, steady wind speed, no canyon effect, no excessive urban shading and close to vulnerable population, e.g. elderly, low-income groups). Notably, urban canyons and shading should be carefully evaluated prior to any installations due to the local acceleration of the wind flow [36] and the enhanced wetting risk associated with lower heat absorption by the water droplets [5], respectively. Microscale urban simulations and experimentally substantiated artificial-intelligence-assisted analyses like the evolutionary algorithm proposed in this study, would be especially valuable in defining the most appropriate installation sites. From a technical and economical perspective, the use of smart logics, able to weigh the injection of water upon a variety of drivers as the one hereby presented, is expected to be a major enabler in urban-scale deployment.

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References

[1] K.R. Gunawardena, M.J. Wells, T. Kershaw, Utilising green and bluespace to mitigate urban heat island intensity, Sci. Total Environ. 584–585 (2017) 1040–1055. doi:10.1016/j.scitotenv.2017.01.158.

[2] M. Santamouris, L. Ding, F. Fiorito, P. Oldfield, P. Osmond, R. Paolini, D. Prasad, A. Synnefa, Passive and active cooling for the outdoor built environment – Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects, Sol. Energy. 154 (2017) 14–33. doi:10.1016/j.solener.2016.12.006.

[3] M. Taleghani, U. Berardi, The effect of pavement characteristics on pedestrians' thermal comfort in Toronto, Urban Clim. 24 (2018) 449–459. doi:10.1016/j.uclim.2017.05.007.

[4] S. Haddad, G. Ulpiani, R. Paolini, A. Synnefa, M. Santamouris, Experimental and Theoretical analysis of the urban overheating and its mitigation potential in a hot arid city – Alice Springs, Archit. Sci. Rev. (2019) 1–16. doi:10.1080/00038628.2019.1674128.

[5] L.A. Dombrovsky, V.P. Solovjov, B.W. Webb, Attenuation of solar radiation by a water mist from the ultraviolet to the infrared range, J. Quant. Spectrosc. Radiat. Transf. 112 (2011) 1182–1190. doi:10.1016/j.jqsrt.2010.08.018.

[6] S. Yu, Water spray geoengineering to clean air pollution for mitigating haze in China's cities, Environ. Chem. Lett. 12 (2014) 109–116. doi:10.1007/s10311-013-0444-0.

[7] A.S. Nouri, J.P. Costa, M. Santamouris, A. Matzarakis, Approaches to outdoor thermal comfort thresholds through public space design: A review, Atmosphere (Basel). 9 (2018). doi:10.3390/atmos9030108.

[8] G. Ulpiani, Water mist spray for outdoor cooling: A systematic review of technologies, methods and impacts, Appl. Energy. 254 (2019) 113647. doi:10.1016/j.apenergy.2019.113647.

[9] H. Barrow, C.W. Pope, Droplet evaporation with reference to the effectiveness of water-mist cooling, Appl. Energy. 84 (2007) 404–412. doi:10.1016/j.apenergy.2006.09.007.

[10] M. Beermann, B.; Berchtold, M.; Baumüller, J.; Gross, G.; Kratz, Städtebaulicher Rahmenplan Klimaanpassung für Die Stadt Karlsruhe (Teil II), Karlsruhe, Germany, 2014. https://fachdokumente.lubw.baden-wuerttemberg.de/servlet/is/109723/U83-W03-N11.pdf?command=downloadContent&filename=U83-W03-N11.pdf.

[11] J. Wang, X. Tu, Z. Wang, J. Huang, Application and Numerical Simulation on Water Mist Cooling for Urban Environment Regulation, in: Lect. Notes Comput. Sci., 2010. doi:10.1007/978-3-642-15859-9.

[12] G. Yoon, H. Yamada, M. Okumiya, Study on a cooling system using water mist sprayers; system control considering outdoor environment., Korea-Japan Jt. Symp. Human-Environment Syst. Cheju, Korea, p. 4. (2008).

[13] C. Huang, D. Ye, H. Zhao, T. Liang, Z. Lin, H. Yin, Y. Yang, The research and application of spray cooling technology in Shanghai Expo, Appl. Therm. Eng. 31 (2011) 3726–3735. doi:10.1016/j.applthermaleng.2011.03.039.

[14] C. Huang, J. Cai, Z. Lin, Q. Zhang, Y. Cui, Solving model of temperature and humidity profiles in spray cooling zone, Build. Environ. 123 (2017) 189–199. doi:10.1016/j.buildenv.2017.06.043.

[15] W. Jun-feng, T. Xin-cheng, Experimental Study and Numerical Simulation on Evaporative Cooling of Fine Water Mist in Outdoor Environment, 2009 Int. Conf. Energy

Environ. Technol. (2009) 156–159. doi:10.1109/ICEET.2009.44.

[16] G. Ulpiani, C. Di Perna, M. Zinzi, Water nebulization to counteract urban overheating : Development and experimental test of a smart logic to maximize energy efficiency and outdoor environmental quality, Appl. Energy. 239 (2019) 1091–1113. doi:10.1016/j.apenergy.2019.01.231.

[17] J.-H. Kim, M.-H. Lee, Y.-H. Yoon, A Verification Study on the Temperature reduction Effect of Water Mist Injection, Int. J. Korea Inst. Ecol. Archit. Environ. 15 (2015) 5–14.

[18] C. Farnham, M. Nakao, M. Nishioka, M. Nabeshima, T. Mizuno, Effect of Water Temperature on Evaporation of Mist Sprayed From a Nozzle, J. Heat Isl. Inst. Int. 10 (2015) 35–44.

[19] G. Ulpiani, E. Di Giuseppe, C. Di Perna, M.D. Orazio, M. Zinzi, Design optimization of mist cooling for Urban Heat Island mitigation: experimental study on the role of injection density, (2019). doi:10.1088/1755-1315/296/1/012025.

[20] G. Ulpiani, E. Di Giuseppe, C. Di Perna, M. D'Orazio, M. Zinzi, Thermal comfort improvement in urban spaces with water spray systems: Field measurements and survey, Build. Environ. 156 (2019) 46–61. doi:https://doi.org/10.1016/j.buildenv.2019.04.007.

[21] B.M. Schneider, Experimental studies on the spray structure in transient, evaporating and non-evaporating fuel jets under high pressure, ETH Zurich, 2003.

[22] B.P. Husted, G. Homstedt, T. Hertzberg, The physics behind water mist systems, IWMA Conf. (2004) 6–8. https://iwma.net/publications/conference-papers/.

[23] H.R. Pruppacher, J.D. Klett, Microphysics of Clouds and Precipitation, 1997.

[24] T. Ishii, M. Tsujimoto, G. Yoon, M. Okumiya, Cooling System with Water Mist Sprayers for Mitigation of Heat-island Drymist system : Uchimizu, Seventh Int. Conf. Urban Clim.

(2009) 2–3.

[25] S.A. Domínguez, F.J. Sánchez, The effect of evaporative cooling techniques on reducing urban heat, in: Urban Clim. Mitig. Tech., Routledge, 2016: pp. 127–144.

[26] A. Atieh, S. Al Shariff, Solar energy powering up aerial misting systems for cooling surroundings in Saudi Arabia, Energy Convers. Manag. 65 (2013) 670–674. doi:10.1016/j.enconman.2011.10.031.

[27] F. Salata, I. Golasi, R. de Lieto Vollaro, A. de Lieto Vollaro, Outdoor thermal comfort in the Mediterranean area. A transversal study in Rome, Italy, Build. Environ. 96 (2016) 46–61. doi:10.1016/j.buildenv.2015.11.023.

[28] ISO, ISO 7726:1998 Ergonomics of the thermal environment -- Instruments for measuring physical quantities, (1998).

[29] M.C. Peel, B.L. Finlayson, T.A. McMahon, Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci. Discuss. 4 (2007) 439–473.

[30] M. Allen, D. Poggiali, K. Whitaker, T.R. Marshall, R.A. Kievit, Raincloud plots: A multi-platform tool for robust data visualization [version 1; peer review: 2 approved], Wellcome Open Res. 4 (2019) 1–41. doi:10.12688/wellcomeopenres.15191.1.

[31] C. Farnham, M. Nakao, M. Nishioka, M. Nabeshima, Quantification of the Effect of Cooling Mists on Individual Thermal Comfort, in: Seventh Int. Conf. Urban Clim., 2009.

[32] R. Stull, Wet-bulb temperature from relative humidity and air temperature, J. Appl. Meteorol. Climatol. 50 (2011) 2267–2269.

[33] G.Y. Yun, J. Ngarambe, P.N. Duhirwe, G. Ulpiani, R. Paolini, S. Haddad, K. Vasilakopoulou, M. Santamouris, Predicting the magnitude and the characteristics of the urban heat island in coastal cities in the proximity of desert landforms. The case of

Sydney, Sci. Total Environ. 709 (2020) 136068. doi:10.1016/j.scitotenv.2019.136068.

[34] C. Rosenzweig, W.D. Solecki, L. Parshall, M. Chopping, G. Pope, R. Goldberg, Characterizing the urban heat island in current and future climates in New Jersey, Environ. Hazards. 6 (2005) 51–62. doi:10.1016/j.hazards.2004.12.001.

[35] J. Wang, B. Huang, D. Fu, P.M. Atkinson, X. Zhang, Response of urban heat island to future urban expansion over the Beijing-Tianjin-Hebei metropolitan area, Appl. Geogr. 70 (2016) 26–36. doi:10.1016/j.apgeog.2016.02.010.

[36] P. Kastner-Klein, E. Fedorovich, M.W. Rotach, A wind tunnel study of organised and turbulent air motions in urban street canyons, J. Wind Eng. Ind. Aerodyn. 89 (2001) 849–861. doi:10.1016/S0167-6105(01)00074-5.

Figure

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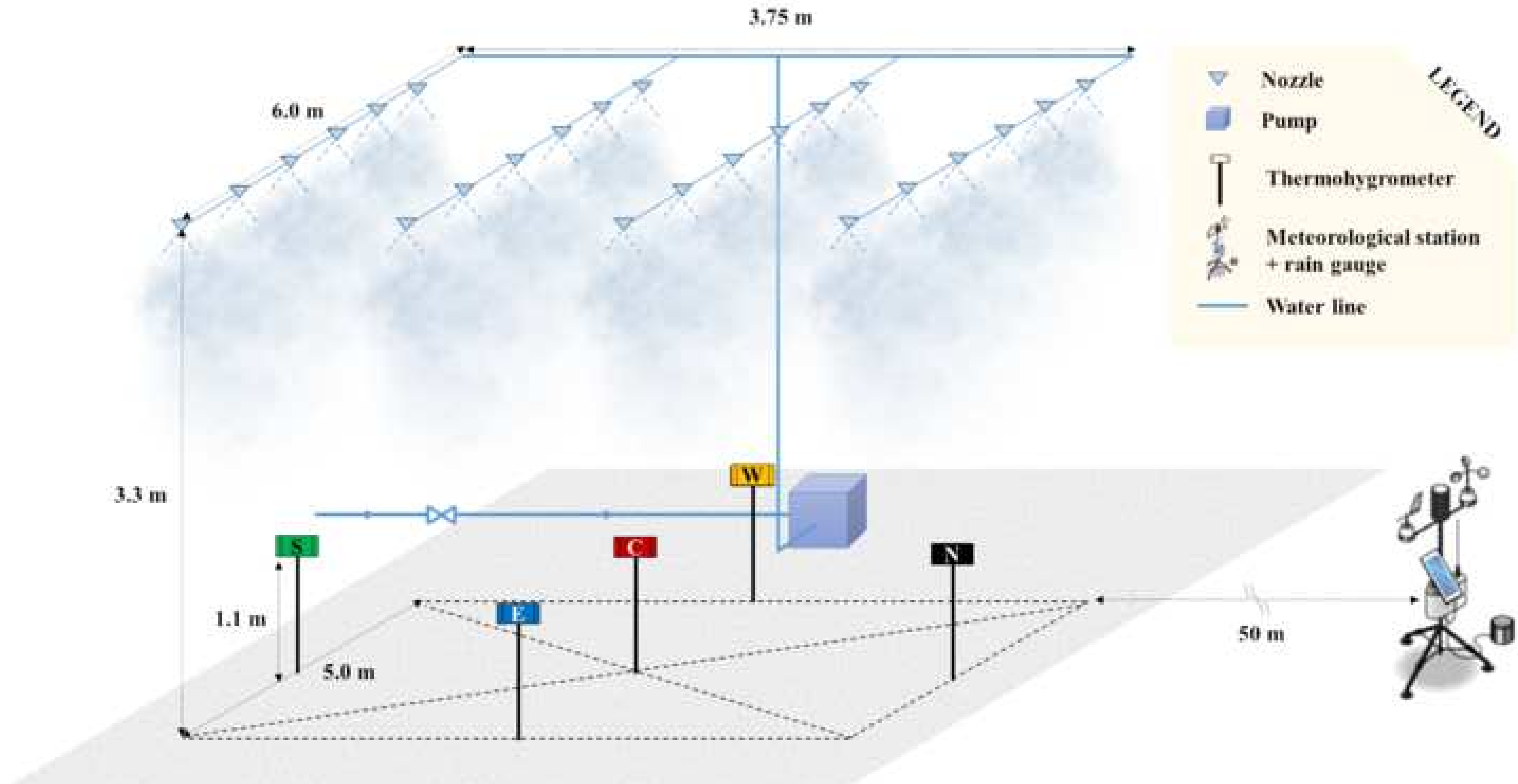

Figure

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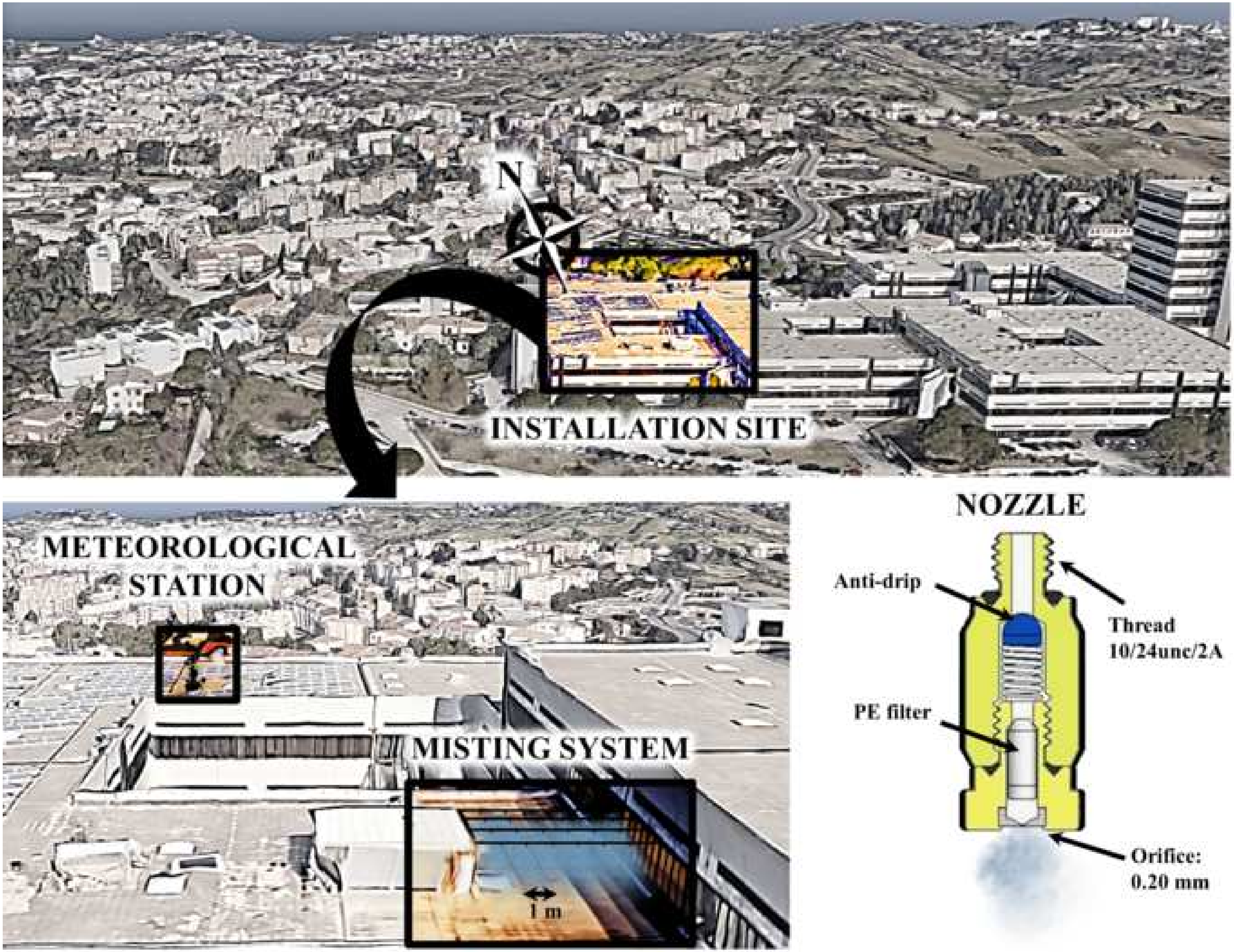

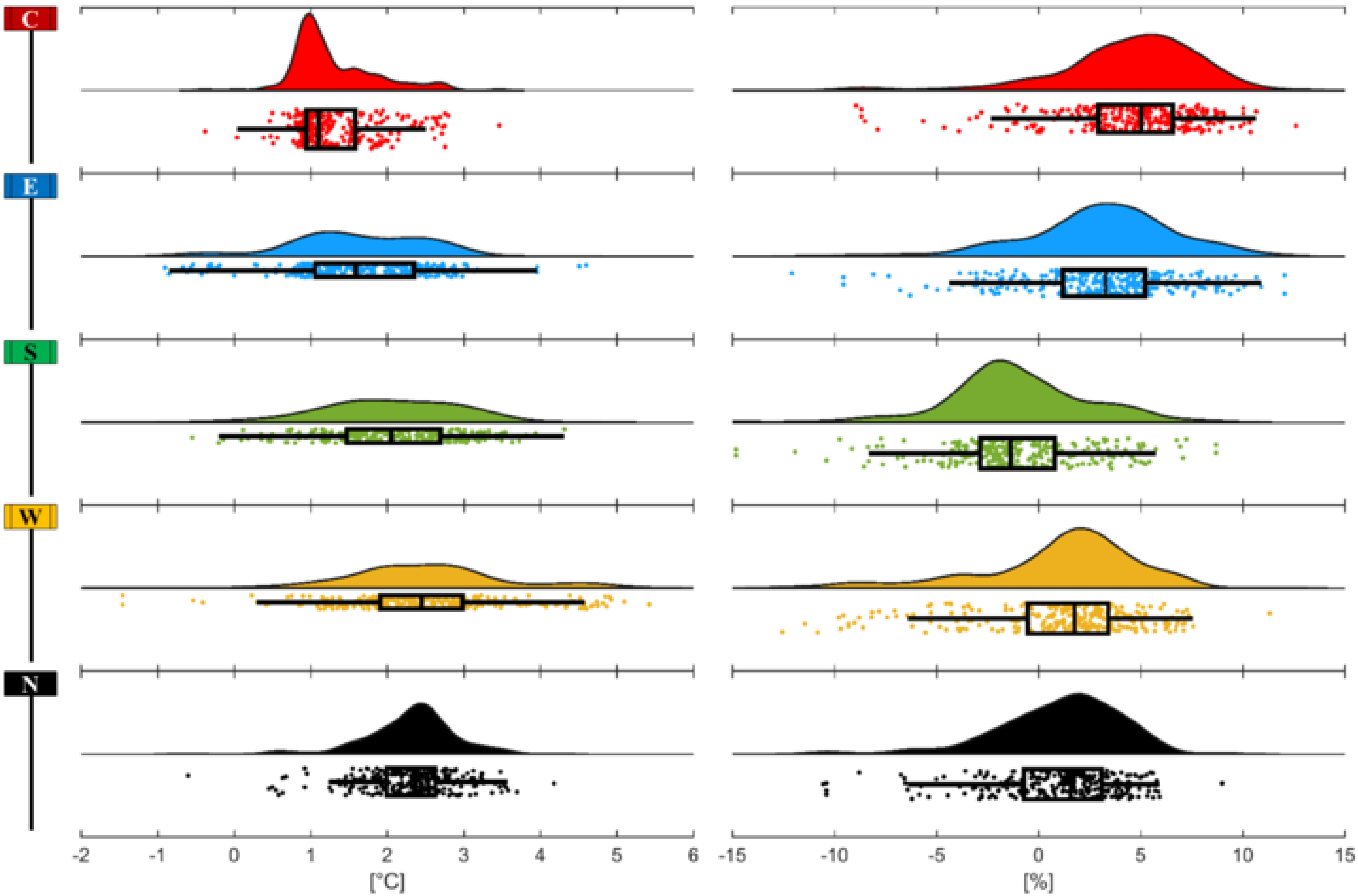
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Figure

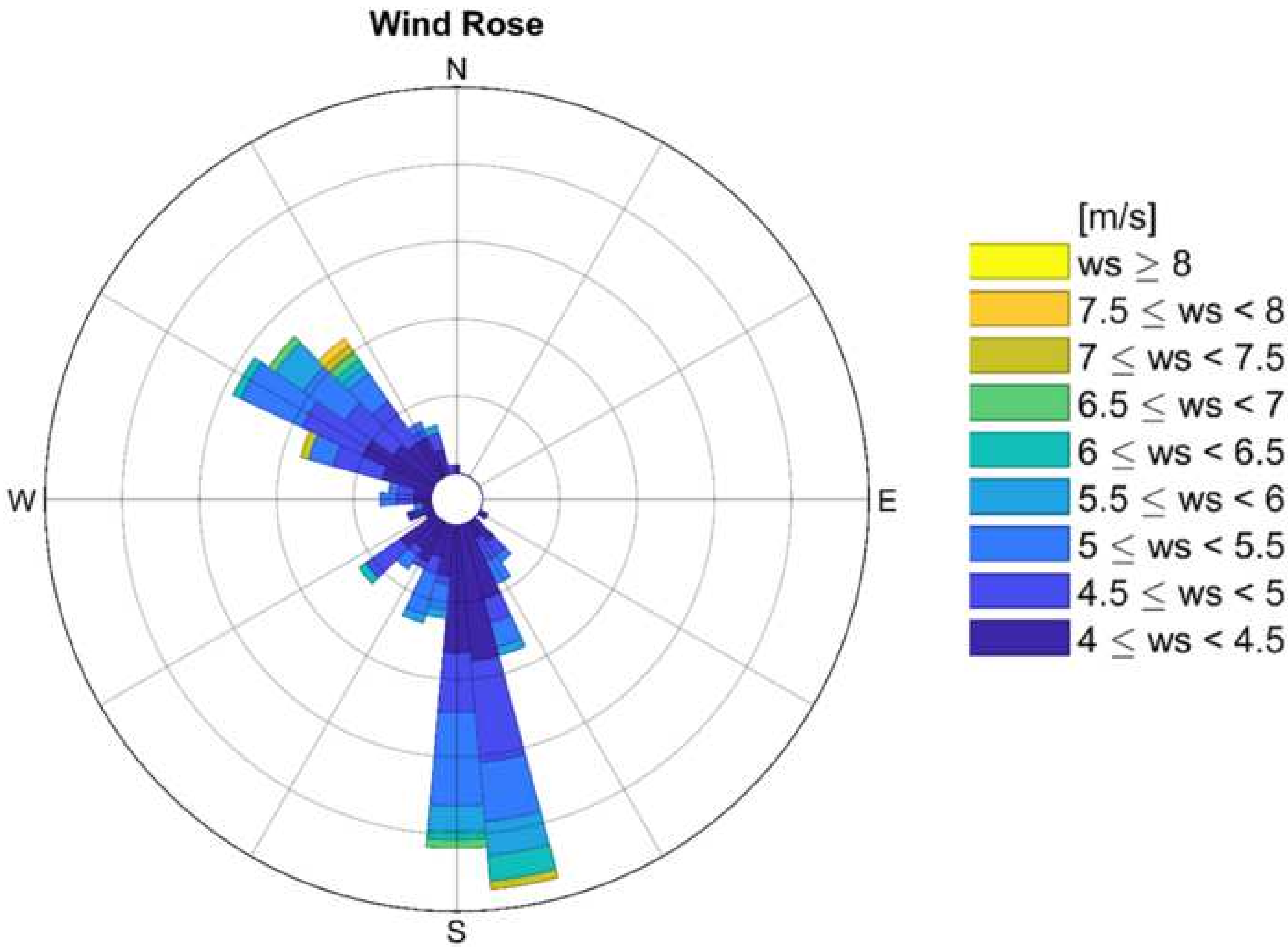
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Figure

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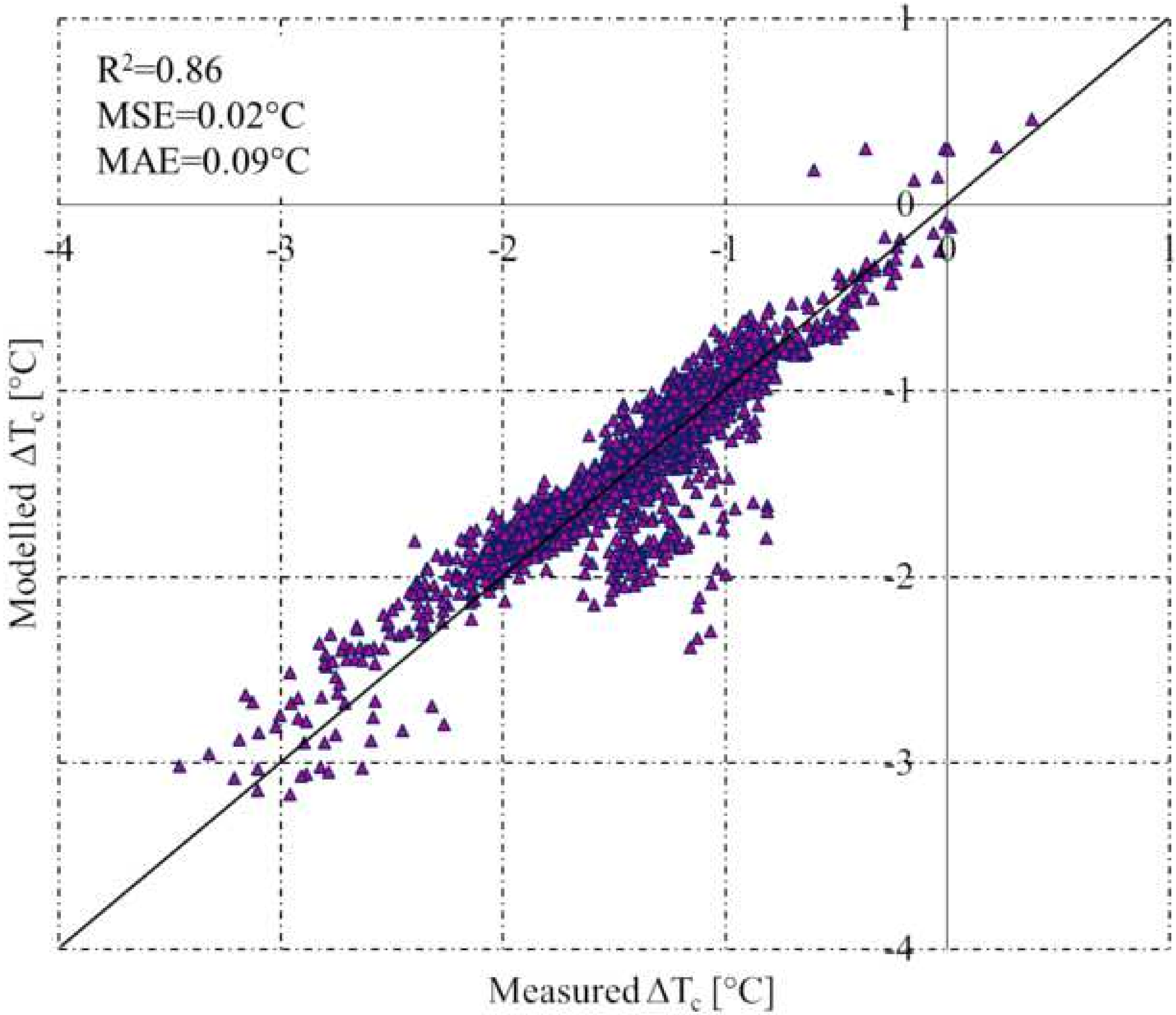

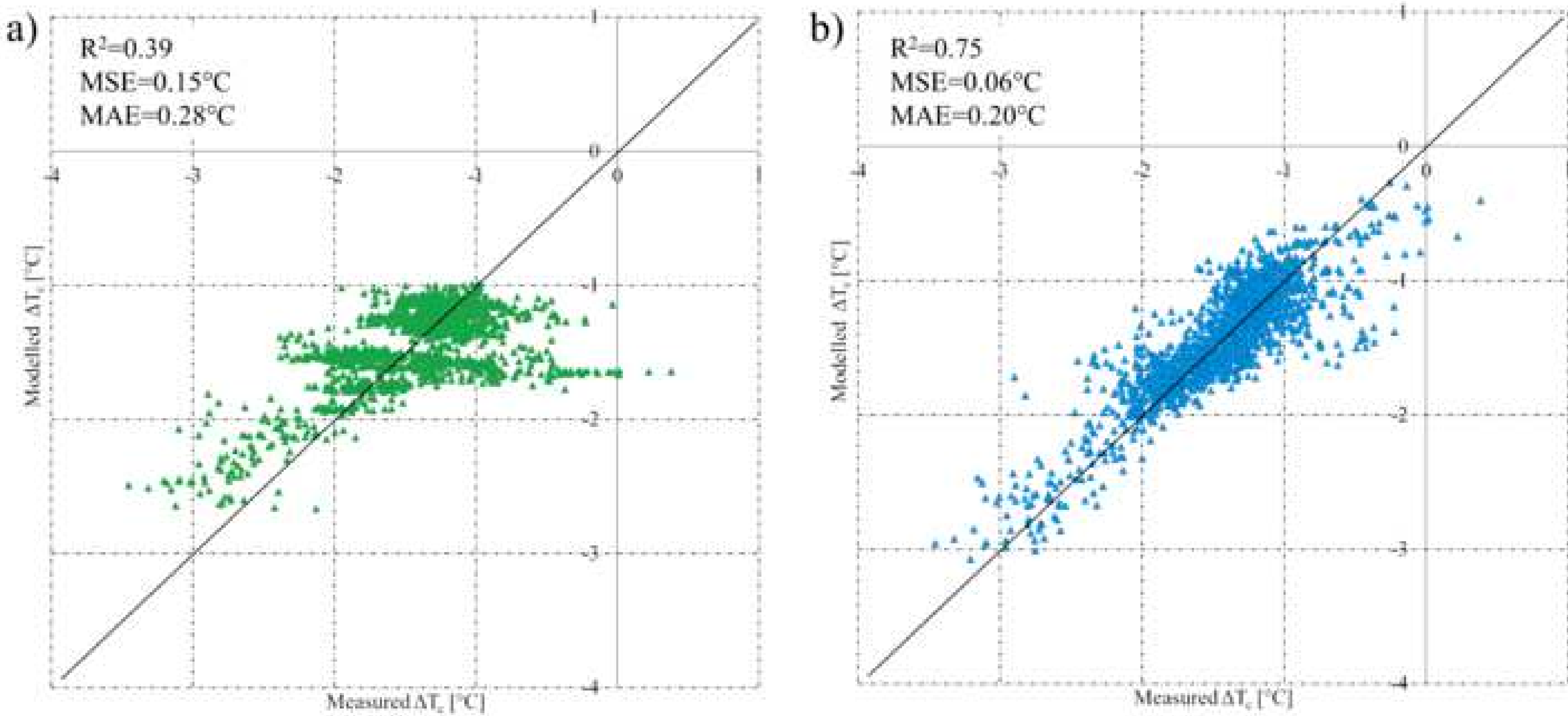
a)
R²=0.39
MSE=0.15°C
MAE=0.28°C
Modelled ΔTc [°C]
Measured ΔTc [°C]
b)
R²=0.75
MSE=0.06°C
MAE=0.20°C
Modelled ΔTc [°C]
Measured ΔTc [°C]

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: