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

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(Article begins on next page)

# Applied Thermal Engineering

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

--Manuscript Draft--

<b>Manuscript Number:</b>	ATE_2020_1837R1
<b>Article Type:</b>	Original Research Papers
<b>Keywords:</b>	water misting; experimental monitoring; urban climate; Evaporative cooling; Sensitivity analysis; artificial intelligence
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<b>Abstract:</b>	<p>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.</p>
<b>Suggested Reviewers:</b>	<p>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.</p> <p>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.</p> <p>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.</p>

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.<sup>1</sup>); ii) the Humidex and the

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<sup>1</sup> 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<sup>2</sup>. 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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<sup>2</sup> 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.

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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.

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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.

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1 **Title**

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

4 **Authors**

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16 **Abstract**

17 Mist cooling is a widely known and applied heat mitigation technology, especially in urban settings.

18 Despite this, conceiving the right installation is no trivial matter as scattered and unstandardized

19 is the knowledge on the multiple interrelations with the local microclimate. This paper investigates

20 how the cooling efficiency of a dry mist system depends on the local meteorological trends. An

21 experimental system of 24 overhead nozzles constantly operating at 0.7 MPa, was installed in Italy

22 and monitored for a week in summertime. Temperature and relative humidity underneath the mist

23 were mapped in five locations with a time step of 10 s, together with the main meteorological

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24 parameters, measured at an undisturbed location, for reference. Cooling and humidification  
25 capacity were characterized as probability density, key summary statistics and relevant confidence  
26 intervals with minimal redundancy and minimal distortion. A supervised learning algorithm was  
27 used to disclose the sensitivity of the recorded temperature drop to the contextual microclimatic  
28 evolution. It was demonstrated that the cooling capacity of the tested system was largely a function  
29 of the local wet bulb depression, as instantaneous reading as well as short-term trend. Additionally,  
30 solar irradiation and wind speed were found to be negatively and positively correlated, respectively.

31

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

34

35 **Acronyms and symbols (alphabetical order)**

36

ANOVA	Analysis of variance	Oh	Ohnesorge number
$\mu$	Dynamic viscosity of the fluid [Ns/m <sup>2</sup> ]	PE	Cooling power index [mcal/cm <sup>2</sup> s]
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 <sub>n</sub>	Nozzle diameter [m]	S	South (position)
E	East (position)	sma	Simple moving average
F	Resulting force [N]	T <sub>db</sub>	Dry-bulb temperature [°C]
g	Gravitational acceleration [m/s <sup>2</sup> ]	T <sub>wb</sub>	Wet-bulb temperature [°C]
I <sub>oh</sub>	Horizontal global solar irradiance [W/m <sup>2</sup> ]	UHI	Urban heat island
IQR	Interquartile range	v	Characteristic velocity of the flow [m/s]
k <sub>a</sub>	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]	$\gamma$	Surface tension [N/m]

MAE	Mean absolute error	$\Delta T_c$	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)	$\rho$	Density of water [kg/m <sup>3</sup> ]
n	Number of 10 s lasting injections in a minute time	$\sigma$	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

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58 applications, targeting the whole sphere of comfort. Their action is not merely thermohygrometric,  
59 but affects all the major environmental parameters, by attenuating solar radiation [5], scavenging  
60 dust [6], breaking the wind force while engendering a local turbulent flow of cooled air, all factors  
61 contributing to an efficient heat removal and to the generation of pleasant spaces in the urban realm,  
62 especially where overheating and pollution risks are prominent. As discussed in recent review  
63 papers [7,8], this technology is especially valuable in dry and warm climates, although good  
64 performance has been demonstrated also in humid locations like Singapore [8]. Increasing interest  
65 has also been expressed by heating-dominated countries, such as UK and Germany, to cope with  
66 the unprecedented escalation of heat-stress events in recent years [9,10]. These countries are less  
67 armored against urban overheating, thus increasing the heat resistance of their infrastructure has  
68 become a priority target. Compared to passive and natural mitigators, misters and other artificial  
69 water features are especially desirable in such contexts where intense outdoor cooling is a sporadic  
70 necessity, given their adjustability, controllability and scalability.

71 Experimental evidence suggests that misting systems can induce a local temperature drop from  
72 few degrees Celsius (1-2 °C), up to over 15 °C [8]. On average, the reduction falls in the 7-8 °C  
73 range, with major deviations due to the selected technology (in terms of nozzle geometry,  
74 operating pressure and layout), the local microclimate and the typology of cooled area (open  
75 outdoor, semi-enclosed, indoor) [11]. The humidification is in the order of 20%. Beyond  
76 technological considerations, the cooling capacity of misting systems depends on the contextual  
77 microclimate. In [12] Yoon and Yamada demonstrated that relative humidity is the governing  
78 parameter, even more than temperature, in the considered range. Humid conditions depreciated the  
79 extent and completeness of the evaporation process. The authors suggested potentially optimal  
80 thermohygrometric boundary conditions: 70% and 30-34 °C as for relative humidity and ambient

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81 temperature, respectively. During the 2010 Shanghai Expo [13], Huang et al. monitored an  
82 extensive misting system of about 136 nozzle and reported temperature drops of 6-12 °C within 1  
83 m of the injections, when the ambient temperature was 34-40 °C and the relative humidity was 32-  
84 55 %. Considering the wet bulb depression ( $\Delta T_{wb}$ , difference between wet bulb and dry bulb  
85 temperatures) as theoretical limit, the authors computed the cooling efficiency by dividing the  
86 actual temperature drop to the ideal wet bulb depression: it reached 90 % in the Expo Pavilion.  
87 The same authors [14] developed a mathematical model to parameterize the thermohygroscopic  
88 conditions in the misted area as a function of several environmental and technological parameters.  
89 They concluded that lower relative humidity and lower wind speeds were precursors to accentuated  
90 performances. Speaking of wind, a 2009 experimental and numerical study [15] investigated its  
91 role when misters were used in open outdoors. It was found that, on average, the cooling was  
92 higher downwind (nearly 4 °C difference). Wind's impact was also highlighted in a recent  
93 publication by Ulpiani et al. [16]. The authors monitored a 24-nozzle overhead system in  
94 Mediterranean urban contexts (open areas), capable of temperature reductions up to 7.5 °C, and  
95 found that the local cooling was largely a function of the temperature and the wind speed.  
96 Generally, a light steady breeze of about 1 m/s is regarded as optimal operating condition, while  
97 under winds blowing at more than 3 m/s, it is suggested to shut off the injection [8]. Finally, Kim  
98 et al. [17] analyzed the role of solar radiation on the cooling capacity of a cross-shaped system of  
99 overhead blast sprayers, by performing Duncan multiple range test and one-way ANOVA.  
100 Statistically, the temperature drop was higher during hot and sunny days. Other factors, such as  
101 water temperature (7 %), were found to play a minor role and were thus examined to a lesser extent  
102 [18].

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

## 2. Materials and methods

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

### 2.1 Theoretical background

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

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

$$\text{Oh} = \frac{\mu}{\sqrt{\rho \gamma d_n}} \quad (2)$$

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:

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

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<sup>2</sup>], v<sub>r,av</sub> is the mean relative velocity between droplet and surrounding air [m/s] and C<sub>D</sub> 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

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4 144 vapor partial pressure) and the wind speed (stimulating convective heat loss and promoting air  
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7 145 mix). Pruppacher and Klett demonstrated that, in typical outdoor air conditions, the evaporation  
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9 146 rate (expressed in terms of change in radius,  $r$ ) is a function of the wet bulb depression [23]:

$$\frac{dr}{dt} \approx - \frac{\Delta T_{wb} \cdot k_a}{L \cdot \rho \cdot r} \quad (4)$$

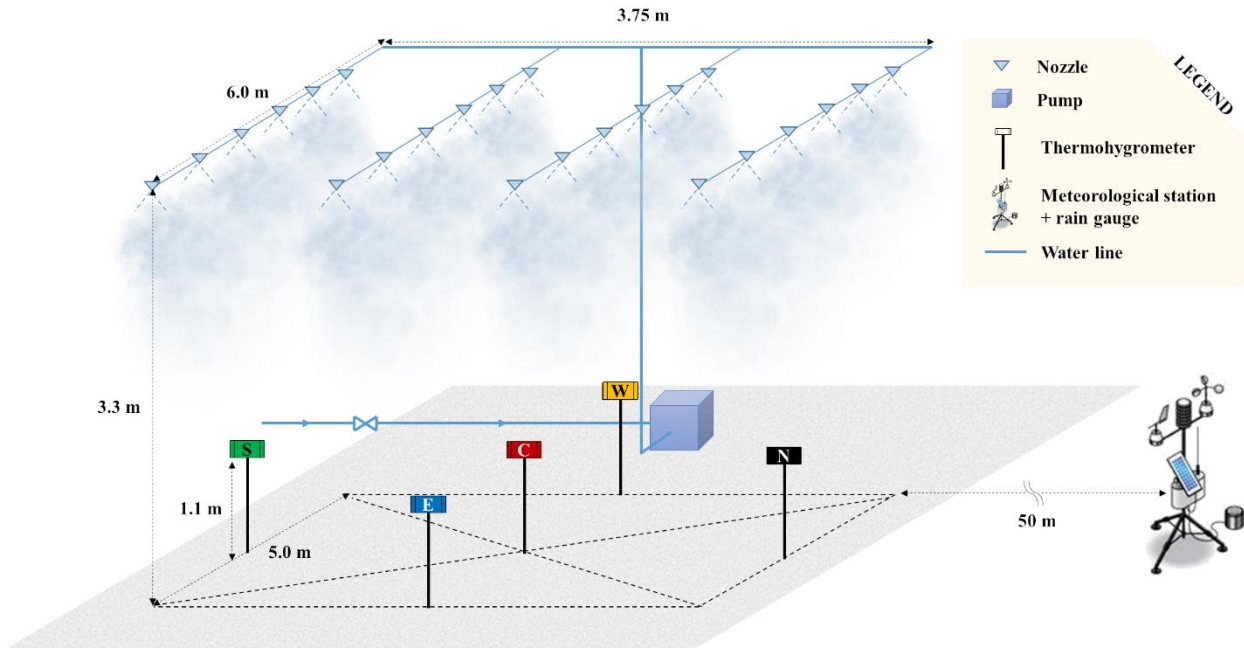
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15 where  $k_a$  is the thermal conductivity of air [W/(mK)] and  $L$  is the latent heat of evaporation  
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17 [J/kg]. This relationship, however, does not contemplate the effect of wind speed on break-  
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19 up mechanisms into child particles, on particle dilution, on convective heat transfer, and  
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21 on local turbulence.  
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25 To gain more insight into the effects of the environmental context on the cooling and the  
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27 humidification that come with the evaporative process inside the mist layer, an  
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29 experimental rig was conceived, based on the above considerations.  
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## 33 34 35 148 **2.2 Experimental setup**

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37 149 The test rig consisted of 24 hollow cone nozzles connected to a high-pressure, self-compensating  
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39 pump (0.7 MPa). As a result of the nozzles' geometry and the operating pressure, the injected  
40 150 droplets' diameter obeyed to a Rosin-Rammler distribution with a Mean Sauter Diameter around  
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42 151  $10 \mu\text{m}$ . The high surface-to-volume ratio ensured flash evaporation within few centimeters of the  
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44 152 orifice. The water flow rate was  $0.09 \text{ m}^3/\text{h}$ . The nozzles were hanged at a height of 3.3 m (in line  
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46 153 with typical settings [8]) and distributed in 4 parallel lines as depicted in Fig. 1. Extensive details  
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48 154 of the experimental setup can be found in [16,20].  
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**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

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171 be responsive to the measured changed in air temperature, relative humidity, wind speed and solar  
172 irradiation. Approximate reasoning, in the form of fuzzy logic, was adopted to chase optimal  
173 comfort conditions. The duration of the misting action was proportional to the offset from the  
174 target neutral temperature (defined from previous comfort-oriented studies [27]) and to the level  
175 of irradiation and was adjusted on the basis of two lumped indexes: the Humidex which accounts  
176 for the combined action of temperature and humidity and the cooling power index (PE) which  
177 accounts for temperature and wind speed. These indexes weight the capability of ambient air in a  
178 given thermodynamic state to accommodate extra humidity and to be cooled by evaporative  
179 processes without imperiling the latent mechanisms of heat transfer. For further details about the  
180 fuzzy logic, the reader is referred to previous research [16], where the efficiency in terms of energy  
181 saving was demonstrated, compared to on-off operation. Comfort enhancement was also  
182 investigated in [20] where PET, SET\* and UTCI differences between misted and undisturbed  
183 locations were analyzed through a variety of statistical metrics (including non-parametric  
184 Spearman correlation test, non-parametric Kruskal-Wallis H test, correlation matrices, Frequent  
185 Pattern (FP)-Growth algorithms) based on comfort questionnaires. Under hot Mediterranean  
186 summers (as in this study), the effect of the logic is to i) switch on/off autonomously depending  
187 on morning and evening conditions, ii) maintain a continuous injection around peak hours, iii)  
188 allow for interruptions under cold and humid or windy conditions (precursor to undesired  
189 humidification).

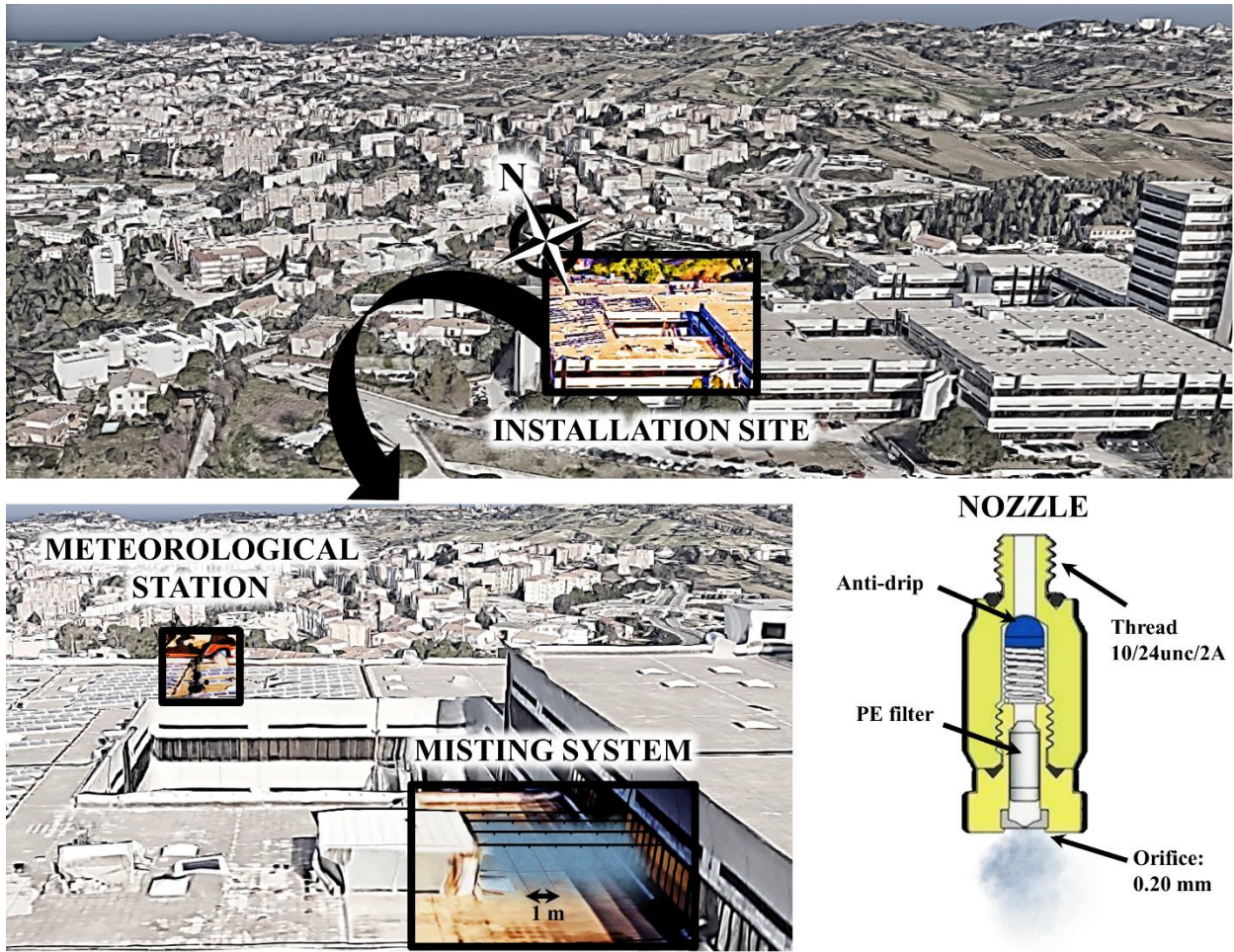
190 The perturbing action of the misting system was characterized by recording the temperature and  
191 relative humidity underneath the lines. Five thermohygrometers were located within the ground-  
192 projected perimeter of the misting matrix at a height of 1.1 m, which represents the suggested  
193 breast level of a standing person and head level of a sitting person in ISO 7726 [28] . One probe

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194 was placed in central position (denoted with “C” in Fig. 1) and the other four were distributed  
195 towards the cardinal directions (denoted with “N” , “S” , “E” and “W” in Fig. 1). The accuracy was  
196  $\pm 0.2$  °C in the  $-20$  °C  $\div$   $80$  °C temperature range, and  $\pm 2$  % in the  $10$   $\div$   $90$  % relative humidity  
197 range. A monitoring station, placed approximately 50 m away from the misted area, recorded the  
198 meteorological parameters (temperature, relative humidity, solar radiation, wind speed and  
199 direction) representative of concomitant undisturbed conditions. The corresponding accuracies  
200 were  $0.2$  °C,  $1.5$  % ,  $< 5$  % ,  $1.5$  % and  $1^\circ$ . The sampling rate was 10 s, the averaging time was 1  
201 min.

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

213



**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].

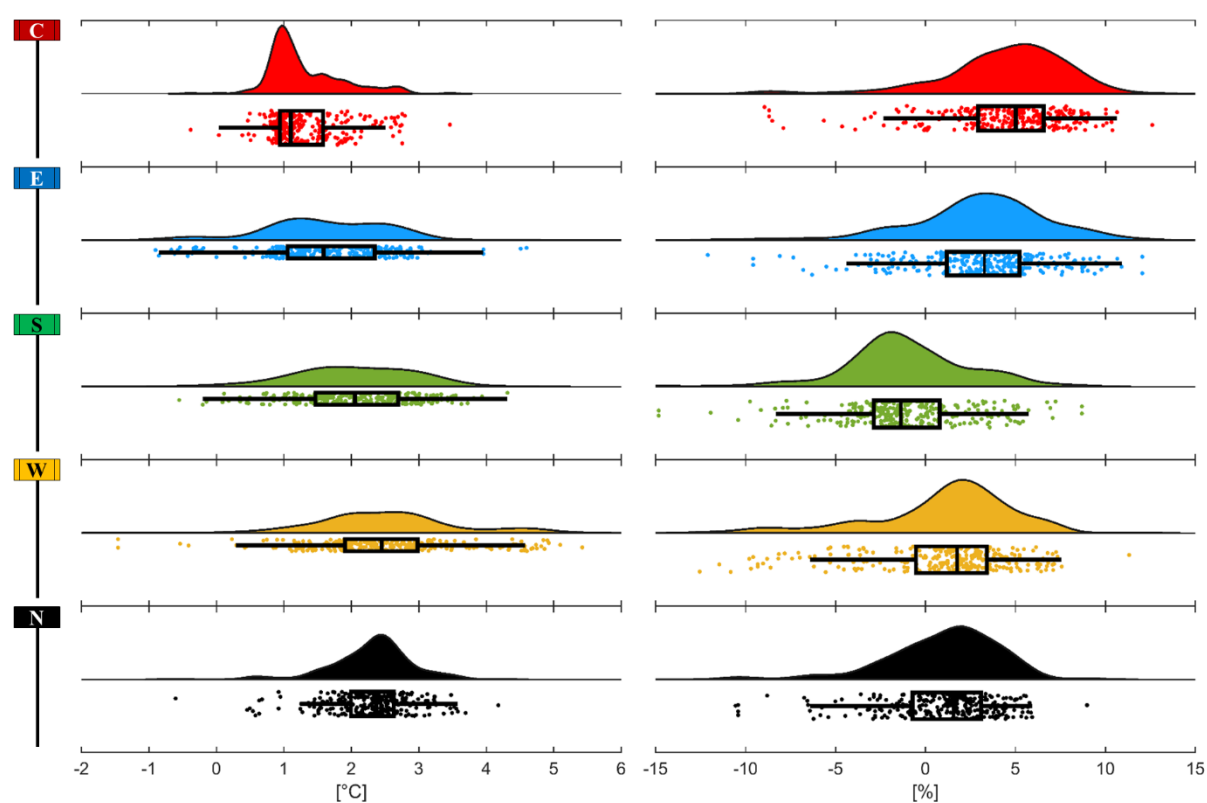
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225 By looking at the probability density of the temperature drop at different values (half violin plots),  
226 it is apparent how the central and the northern locations were the only ones with a pronounced  
227 characteristic response to evaporative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

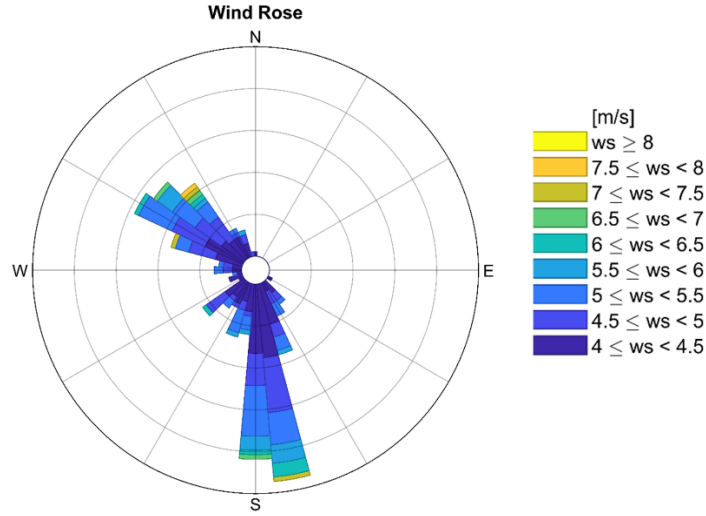
239 The relative humidity increased by maximum 12.6 % in the middle of the mist layer, while tended  
240 to stay lower downwind, at the southern point of measurement. Considering that the average  
241 relative humidity at the undisturbed location was 57.67 %, it was proved that under smart  
242 controlled operation the maximum humidity could be reasonably maintained below 70 %, which  
243 is the proposed threshold by Ishii et al. for misting systems [24]. By looking at the probability  
244 density, every location showed a pronounced peak, but for different RH values: the central location  
245 peaked at the highest level (around 5.0 %), followed by the eastern location (around 3.5 %) and  
246 the western/northern locations (both around 2.0 %). Unexpectedly, the peak of the bell at the  
247 southern location fell into the negative side of the x-axis, meaning that the probability of having a

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248 drier environment than at the reference location was high. This, again, can be explained by looking  
249 at Fig. 4: strong southern winds tended to effectively remove the droplets, thus impeding the local  
250 rise in relative humidity. Additionally, compared to the reference location, the southern probe was  
251 inside the wind channel created by the walls onto which the misting lines were secured, thus being  
252 locally affected by an accelerated airflow.  
253 All distributions were rather symmetric around the median, but at the northern location, where a  
254 higher chance of lower humidity gains than the median was recorded.



256  
257 **Fig. 3** Raincloud plots of temperature drop (left side) and relative humidity gain (right side) at  
258 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]:

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

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).

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

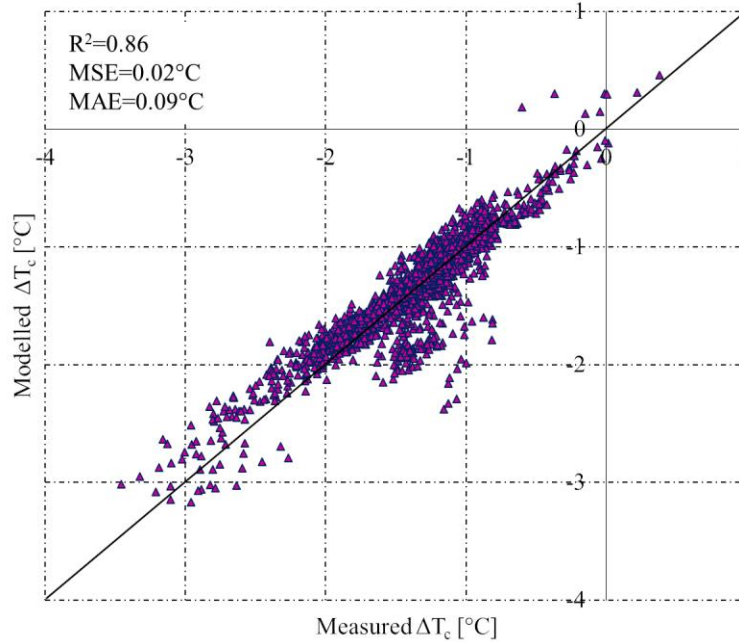
277 The input dataset comprised the wet-bulb depression, all the outputs of the meteorological station  
278 and the duration of the misting, represented by the parameter  $n$ , namely the number of 10 minute  
279 lasting operations in a minute time ( $0 \leq n \leq 6$ ). The training and testing datasets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

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

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

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

287 The  $R^2$  approached 0.86 with a maximum absolute error of 0.83 °C, a mean absolute error of  
288 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

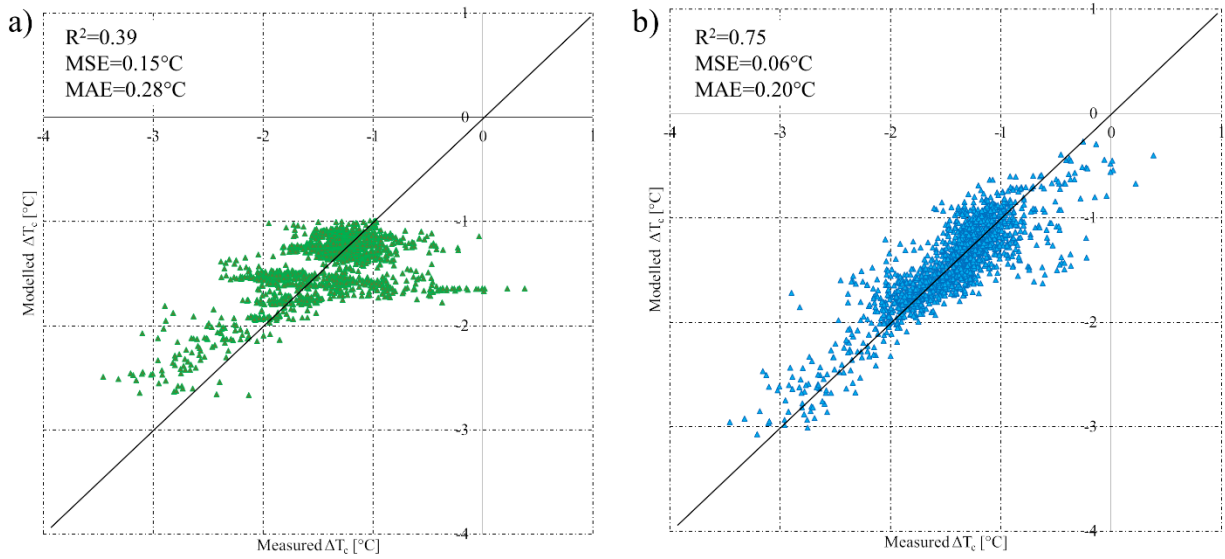
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305 between measured and modelled  $\Delta T_c$  occurred right at higher wind speeds, meaning that the  
 306 beneficial effect of wind speed on cooling capacity is limited to low velocities.

307  
 308 **Table 1.** Sensitivity analysis

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

309  
 310 The same evolutionary algorithm was later applied only considering the availability of data from  
 311 the reference station (without any measurement underneath the mist) which is likely to be the case  
 312 in real installations. The penalty in the predicting capacity is demonstrated in Fig. 6. Fig 6a  
 313 represents the results obtained when wind speed was the only environmental parameter retained in  
 314 the final optimized equation and Fig 6b when both wind speed and solar irradiation were  
 315 contemplated. The importance of knowing the wet bulb depression in the area emerges clearly,  
 316 although it is quite interesting to observe that wind speed and solar radiation are good estimators  
 317 of the overall trend. **On the other side, knowing irradiation only led to no significant prediction of**  
 318 **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  $36.3^{\circ}\text{C}$  with a median of  $25.7^{\circ}\text{C}$ , while the relative humidity reached  $87.1\%$  maintaining a median of about  $62.4^{\circ}\text{C}$ , with the highest values recorded overnight when the misting was inactive. In the misted area, the

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334 temperature at about 2.2 m of the injection and 1.1 m above the ground could be reduced by up to  
335 7.4 °C by injecting pulverized water droplets, while maintaining the humidity gain below 13 %.

336 By means of evolutionary algorithms, the temperature drop in the misted area could be expressed  
337 as a function of only 4 parameters with good accuracy ( $R^2 = 0.86$ ): wet-bulb depression, solar  
338 irradiation, wind speed and injection duration, in order of decreasing sensitivity. A strong positive  
339 correlation was established between the achieved cooling effect and the potential capacity of the  
340 air volume to accommodate extra moisture, represented by the wet bulb depression. The  
341 temperature drop was emphasized when the wet bulb depression stayed higher in the previous 30  
342 s. A negative correlation emerged between global horizontal irradiation and temperature drop,  
343 which entails that the solar-induced temperature increase outweighed the solar-induced  
344 enhancement of the evaporative rate. Another positive correlation was identified between wind  
345 speed and temperature drop, although the sensitivity was much reduced. Faster winds engendered  
346 efficient heat removal mechanisms and helped spread the droplets, thus reducing the risk of  
347 coalescence and augmenting the changes of break-ups into child particles. On the other side, the  
348 predictability of the temperature drop drastically declined at high wind speeds suggesting the  
349 existence of a threshold over which the positive impact of wind-driven dilution reverses, in line  
350 with previous research [19]. Further investigation will be devoted to determining these thresholds  
351 in different climatic contexts, to quantifying the time needed for outdoor temperatures to fall back  
352 into uncomfortable limits after injection cessation and to defining bespoke strategies against future  
353 escalation of urban heat islands [33–35]. Overall, mist cooling is a high-impact local-scale urban  
354 overheating countermeasure. It is not meant to be used on large areas not to introduce excessive  
355 humidity in the air, adversely impact on water management during droughts and not to jeopardize  
356 passersby's right to decide whether or not to be directly exposed to the mist. A city-scale

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357 application would be achieved by spreading several small-scale installations in appropriate  
358 locations (city hot spots with low, steady wind speed, no canyon effect, no excessive urban shading  
359 and close to vulnerable population, e.g. elderly, low-income groups). Notably, urban canyons and  
360 shading should be carefully evaluated prior to any installations due to the local acceleration of the  
361 wind flow [36] and the enhanced wetting risk associated with lower heat absorption by the water  
362 droplets [5], respectively. Microscale urban simulations and experimentally substantiated  
363 artificial-intelligence-assisted analyses like the evolutionary algorithm proposed in this study,  
364 would be especially valuable in defining the most appropriate installation sites. From a technical  
365 and economical perspective, the use of smart logics, able to weigh the injection of water upon a  
366 variety of drivers as the one hereby presented, is expected to be a major enabler in urban-scale  
367 deployment.

368

### 369 **Acknowledgments**

370 Authors warmly thank the Italian national agency for new technologies, energy and sustainable  
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372 modello integrato di smart district urbano - for providing the resources to build the prototype.

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## **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.

1 **Title**

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

3

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15

16 **Abstract**

17 Mist cooling is a widely known and applied heat mitigation technology, especially in urban settings.

18 Despite this, conceiving the right installation is no trivial matter as scattered and unstandardized

19 is the knowledge on the multiple interrelations with the local microclimate. This paper investigates

20 how the cooling efficiency of a dry mist system depends on the local meteorological trends. An

21 experimental system of 24 overhead nozzles constantly operating at 0.7 MPa, was installed in Italy

22 and monitored for a week in summertime. Temperature and relative humidity underneath the mist

23 were mapped in five locations with a time step of 10 s, together with the main meteorological

24 parameters, measured at an undisturbed location, for reference. Cooling and humidification  
 25 capacity were characterized as probability density, key summary statistics and relevant confidence  
 26 intervals with minimal redundancy and minimal distortion. A supervised learning algorithm was  
 27 used to disclose the sensitivity of the recorded temperature drop to the contextual microclimatic  
 28 evolution. It was demonstrated that the cooling capacity of the tested system was largely a function  
 29 of the local wet bulb depression, as instantaneous reading as well as short-term trend. Additionally,  
 30 solar irradiation and wind speed were found to be negatively and positively correlated, respectively.

31

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

34

35 **Acronyms and symbols (alphabetical order)**

36

ANOVA	Analysis of variance	Oh	Ohnesorge number
$\mu$	Dynamic viscosity of the fluid [Ns/m <sup>2</sup> ]	PE	Cooling power index [mcal/cm <sup>2</sup> s]
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 <sub>n</sub>	Nozzle diameter [m]	S	South (position)
E	East (position)	sma	Simple moving average
F	Resulting force [N]	T <sub>db</sub>	Dry-bulb temperature [°C]
g	Gravitational acceleration [m/s <sup>2</sup> ]	T <sub>wb</sub>	Wet-bulb temperature [°C]
I <sub>oh</sub>	Horizontal global solar irradiance [W/m <sup>2</sup> ]	UHI	Urban heat island
IQR	Interquartile range	v	Characteristic velocity of the flow [m/s]
k <sub>a</sub>	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]	$\gamma$	Surface tension [N/m]

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

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**1. Introduction**

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

51 Among the technological alternatives (e.g. cooling towers, sprinklers, fountains, ponds), dry  
52 misters are gaining popularity as, beyond being a very locally impactful cooling technique, their  
53 working principle well responds to growing concerns about energy consumption, water usage and  
54 climate-anxiety. By pulverizing water into micrometric particles, dry misters attain flash and  
55 complete evaporation of the injected droplets, drawing the necessary heat from the surrounding  
56 air. The resulting water consumption is extremely modest and the risk of skin wettedness can be  
57 easily averted by appropriate layouts. Furthermore, dry misters lend themselves to a variety of

58 applications, targeting the whole sphere of comfort. Their action is not merely thermohygrometric,  
59 but affects all the major environmental parameters, by attenuating solar radiation [5], scavenging  
60 dust [6], breaking the wind force while engendering a local turbulent flow of cooled air, all factors  
61 contributing to an efficient heat removal and to the generation of pleasant spaces in the urban realm,  
62 especially where overheating and pollution risks are prominent. As discussed in recent review  
63 papers [7,8], this technology is especially valuable in dry and warm climates, although good  
64 performance has been demonstrated also in humid locations like Singapore [8]. Increasing interest  
65 has also been expressed by heating-dominated countries, such as UK and Germany, to cope with  
66 the unprecedented escalation of heat-stress events in recent years [9,10]. These countries are less  
67 armored against urban overheating, thus increasing the heat resistance of their infrastructure has  
68 become a priority target. Compared to passive and natural mitigators, misters and other artificial  
69 water features are especially desirable in such contexts where intense outdoor cooling is a sporadic  
70 necessity, given their adjustability, controllability and scalability.

71 Experimental evidence suggests that misting systems can induce a local temperature drop from  
72 few degrees Celsius (1-2 °C), up to over 15 °C [8]. On average, the reduction falls in the 7-8 °C  
73 range, with major deviations due to the selected technology (in terms of nozzle geometry,  
74 operating pressure and layout), the local microclimate and the typology of cooled area (open  
75 outdoor, semi-enclosed, indoor) [11]. The humidification is in the order of 20%. Beyond  
76 technological considerations, the cooling capacity of misting systems depends on the contextual  
77 microclimate. In [12] Yoon and Yamada demonstrated that relative humidity is the governing  
78 parameter, even more than temperature, in the considered range. Humid conditions depreciated the  
79 extent and completeness of the evaporation process. The authors suggested potentially optimal  
80 thermohygrometric boundary conditions: 70% and 30-34 °C as for relative humidity and ambient

81 temperature, respectively. During the 2010 Shanghai Expo [13], Huang et al. monitored an  
82 extensive misting system of about 136 nozzle and reported temperature drops of 6-12 °C within 1  
83 m of the injections, when the ambient temperature was 34-40 °C and the relative humidity was 32-  
84 55 %. Considering the wet bulb depression ( $\Delta T_{wb}$ , difference between wet bulb and dry bulb  
85 temperatures) as theoretical limit, the authors computed the cooling efficiency by dividing the  
86 actual temperature drop to the ideal wet bulb depression: it reached 90 % in the Expo Pavilion.  
87 The same authors [14] developed a mathematical model to parameterize the thermohygro-metric  
88 conditions in the misted area as a function of several environmental and technological parameters.  
89 They concluded that lower relative humidity and lower wind speeds were precursors to accentuated  
90 performances. Speaking of wind, a 2009 experimental and numerical study [15] investigated its  
91 role when misters were used in open outdoors. It was found that, on average, the cooling was  
92 higher downwind (nearly 4 °C difference). Wind's impact was also highlighted in a recent  
93 publication by Ulpiani et al. [16]. The authors monitored a 24-nozzle overhead system in  
94 Mediterranean urban contexts (open areas), capable of temperature reductions up to 7.5 °C, and  
95 found that the local cooling was largely a function of the temperature and the wind speed.  
96 Generally, a light steady breeze of about 1 m/s is regarded as optimal operating condition, while  
97 under winds blowing at more than 3 m/s, it is suggested to shut off the injection [8]. Finally, Kim  
98 et al. [17] analyzed the role of solar radiation on the cooling capacity of a cross-shaped system of  
99 overhead blast sprayers, by performing Duncan multiple range test and one-way ANOVA.  
100 Statistically, the temperature drop was higher during hot and sunny days. Other factors, such as  
101 water temperature (7 %), were found to play a minor role and were thus examined to a lesser extent  
102 [18].

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

111

## 112 **2. Materials and methods**

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

117

### 118 **2.1 Theoretical background**

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

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

$$\text{Oh} = \frac{\mu}{\sqrt{\rho \gamma d_n}} \quad (2)$$

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

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

131 where the subscript “av” stands for average values for the mist cloud, F is the resulting force [N],  
 132 m is the droplet mass [kg], g is the gravitational acceleration [m/s<sup>2</sup>],  $v_{r,av}$  is the mean relative  
 133 velocity between droplet and surrounding air [m/s] and  $C_D$  is drag coefficient, which for small  
 134 droplets can be assumed equal to  $24/\text{Re}$  (or other empirical relationships [18]). When the droplet  
 135 diameter is in the order of few microns (as in the case of dry misters) the resulting throw length is  
 136 extremely short, even if the flow is initially very pressurized (1-2 MPa). This explains why  
 137 overhead misting lines can be safely and efficiently placed close to passersby. This also suggests  
 138 that, when characterizing the cooling capacity of a real installation, the sensor network should be  
 139 placed in the proximity of the injection. Specifically, since the vertical cooling and humidification  
 140 profiles obey to a Lorentzian distribution, hitting the peak at approximately 0.5 m of the injection  
 141 [20], temperature and/or humidity detectors should be placed at no more than few meters away  
 142 from the nozzles. While decelerating, the droplets evaporate. The rate depends on the size (exposed  
 143 surface-to-volume ratio), the relative humidity and temperature of the surroundings (dictating the

144 vapor partial pressure) and the wind speed (stimulating convective heat loss and promoting air  
145 mix). Pruppacher and Klett demonstrated that, in typical outdoor air conditions, the evaporation  
146 rate (expressed in terms of change in radius,  $r$ ) is a function of the wet bulb depression [23]:

$$\frac{dr}{dt} \approx - \frac{\Delta T_{wb} \cdot k_a}{L \cdot \rho \cdot r} \quad (4)$$

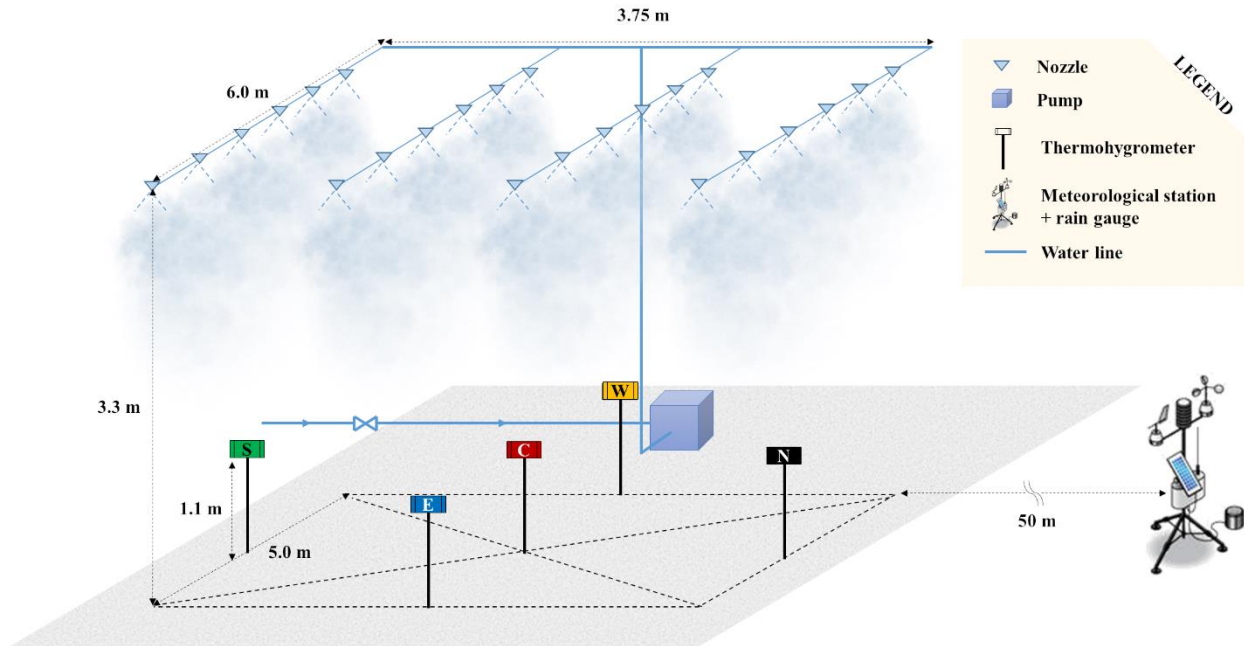
where  $k_a$  is the thermal conductivity of air [W/(mK)] and  $L$  is the latent heat of evaporation [J/kg]. This relationship, however, does not contemplate the effect of wind speed on break-up mechanisms into child particles, on particle dilution, on convective heat transfer, and on local turbulence.

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.

147

## 148 **2.2 Experimental setup**

149 The test rig consisted of 24 hollow cone nozzles connected to a high-pressure, self-compensating  
150 pump (0.7 MPa). As a result of the nozzles' geometry and the operating pressure, the injected  
151 droplets' diameter obeyed to a Rosin-Rammler distribution with a Mean Sauter Diameter around  
152 10  $\mu\text{m}$ . The high surface-to-volume ratio ensured flash evaporation within few centimeters of the  
153 orifice. The water flow rate was 0.09  $\text{m}^3/\text{h}$ . The nozzles were hanged at a height of 3.3 m (in line  
154 with typical settings [8]) and distributed in 4 parallel lines as depicted in Fig. 1. Extensive details  
155 of the experimental setup can be found in [16,20].



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

156

157

158

159 The distinctive feature of the misting system in object lies in the control of the injection. Misting  
 160 systems are typically operated in a continuous or on-off mode. The latter is beneficial in terms of  
 161 comfort as it helps containing the humidification, without congesting the air with overabundant  
 162 evaporating droplets [24,25]. On the other side, given the risk of Legionella contamination, the  
 163 water circulating in the hydraulic circuit must be discharged at any switch off, thus causing higher  
 164 water wastage. Also, no guidelines or well-established procedures support the selection of on-off  
 165 timing for intermittent operations: generally, the injection time varies from seconds to tens of  
 166 minutes and its setting is left to the user [8]. Smart logics could be especially beneficial i) in  
 167 optimizing the injection on the basis of the concomitant ambient conditions and comfort  
 168 enhancement potential and ii) in rationalizing the amount of energy needed to operate the system  
 169 thus making self-sustained solutions (e.g. PV-powered ones) more practical [16,26]. Against this  
 170 backdrop, the experimental system in object was devised so that the duration of the injection could

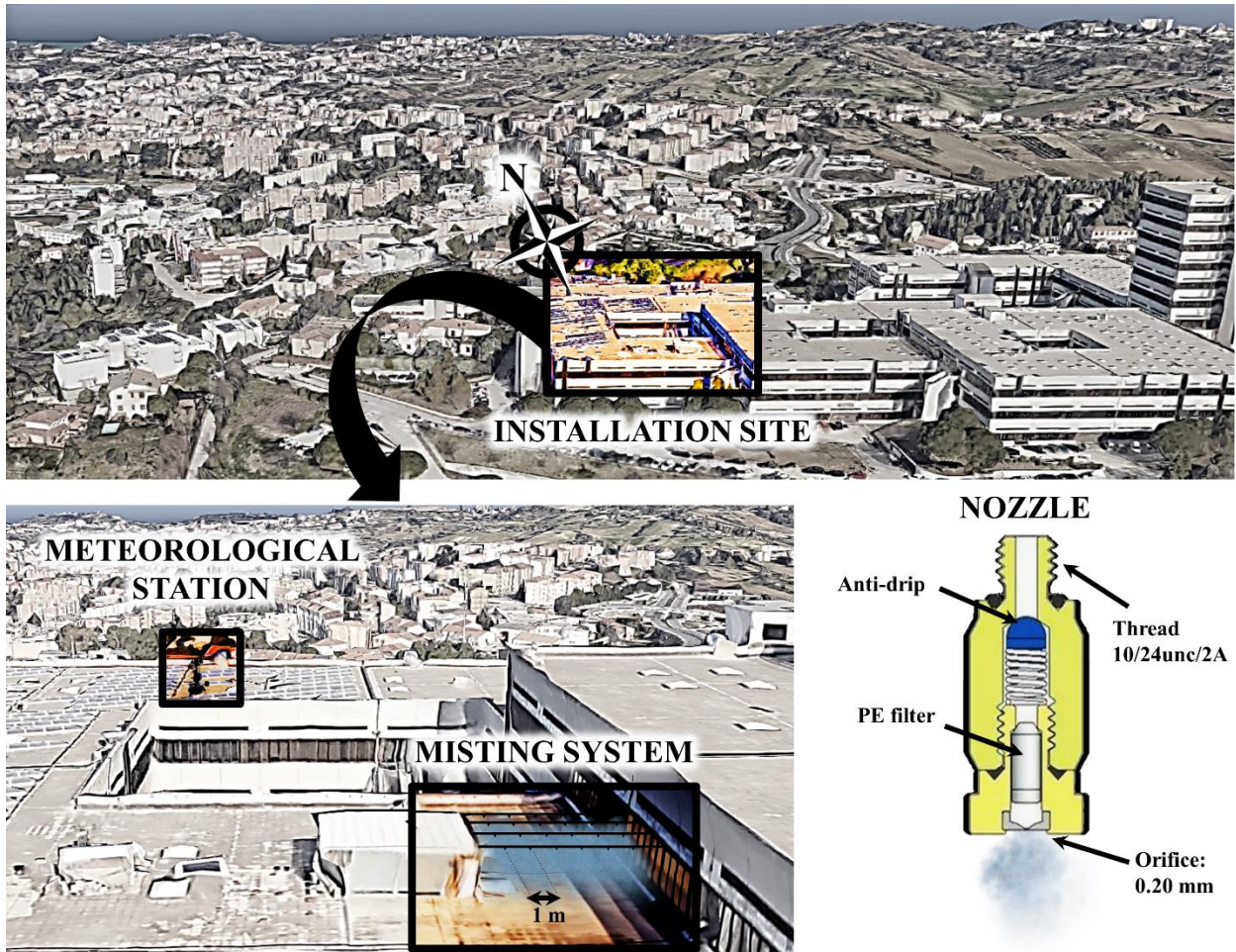
171 be responsive to the measured changes in air temperature, relative humidity, wind speed and solar  
172 irradiation. Approximate reasoning, in the form of fuzzy logic, was adopted to chase optimal  
173 comfort conditions. The duration of the misting action was proportional to the offset from the  
174 target neutral temperature (defined from previous comfort-oriented studies [27]) and to the level  
175 of irradiation and was adjusted on the basis of two lumped indexes: the Humidex which accounts  
176 for the combined action of temperature and humidity and the cooling power index (PE) which  
177 accounts for temperature and wind speed. These indexes weight the capability of ambient air in a  
178 given thermodynamic state to accommodate extra humidity and to be cooled by evaporative  
179 processes without imperiling the latent mechanisms of heat transfer. For further details about the  
180 fuzzy logic, the reader is referred to previous research [16], where the efficiency in terms of energy  
181 saving was demonstrated, compared to on-off operation. Comfort enhancement was also  
182 investigated in [20] where PET, SET\* and UTCI differences between misted and undisturbed  
183 locations were analyzed through a variety of statistical metrics (including non-parametric  
184 Spearman correlation test, non-parametric Kruskal-Wallis H test, correlation matrices, Frequent  
185 Pattern (FP)-Growth algorithms) based on comfort questionnaires. Under hot Mediterranean  
186 summers (as in this study), the effect of the logic is to i) switch on/off autonomously depending  
187 on morning and evening conditions, ii) maintain a continuous injection around peak hours, iii)  
188 allow for interruptions under cold and humid or windy conditions (precursor to undesired  
189 humidification).

190 The perturbing action of the misting system was characterized by recording the temperature and  
191 relative humidity underneath the lines. Five thermohygrometers were located within the ground-  
192 projected perimeter of the misting matrix at a height of 1.1 m, which represents the suggested  
193 breast level of a standing person and head level of a sitting person in ISO 7726 [28]. One probe

194 was placed in central position (denoted with “C” in Fig. 1) and the other four were distributed  
195 towards the cardinal directions (denoted with “N” , “S” , “E” and “W” in Fig. 1). The accuracy was  
196  $\pm 0.2$  °C in the  $-20$  °C  $\div$   $80$  °C temperature range, and  $\pm 2$  % in the  $10$   $\div$   $90$  % relative humidity  
197 range. A monitoring station, placed approximately 50 m away from the misted area, recorded the  
198 meteorological parameters (temperature, relative humidity, solar radiation, wind speed and  
199 direction) representative of concomitant undisturbed conditions. The corresponding accuracies  
200 were  $0.2$  °C,  $1.5$  % ,  $< 5$  % ,  $1.5$  % and  $1^\circ$ . The sampling rate was 10 s, the averaging time was 1  
201 min.

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

213



214

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

217

218 **3. Results**

219 **3.1 Cooling performance and humidification**

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

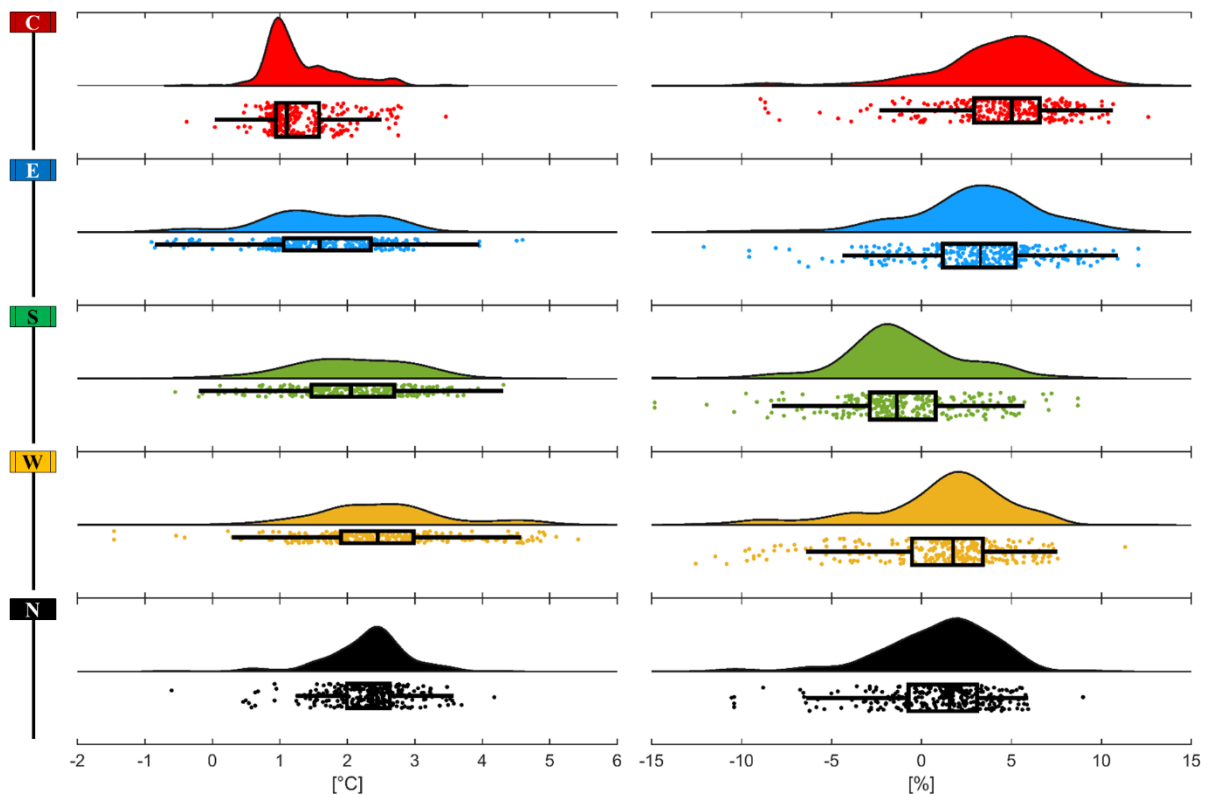
225 By looking at the probability density of the temperature drop at different values (half violin plots),  
226 it is apparent how the central and the northern locations were the only ones with a pronounced  
227 characteristic response to evaporative cooling: the former showed a sharp peak around 1.0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

239 The relative humidity increased by maximum 12.6 % in the middle of the mist layer, while tended  
240 to stay lower downwind, at the southern point of measurement. Considering that the average  
241 relative humidity at the undisturbed location was 57.67 %, it was proved that under smart  
242 controlled operation the maximum humidity could be reasonably maintained below 70 %, which  
243 is the proposed threshold by Ishii et al. for misting systems [24]. By looking at the probability  
244 density, every location showed a pronounced peak, but for different RH values: the central location  
245 peaked at the highest level (around 5.0 %), followed by the eastern location (around 3.5 %) and  
246 the western/northern locations (both around 2.0 %). Unexpectedly, the peak of the bell at the  
247 southern location fell into the negative side of the x-axis, meaning that the probability of having a

248 drier environment than at the reference location was high. This, again, can be explained by looking  
249 at Fig. 4: strong southern winds tended to effectively remove the droplets, thus impeding the local  
250 rise in relative humidity. Additionally, compared to the reference location, the southern probe was  
251 inside the wind channel created by the walls onto which the misting lines were secured, thus being  
252 locally affected by an accelerated airflow.

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

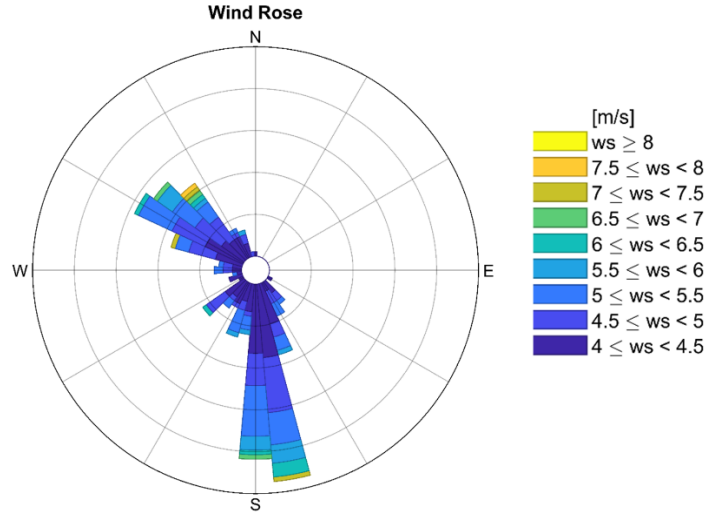
255



256

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

259



260

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

263

### 264 3.2 Driving forces

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

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

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

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

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

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

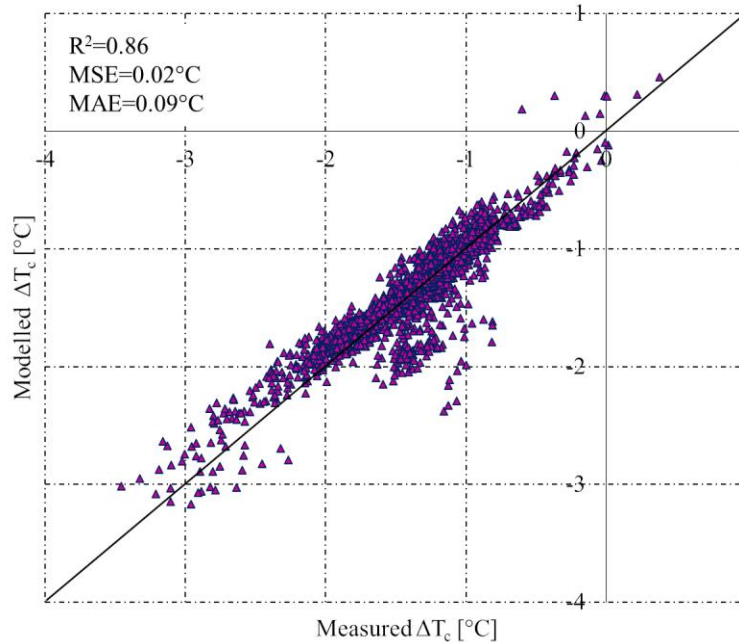
281 Through a supervised gene-programming, different candidate functions evolved through mutation  
 282 and competed until the fittest candidate was obtained (max  $R^2$ ). An 8-coefficient equation was  
 283 eventually proposed:

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

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

287 The  $R^2$  approached 0.86 with a maximum absolute error of 0.83 °C, a mean absolute error of  
 288 0.09 °C and a mean squared error of 0.02 °C.

289



290

291

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

294

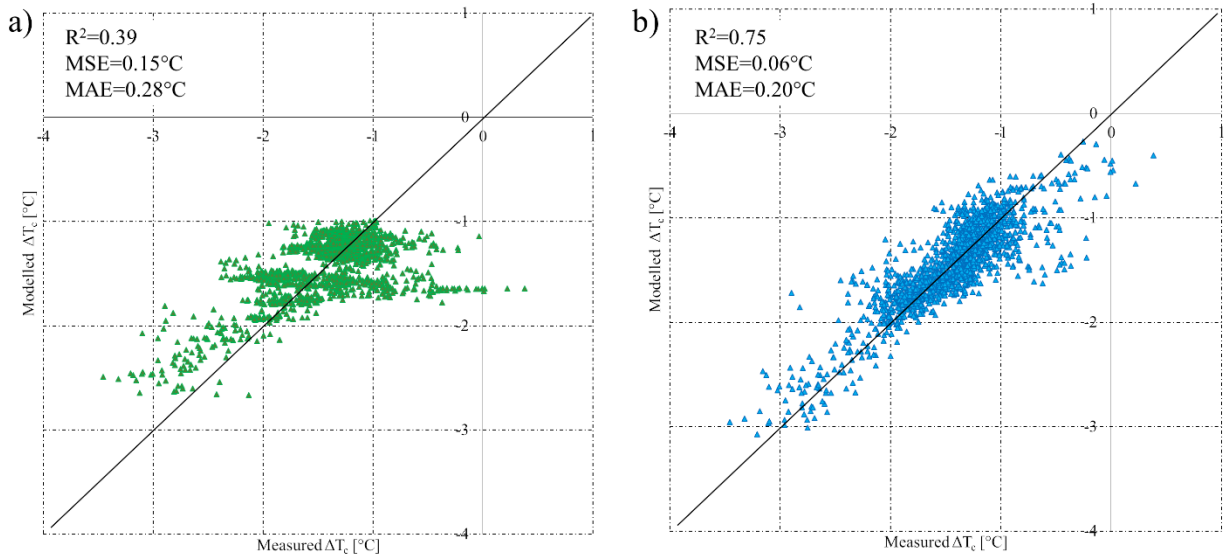
295 Hence, further evidence was collected about how the cooling capacity of misting systems is largely  
 296 a function of the local wet bulb depression even in complex outdoor contexts. Interestingly, both  
 297 the instantaneous and the previous 30 s average were driving factors. A sensitivity analysis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

305 between measured and modelled  $\Delta T_c$  occurred right at higher wind speeds, meaning that the  
 306 beneficial effect of wind speed on cooling capacity is limited to low velocities.

307  
 308 **Table 1.** Sensitivity analysis

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

309  
 310 The same evolutionary algorithm was later applied only considering the availability of data from  
 311 the reference station (without any measurement underneath the mist) which is likely to be the case  
 312 in real installations. The penalty in the predicting capacity is demonstrated in Fig. 6. Fig 6a  
 313 represents the results obtained when wind speed was the only environmental parameter retained in  
 314 the final optimized equation and Fig 6b when both wind speed and solar irradiation were  
 315 contemplated. The importance of knowing the wet bulb depression in the area emerges clearly,  
 316 although it is quite interesting to observe that wind speed and solar radiation are good estimators  
 317 of the overall trend. On the other side, knowing irradiation only led to no significant prediction of  
 318 the temperature drop.



319

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

324

#### 325 4 Discussion and conclusions

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

331 During the campaign, the temperature in the undisturbed location peaked at  $36.3^\circ\text{C}$  with a median  
 332 of  $25.7^\circ\text{C}$ , while the relative humidity reached 87.1 % maintaining a median of about  $62.4^\circ\text{C}$ ,  
 333 with the highest values recorded overnight when the misting was inactive. In the misted area, the

334 temperature at about 2.2 m of the injection and 1.1 m above the ground could be reduced by up to  
335 7.4 °C by injecting pulverized water droplets, while maintaining the humidity gain below 13 %.

336 By means of evolutionary algorithms, the temperature drop in the misted area could be expressed  
337 as a function of only 4 parameters with good accuracy ( $R^2 = 0.86$ ): wet-bulb depression, solar  
338 irradiation, wind speed and injection duration, in order of decreasing sensitivity. A strong positive  
339 correlation was established between the achieved cooling effect and the potential capacity of the  
340 air volume to accommodate extra moisture, represented by the wet bulb depression. The  
341 temperature drop was emphasized when the wet bulb depression stayed higher in the previous 30  
342 s. A negative correlation emerged between global horizontal irradiation and temperature drop,  
343 which entails that the solar-induced temperature increase outweighed the solar-induced  
344 enhancement of the evaporative rate. Another positive correlation was identified between wind  
345 speed and temperature drop, although the sensitivity was much reduced. Faster winds engendered  
346 efficient heat removal mechanisms and helped spread the droplets, thus reducing the risk of  
347 coalescence and augmenting the changes of break-ups into child particles. On the other side, the  
348 predictability of the temperature drop drastically declined at high wind speeds suggesting the  
349 existence of a threshold over which the positive impact of wind-driven dilution reverses, in line  
350 with previous research [19]. Further investigation will be devoted to determining these thresholds  
351 in different climatic contexts, to quantifying the time needed for outdoor temperatures to fall back  
352 into uncomfortable limits after injection cessation and to defining bespoke strategies against future  
353 escalation of urban heat islands [33–35]. Overall, mist cooling is a high-impact local-scale urban  
354 overheating countermeasure. It is not meant to be used on large areas not to introduce excessive  
355 humidity in the air, adversely impact on water management during droughts and not to jeopardize  
356 passersby's right to decide whether or not to be directly exposed to the mist. A city-scale

357 application would be achieved by spreading several small-scale installations in appropriate  
358 locations (city hot spots with low, steady wind speed, no canyon effect, no excessive urban shading  
359 and close to vulnerable population, e.g. elderly, low-income groups). Notably, urban canyons and  
360 shading should be carefully evaluated prior to any installations due to the local acceleration of the  
361 wind flow [36] and the enhanced wetting risk associated with lower heat absorption by the water  
362 droplets [5], respectively. Microscale urban simulations and experimentally substantiated  
363 artificial-intelligence-assisted analyses like the evolutionary algorithm proposed in this study,  
364 would be especially valuable in defining the most appropriate installation sites. From a technical  
365 and economical perspective, the use of smart logics, able to weigh the injection of water upon a  
366 variety of drivers as the one hereby presented, is expected to be a major enabler in urban-scale  
367 deployment.

368

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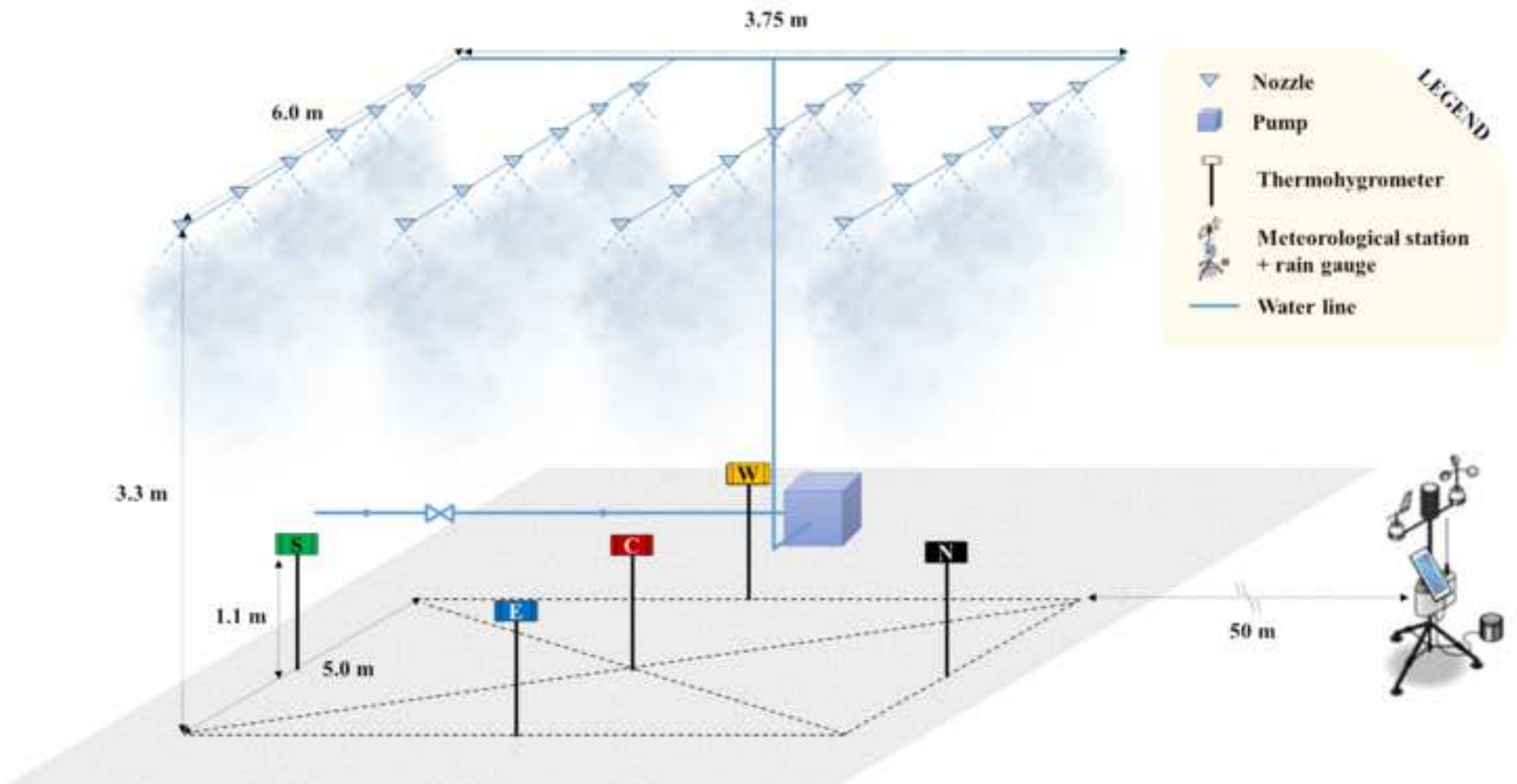
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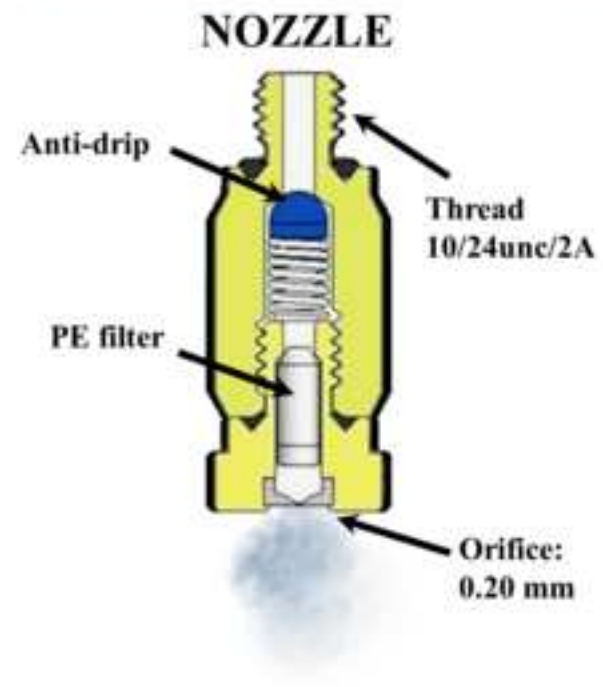
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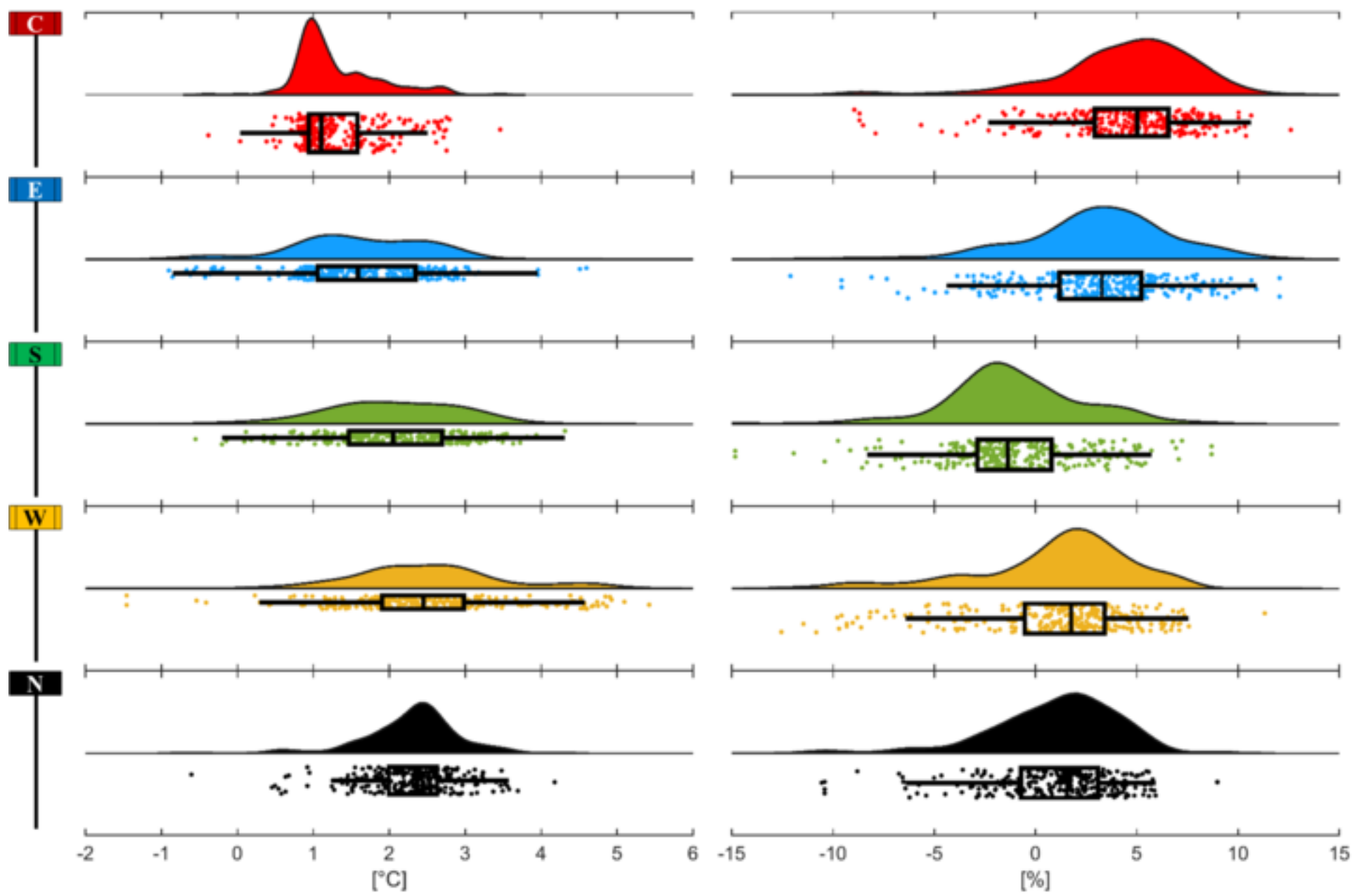
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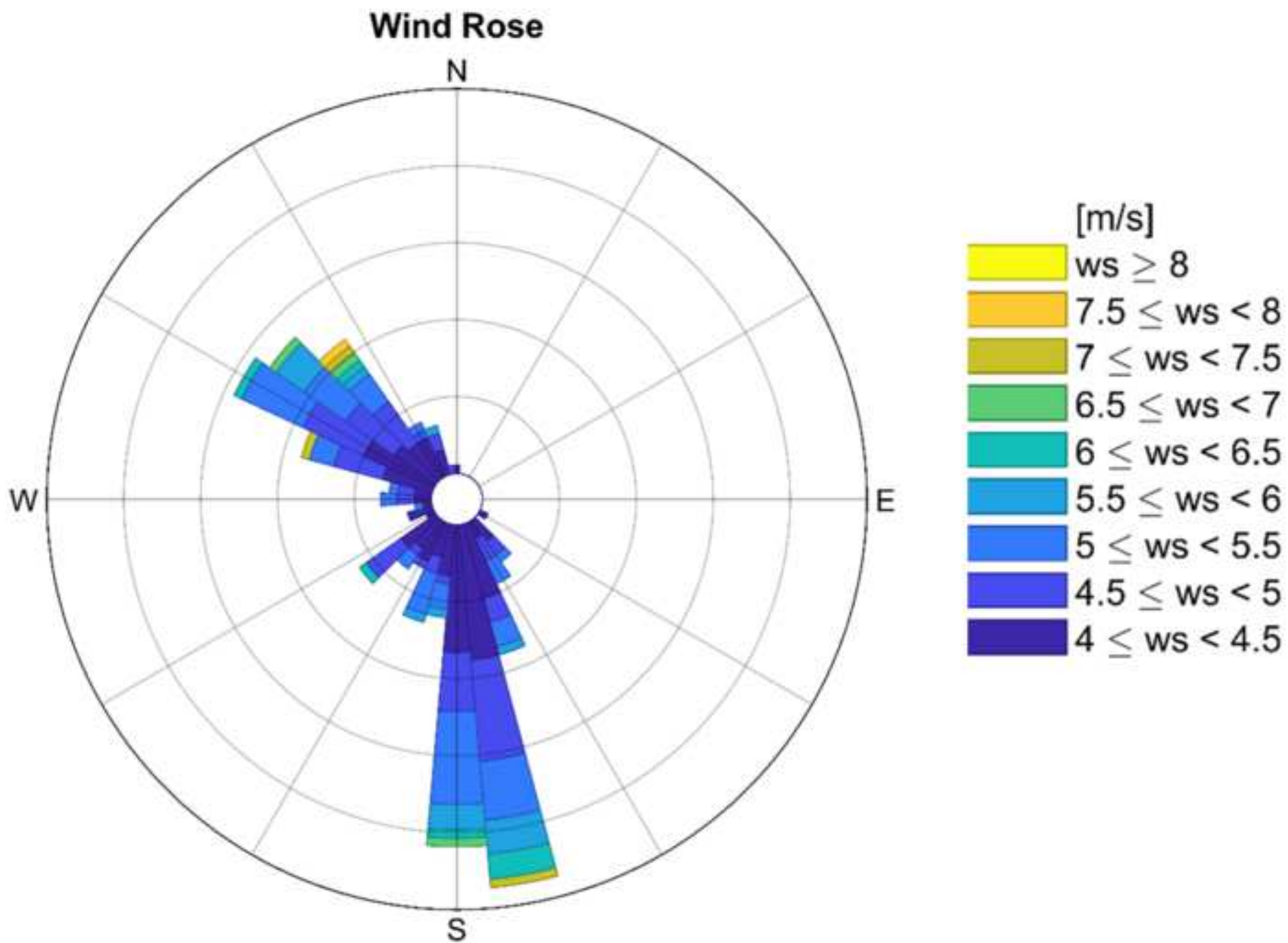
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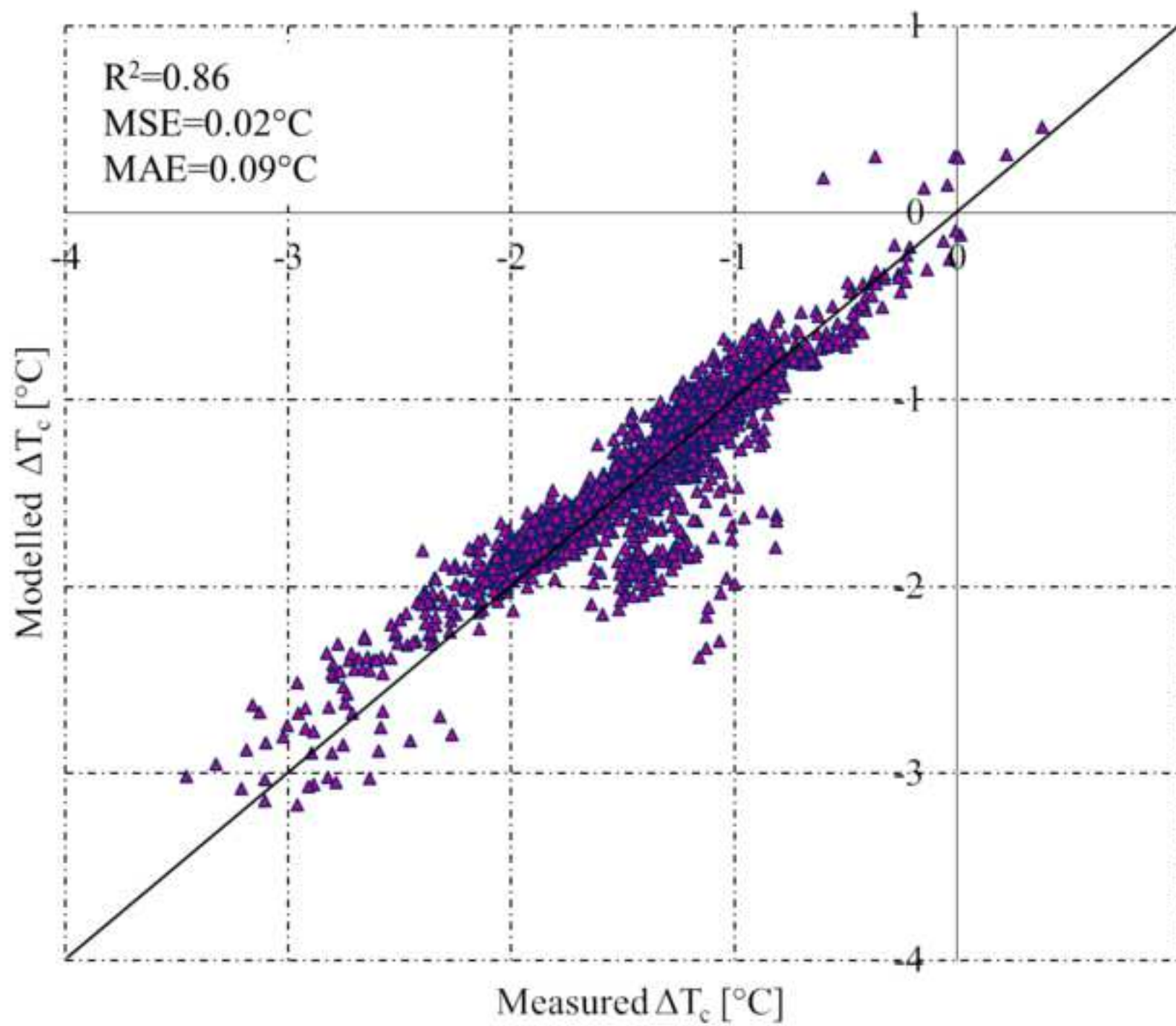
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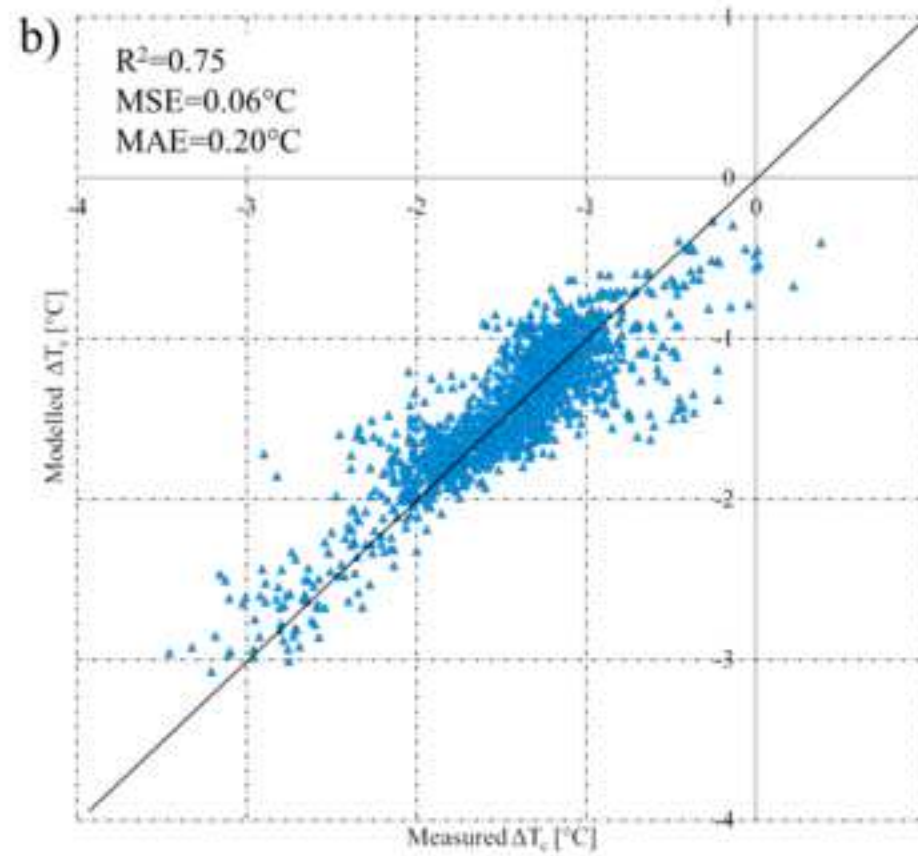
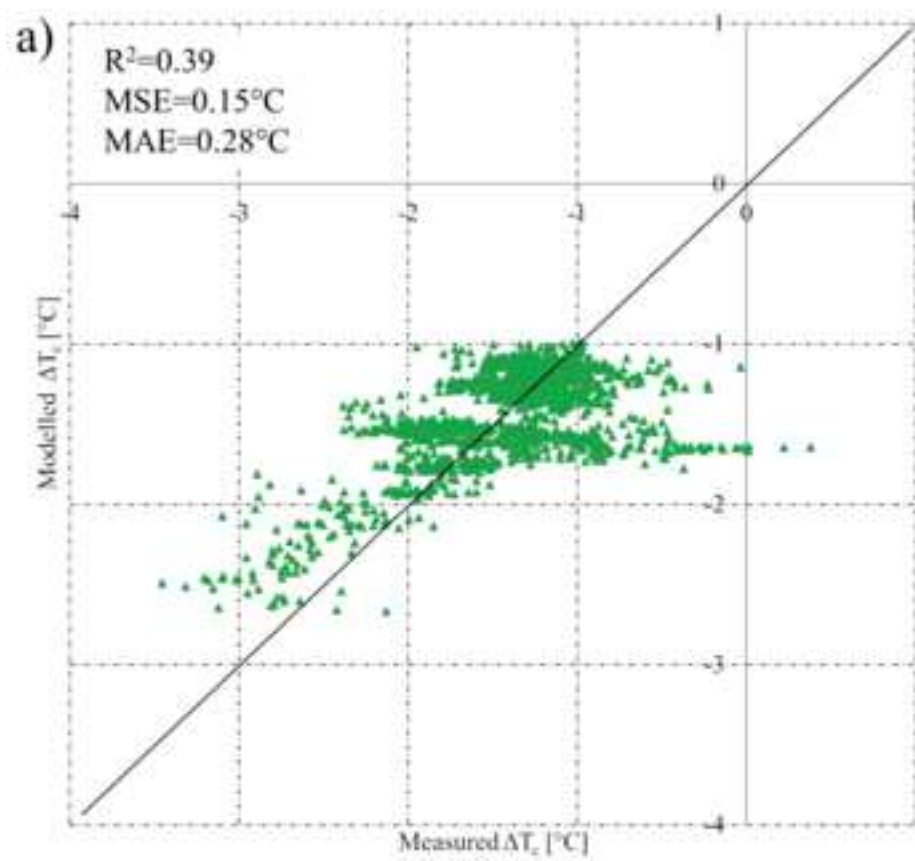


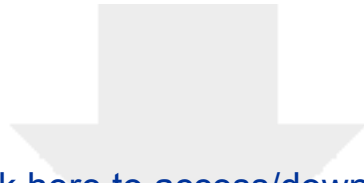












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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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