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# Estimating the cooling potential of irrigating green spaces in 100 global cities with arid, temperate or continental climates

Pui Kwan Cheung[a,*], Stephen J. Livesley[a], Kerry A. Nice[b,c]

[a] School of Ecosystem and Forest Sciences, Burnley Campus, 500 Yarra Boulevard, University of Melbourne, Melbourne, VIC 3121, Australia
[b] Transport, Health, and Urban Design Lab, Faculty of Architecture, Building, and Planning, University of Melbourne, Melbourne, VIC 3010, Australia
[c] School of Earth, Atmosphere and Environment, Monash University, Australia

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ABSTRACT

Modern agricultural irrigation can produce extensive cooling that is strong enough to mask the current effect of global climate change. Irrigating urban green spaces therefore has the potential to mitigate heat stress in cities. However, the cooling potentials of irrigating urban green space in different climate regions of the world have never been estimated. Here we conducted a systematic literature review to determine air temperature reductions in past experimental, observational and modelling studies ($N = 17$). We developed an empirical model with the irrigation cooling effect as the dependent variable and background air temperature and rainfall of the study area as the independent variables. The model was subsequently used to estimate the cooling potential of irrigating green spaces in 100 global cities with arid, temperate and continental climates. We predict that 91 of the 100 cities will receive a cooling benefit from irrigating urban green space (mean = −1.09 °C), whereas the remaining nine cities will experience a slight warming effect (mean = +0.76 °C). The cooling potential of irrigating urban green space is greatest in arid cities (mean = −1.65 °C).

## 1. Introduction

The superimposing effect of global climate change (Matzarakis & Amelung, 2008), heatwaves (He et al., 2021) and urban heat islands (Tan et al., 2010) is expected to exacerbate heat stress in cities around the world and threaten human health (Basu & Samet, 2002). Heat stress in urban areas is stronger than rural areas because urban materials and morphology are conducive to heat accumulation (Oke, 1982) and the dominance of dry impervious surface favours the release of heat in the form of sensible heat over latent heat (Li et al., 2015). In response to the growing threat of heat stress, different strategies have been proposed to cool the urban environment (Ronchi et al., 2020; Santamouris et al., 2017), such as urban greening (Bowler et al., 2010; Coccolo et al., 2018), the use of reflective materials (Al-Obaidi et al., 2014; Santamouris et al., 2017), urban design for shading and ventilation (Arnfield, 1990; He et al., 2020; Unal Cilek & Cilek, 2021), and irrigating urban green space (Gao & Santamouris, 2019; Livesley et al., 2021).

Urban vegetation plays an important role in moderating urban climate. The cooling effect of urban vegetation is achieved mainly through the interception of solar radiation and evapotranspiration (Tan et al., 2018; Zheng et al., 2021). Urban greenery can be part of the city landscape such as parks and roadside trees; it can also be integrated into the exterior of the buildings, forming green roofs and green walls (Norton et al., 2015). Different forms of urban greenery can cool different parts of the city (Yang et al., 2021). Tree planting is a highly effective measure to mitigate heat stress in urban parks and open spaces (Rahman et al., 2020; Wu et al., 2019). Direct solar radiation is the key factor that contributes to outdoor heat stress, particular in tropical and subtropical regions (Emmanuel et al., 2007; Lin et al., 2010). A single tree with dense foliage can reduce the air temperature under its canopy by up to 2.1 °C in the humid subtropical climate (Cheung & Jim, 2018). Urban parks can create a cool sanctuary from the heat stress in urban areas and they have the potential to cool their surrounding areas. A systematic literature review has showed that urban parks are on average 0.91 °C cooler than the surrounding built-up areas (Bowler et al., 2010). Under certain conditions, the cool air inside the parks can spill over to the surrounding areas, a phenomenon known as ‘park cool island’ effect (PCI) (Spronken-Smith & Oke, 1998). The PCI effect can extend to a distance about the same as the width of the park (Jauregui, 1990) at a notable magnitude (∼ 1 °C in mean air temperature) (Doick et al., 2014).

The cooling effect of urban vegetation is heavily dependent on

* Corresponding author.
*E-mail addresses:* puikwanc@student.unimelb.edu.au (P.K. Cheung), sjlive@unimelb.edu.au (S.J. Livesley), kerry.nice@unimelb.edu.au (K.A. Nice).

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background climate (Yu et al., 2018) and irrigation (Spronken-Smith & Oke, 1998). Yu et al. (2018) compared the cooling effect of urban vegetation in temperate monsoon climate and Mediterranean climates. The study found that the cooling effect of tree covered green spaces is positively correlated to background land surface temperature in the temperate monsoon climate, whereas there is only a weak correlation in the Mediterranean climate. Moreover, a higher wind speed can enhance the cooling effect of trees in the Mediterranean climate but not in the temperate monsoon climate. A higher precipitation can increase the cooling effect of grass covered green spaces in both climate regions. The results suggest that background climate is an important factor to consider when designing urban vegetation for mitigating heat stress. Spronken-Smith and Oke (1998) investigated the thermal environment in the urban parks in Vancouver, Canada and Sacramento, US. They found that the surface temperature of irrigated grass (22–26 °C) was much lower than the dry grass (30–36 °C) within a park. In terms of air temperature, the daytime mean PCI of two parks with irrigated grass (2.2 °C) was somewhat stronger than those with unirrigated grass (1.4 °C). These studies indicated that irrigation has the potential to enhance the cooling effect of urban vegetation, particularly grass, and that the level of enhancement may be dependent on the background climate.

Irrigating urban green space for cooling is an emerging and promising heat mitigation strategy (Coutts et al., 2013; Livesley et al., 2021). In urban areas, the soil moisture can be limited on pervious surface because traditional stormwater infrastructure generally prioritise the quick removal of stormwater from cities to avoid flooding over soil infiltration. The high coverage of impervious surface also restricts the recharge of soil moisture in rainfall events, which forces more energy to be converted to sensible heat in the dry urban landscape. Urban irrigation can provide the moisture required for evapotranspiration and allow more energy to be converted to latent heat instead of sensible heat (Williams & Torn, 2015), thereby reducing air and surface temperatures, as well as heat stress. The cooling effect of irrigation is mainly achieved through direct evaporation from the vegetation and soil surface, and enhanced transpiration from vegetation, both leading to increased latent heat flux. This study will focus on the potentials of irrigating urban green spaces to cool cities and communities.

Although some urban studies have monitored the microclimate of irrigated urban green spaces (Potchter et al., 2006; Spronken-Smith & Oke, 1998), those studies did not focus on measuring the cooling effect of irrigation. Irrigation has a long history of practice in agriculture. Insights can be borrowed from agricultural irrigation studies to understand the climate impacts of irrigating vegetated surfaces. On regional and global scales, the impacts of modern agricultural irrigation on near-surface air temperature have been extensively studied using observational data (Bonfils & Lobell, 2007; Shi et al., 2014; Yoshida et al., 2012) and climate models (Cook et al., 2011; Qian et al., 2013; Sacks et al., 2009). Irrigation has been estimated to reduce mean air temperature by up to 3 °C in certain parts of the world, such as northern India (Puma & Cook, 2010). Globally, it has been estimated that the collective impact of current irrigation reduces mean air temperature by 0.21 °C (Cook et al., 2015). Although the reported magnitudes of cooling vary between different global climate models (Puma & Cook, 2010) and model sensitivity (Thiery et al., 2017), it is clear that the air temperature reduction is significant and can partially mask regional and global warming trends (Cook et al., 2015; Kueppers et al., 2007; Puma & Cook, 2010). In recent years, there has been more evidence that irrigating urban green spaces can induce a noticeable cooling effect. A modelling study has predicted that the mean daily air temperature can be reduced by up to 2.3 °C from irrigating all pervious surfaces in a suburb in Adelaide, Australia (Broadbent et al., 2017). It was also estimated irrigating all urban green spaces can completely offset the urban heat island effect during the heatwaves in Paris, France (Daniel et al., 2018). Given that the cooling effect of irrigation is particularly strong within irrigated areas (Cook et al., 2015; Yang et al., 2016), it can be hypothesised that irrigating urban green spaces has the potential to mitigate urban heat stress in global cities.

Since the rate of evapotranspiration depends on the immediate meteorological conditions, when water availability is not limiting, the cooling effect of irrigation can change notably with the background climate of the region (Cook et al., 2015; Puma & Cook, 2010; Thiery et al., 2017). Therefore, it is necessary to examine the relationship between cooling magnitude and background climate before using irrigation for climate change adaptation. Although the concept of irrigation cooling effect has been discussed in several original research and review papers (Broadbent et al., 2017; Coutts et al., 2013; Daniel et al., 2018; Gao & Santamouris, 2019; Gao et al., 2020), these studies did not consider the relationship between background climate and the potential cooling effect of irrigation. There have been few studies, either experimental, observational or modelling, specifically focused on the cooling impact of irrigating urban green space (Broadbent et al., 2017; Chen et al., 2018). Since irrigation has been dominated by agriculture throughout the 20th century, studies that have assessed the cooling effect of irrigation globally, have only considered areas that have historically been irrigated for agriculture (Supplementary Fig. 1), and as such have not included major urban areas (Cook et al., 2011; Sacks et al., 2009; Thiery et al., 2017). Furthermore, studies that have quantified the cooling effect of irrigation in cities and regions have neglected the influence of background climate (Broadbent et al., 2017; Kanamaru & Kanamitsu, 2008; Yang & Wang, 2015) as they mostly focused on a single climate region. These studies of irrigation in cities and regions have provided a unique opportunity for a retrospective analysis of the relationship between background climate and irrigation cooling effect. This study is believed to be the first to use a retrospective analysis to determine such a relationship.

In this study, we used a systematic review to identify regional, city-scale and experimental studies that report the difference in mean air temperature between irrigated and non-irrigated scenarios or sites. The magnitude of irrigation cooling in these studies was then related to background climate conditions of that region and for the study time period using a global historical climate database, the Global Land Data Assimilation System (GLDAS). From these data a simple, multiple-linear regression model was developed to predict irrigation cooling effect according to background climate conditions for arid, temperate and continental regions. The aims of this study are to: (1) develop a model from the relationships between background climate and the effect of irrigation on air temperature, and (2) use that model to assess the cooling potential of irrigating green spaces in arid, temperate and continental climate regions and 100 cities in these regions based on their background climate.

## 2. Systematic search for irrigation studies that report air temperature impacts

To collect the published data on the cooling effect of irrigating green spaces or other pervious surfaces, a literature search without time period limits was conducted with Google Scholar (Google Scholar, 2020) using the Boolean search terms: (‘watering’ OR ‘irrigation’) AND (‘effect’ OR ‘impact’) AND ‘air temperature’) (Fig. 1). The titles and abstracts of the first 1000 results sorted by relevance were screened to identify studies that measured or modelled near ground-level air temperature at irrigated and non-irrigated sites. Non peer-reviewed and non-English language journal articles were excluded. Also, global studies were excluded because the effect of a specific climate on irrigation cooling cannot be assessed. To allow a robust analysis of the relationship between irrigation-induced cooling effect and background climate, four additional inclusion criteria were applied : (1) the study area and time period were reported; (2) a non-irrigated site (control) was clearly identified and described; (3) the comparison between irrigated and non-irrigated sites did not involve a change in land cover or vegetation type; and (4) the impact of irrigation could be reported as a difference in mean air

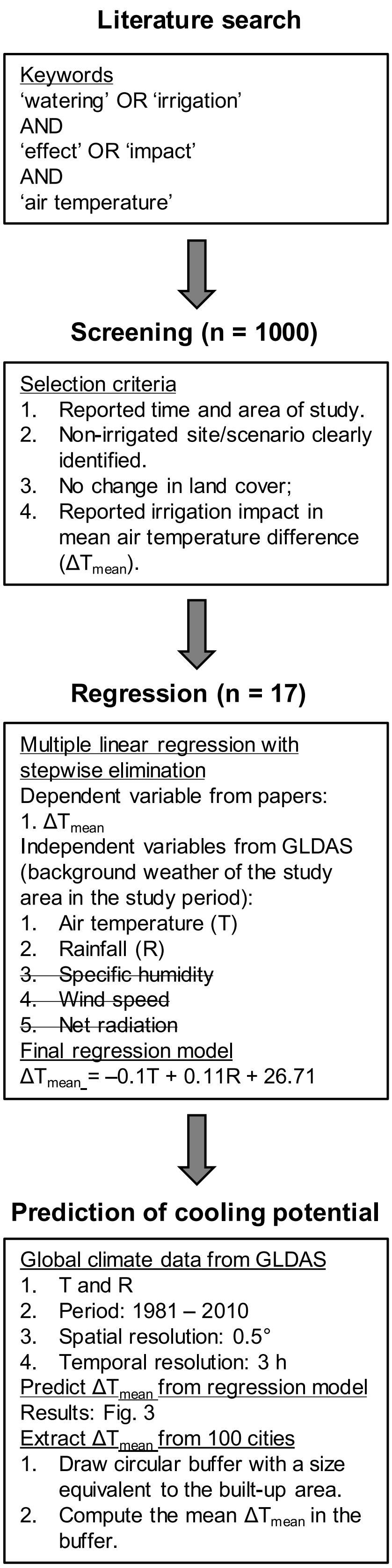


**Fig. 1.** Research procedures of this study. This study began with a literature search using Google Scholar. We screened 1000 papers and identified 17 of them that reported $\Delta T_{mean}$ and their study area and period. We then developed a regression model to predict $\Delta T_{mean}$ from background air temperature and rainfall. Finally, the cooling potential of irrigation was predicted for 100 global cities using the regression model.

temperature over the whole study period ($\Delta T_{mean}$). We further applied a non-parametric outlier test to remove studies that reported data that fell outside the range of the median ± 1.5 × the inter-quartile range (Jung et al., 2010). We identified 17 studies that met the above criteria ($N = 19$; one study with three study areas). We identified another 57 peer-reviewed irrigation studies that did not meet the four above-mentioned inclusion criteria and were excluded (Supplementary Table 1).

## 3. Methods

### 3.1. Regression model of air temperature change and background climate conditions

To estimate the cooling potential of irrigating green space in cities in the three climate regions covered by the 17 study datasets (arid, temperate and continental), the relationship between $\Delta T_{mean}$ and background climate conditions was determined using stepwise multiple linear regression. The $\Delta T_{mean}$ was directly collected in some of the 17 studies, and in the others it was extracted from the .figures presented using ImageJ analysis (Schneider et al., 2012). If a study reported a monthly $\Delta T_{mean}$ in summer, then the mean background climate conditions of June, July and August (JJA) were used for studies in the northern hemisphere and the mean of December, January and February (DJF) for the southern hemisphere. Historical climate data were retrieved from GLDAS, developed by the National Aeronautics and Space Administration (NASA) and Atmospheric Administration (NOAA) (Rodell et al., 2004). GLDAS data wwere accessed through the Giovanni portal for the necessary spatial extent and time period of each of the 19 study areas. GLDAS provides gridded global climate data at a spatial resolution of 0.25° and a temporal resolution of 3 h. Five background climate conditions were extracted: mean near-surface air temperature, specific air humidity, wind speed, net radiation and rainfall. These five meteorological variables can influence evapotranspiration within a vegetated landscape (Jung et al., 2010).

A multiple linear regression model was first constructed with the $\Delta T_{mean}$ data as dependent variable and the five background climate conditions as independent variables. A bi-directional stepwise elimination procedure was then applied to add or remove the independent variables one at a time from the full model until the Akaike Information Criterion (AIC) of the model was minimised (Hastie & Pregibon, 1992). AIC is a measure of the quality of a model and the best model is the one with the smallest AIC (Akaike, 1974). The above analysis was conducted in R Studio 1.3.959 (R Core Team, 2020).

### 3.2. Predicting the potential cooling benefit of irrigating urban green space in 100 global cities

Since only air temperature and rainfall were included in the final mode, a global map of estimated irrigation cooling potentials was produced based on the gridded 30-year (1981–2010) mean air temperature and rainfall data from the GLDAS (Rodell et al., 2004) (Fig. 2). The climate data in JJA and DJF were used for the northern and southern hemispheres, respectively. The tropical and polar regions in the updated Köppen-Geiger climate classification were excluded because the 17 studies only covered the arid, temperate and continental climates. To estimate the irrigation cooling potentials in cities, 100 populous cities were selected from the arid, temperate and continental climates. The built-up areas of the cities were retrieved from Demographia (Demographia, 2020), local government statistics or satellite images. A circular buffer with a size equivalent to the built-up area was drawn around each city and the area-weighted $\Delta T_{mean}$ of that city was extracted from the global map. When the cooling or warming potential is mentioned in this study, negative values imply cooling and positive values imply warming.

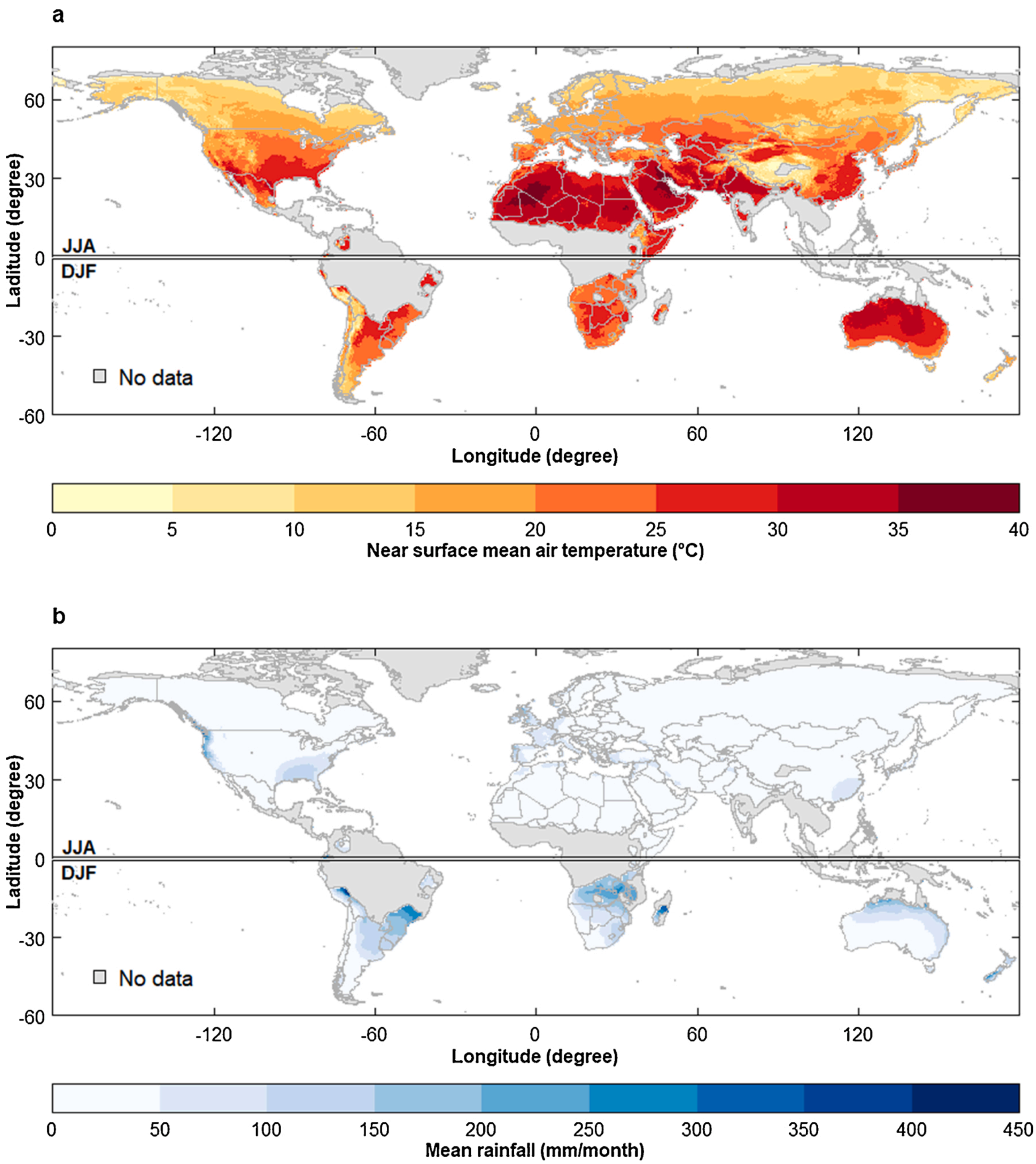


**Fig. 2.** 30-year (1981–2010) (a) near surface mean air temperature and (b) mean rainfall in JJA (northern hemisphere) and DJF (southern hemisphere). Tropical and Polar regions in the updated Köppen-Geiger climate classification are greyed out and denoted by 'No data'. Data were retrieved from the GLDAS (Rodell et al., 2004).

## 4. Results

We have identified 17 studies that reported $\Delta T_{mean}$ in the literature (Table 1). We have a total of 19 cases because one of the studies reported the $\Delta T_{mean}$ in three study areas. The USA was the most common study area in terms of country (8 cases), followed by China (6 cases). The dataset covered arid (B), temperate (C) and continental (D) climate zones and nine sub-climate regions (BSk, BWh, BWk, Cfa, Csa, Cwa, Dfa and Dwa) in the updated Köppen-Geiger climate classification scheme (Fig. 3) (Peel et al., 2007). Four cases were experimental or observational studies and the rest were modelling studies. The models used in these studies included WRF, RegCM4, SCAM, SURFEX, RSM, NCAR/-Penn STAT MM5 and RAMS. The study sites varied from highly homogenous experimental farmlands, complex city landscapes to large regional lands. Only seven studies reported irrigation rate, which ranged from 0.4 to 15 mm/day with a mean of 4.5 mm/day. The $\Delta T_{mean}$ reported in the 19 cases ranged from −2.67 °C (Yang & Wang, 2015) to 0.00 °C (Chen et al., 2017) with a mean of −0.77 °C.

The strongest multiple linear regression model contained the independent variables of air temperature and rainfall (Table 2), which explained 15.2 % and 32.9 % of the variability in $\Delta T_{mean}$, respectively. This model was statistically significant (*F*-statistic: 7.397 on 2 and 16 DF, $p < 0.01$, $R^2 = 48.0$ %). The model indicated that, for every 1 °C increase in background mean air temperature and a constant rainfall, $\Delta T_{mean}$ will decrease by 0.10 °C. Moreover, for every 10 mm/month increase in rainfall and a constant background mean air temperature, $\Delta T_{mean}$ will increase 0.11 °C. There did not appear to be any obvious trend according to whether data were sourced from experimental or modelling studies, or from arid, temperate or continental climate regions (Fig. 4). In other words, the research method and climate region

**Table 1**
Characteristics of the 17 studies ($N = 19$; one study with three study areas) that are included this study. The key inclusion criteria are that the study has reported the irrigation-induced change in mean air temperature and the comparison between the irrigated and non-irrigated sites did not involve a land cover or land use change (see Methods for detailed criteria).

| Year | Location | Climate classification | Approach | Model | Environment | Irrigated surface | Irrigation rate (mm/day) | $\Delta T_{mean}$ (°C) | Citation |
|---|---|---|---|---|---|---|---|---|---|
| 2017 | Yellow River Basin, China | BSk | Modelling | WRF and Noah LSM | Regional scale | Crop | NA | −0.10 | (Chen et al., 2017) |
| 2002 | Murrumbidgee-Coleambally-Murray Irrigation Areas, Australia | BSk | Observational | NA | Regional scale | Crop | NA | −1.40 | (Geerts, 2002) |
| 2014 | Haihe River Basin, China | BSk | Modelling | RegCM4 and CLM | Regional scale | Crop | 0.4 | −0.34 | (Zou et al., 2014) |
| 2015 | Gezira, Sudan | BWh | Observational | NA | Experimental farmland | NA | NA | −1.00 | (Alter et al., 2015) |
| 2015 | Phoenix, USA | BWh | Modelling | UCM | City | Mesic | 3.9 | −2.67 | (Yang & Wang, 2015) |
| 2017 | Yellow River Basin, China | BWk | Modelling | WRF and Noah LSM | Regional scale | Crop | NA | 0.00 | (Chen et al., 2017) |
| 2012 | Zhangye, China | BWk | Modelling | SCAM and CLM | City | Vegetation | NA | −1.42 | (Wen & Jin, 2012) |
| 2015 | Toowoomba, Queensland, Australia | Cfa | Observational | NA | Experimental farmland | Crop | NA | −0.43 | (Hancock et al., 2015) |
| 2012 | The Great Plains, USA | Cfa | Modelling | WRF and Noah LSM | Experimental farmland | Crop | NA | −0.16 | (Harding & Snyder, 2012) |
| 2014 | The Great Plains, USA | Cfa | Modelling | WRF and Noah LSM | Experimental farmland | Crop | NA | −1.00 | (Huber et al., 2014) |
| 2020 | Po Valley, Italy | Cfa | Modelling | WRF-ARW | Regional scale | Crop | 5.7 | −1.17 | (Valmassoi et al., 2019) |
| 2018 | Mawson Lakes, Adelaide, Australia | Csa | Modelling | SURFEX (TEB-SBL, TEB-Veg) | City | Pervious surface | 15.0 | −1.50 | (Broadbent et al., 2018) |
| 2008 | California Central Valley, USA | Csa | Modelling | RSM and OSU | Regional scale | NA | NA | −0.02 | (Kanamaru & Kanamitsu, 2008) |
| 2011 | California Central Valley, USA | Csa | Modelling | NCAR/Penn State MM5 | Regional scale | NA | NA | −2.10 | (Sorooshian et al., 2011) |
| 2017 | California Central Valley, USA | Csa | Modelling | WRF and Noah LSM | Regional scale | Crop | 3.6 | −1.11 | (Yang et al., 2017) |
| 2017 | Yellow River Basin, China | Cwa | Modelling | WRF and Noah LSM | Regional scale | Crop | NA | −0.10 | (Chen et al., 2017) |
| 2003 | Nebraska, USA | Dfa | Modelling | RAMS and LEAF-2 | Regional scale | Crop | NA | −0.60 | (Adegoke et al., 2003) |
| 2018 | Mead, Nebraska, USA | Dfa | Experimental | NA | Experimental farmland | Maize | 2.6 | −0.26 | (Chen et al., 2018) |
| 2016 | Huang-Huai-Hai Plain, China | Dwa | Modelling | WRF and Noah LSM | Regional scale | Crop | 0.4 | −0.23 | (Yang et al., 2016) |

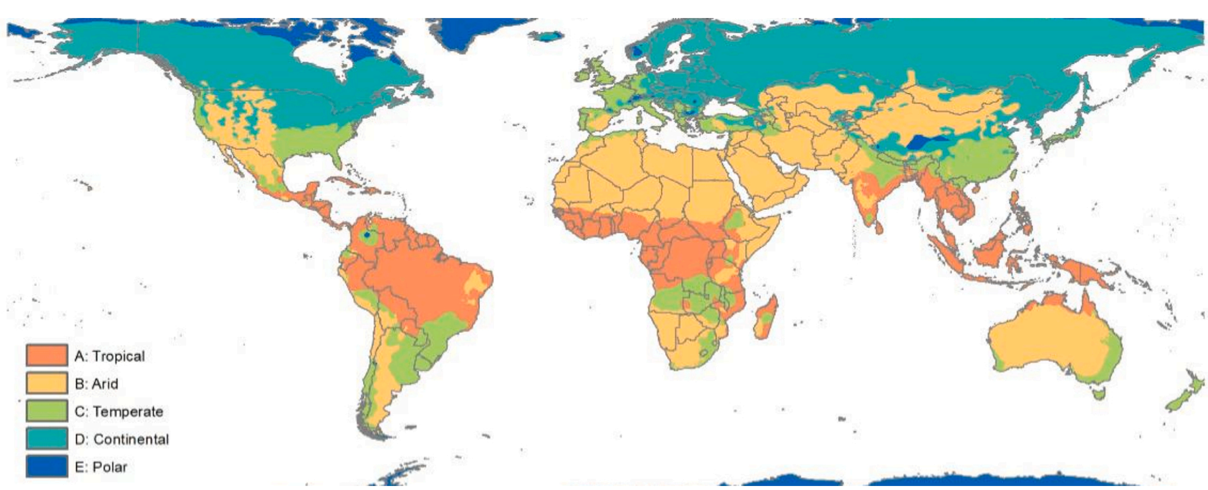


**Fig. 3.** Simplified Köppen-Geiger climate map of the world. Regions are grouped into five broad climate zones: A: Tropical, B: Arid, C: Temperate, D: Continental and E: Polar. Redrawn based on Peel et al. (2007).

did not directly determine $\Delta T_{mean}$. However, $\Delta T_{mean}$ showed a decreasing trend with increasing mean air temperature (Fig. 4a) and an increasing trend with increasing rainfall (Fig. 4b).

The cooling potentials of irrigation are more apparent in the arid climate region than temperate and continental regions (Fig. 5). North Africa, the Middle East and north India have the highest irrigation

**Table 2**
Results of the stepwise multiple linear regression model on irrigated-induced change in mean air temperature.

| Variable | Unit of comparison | Estimate | SE | *t* | *p* | $R^2$ |
|---|---|---|---|---|---|---|
| (Intercept) | NA | 26.71 | 11.46 | 2.3 | <0.05 | NA |
| Air temperature | 1 °C | −0.10 | 0.04 | −2.5 | <0.05 | 15.2 % |
| Rainfall | 10 mm/month | 0.11 | 0.03 | 3.4 | <0.01 | 32.9 % |
| *F*-statistic: 7.397 on 2 and 16 DF, $p<0.01$, $R^2 = 48.0$ %. | | | | | | |

The full model consists of five dependent variables of the background climate (air temperature, specific humidity, wind speed, net radiation and rainfall) with the irrigation-induced change in mean air temperature being the independent variable. Specific humidity, wind speed and net radiation are removed from the full model in the bi-directional stepwise elimination procedure to optimise the quality of the model.

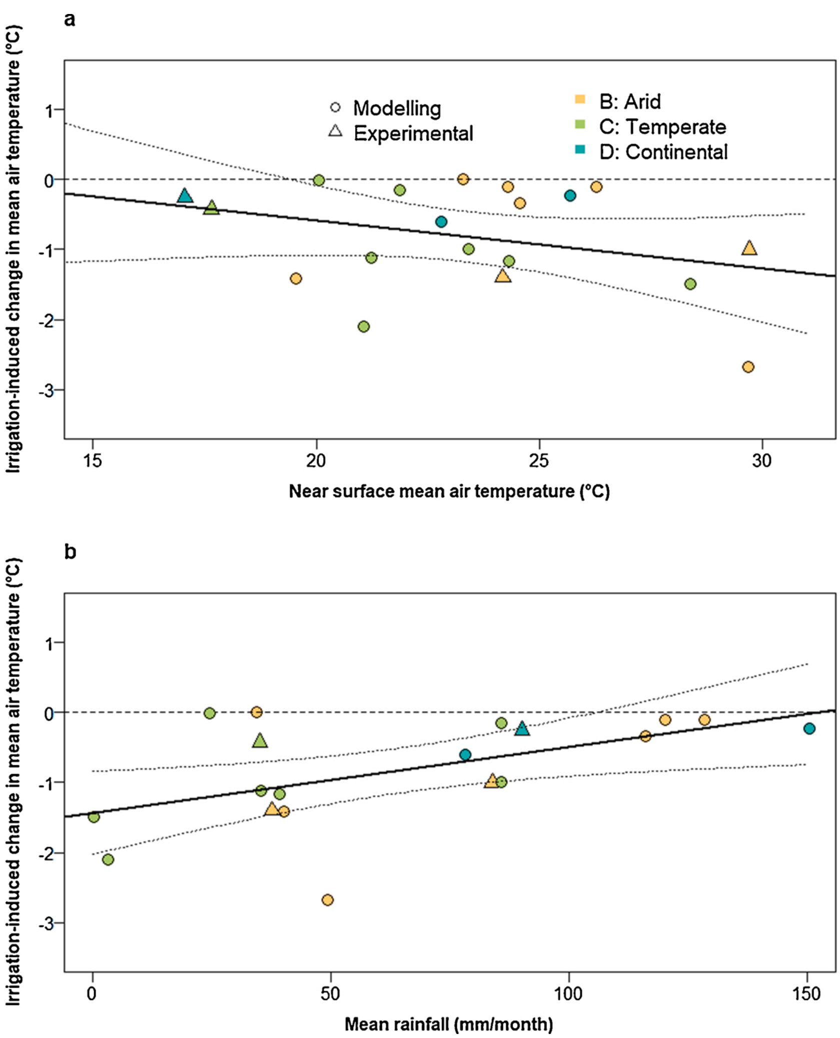


**Fig. 4.** Scatter plot of irrigation-induced change in mean air temperature against the (a) near surface mean air temperature, and (b) mean rainfall. Both variables are the means of the study period. The dataset consists of 17 studies (*N* = 19; one study with three study areas) that reported the irrigation-induced change in mean air temperature. The mean background air temperature and rainfall data are retrieved from the GLDAS (Rodell et al., 2004). The dotted lines surrounding the linear regression line represent the 95 % confidence interval.

cooling potentials (−3 to −2 °C), and these geographic areas have high mean air temperature (>30 °C) (Fig. 2a) and low rainfall (<50 mm/month) (Fig. 2b). An irrigation cooling potential between −2 and −1 °C is also predicted for central Asia, east and south China, mid-west and south-west USA, northern Mexico, southern Africa and southern and western Australia. These regions have moderate mean air temperature (15–30 °C) and low monthly rainfall (<50 mm). The majority of Europe, Russia, Canada, Argentina and east coast of Australia have an estimated cooling potential between −1 and 0 °C. Irrigation is predicted to cause warming of up to 3 °C along the east coast of North America, south Peru, southeast Brazil, Zambia, Madagascar, the UK, Tibet, and New Zealand. These regions have relatively high rainfall (>100 mm) (Fig. 2b)

The majority of the 100 cities (91) are estimated to benefit from irrigation cooling of their urban green space (Supplementary Table 2). Nine cities could potentially cool their urban green spaces by between −3.00 and −2.01 °C, 33 cities between −2.00 and −1.01 °C, and 49 cities between −1.00 and 0.00 °C. The three cities with the strongest estimated cooling benefit from irrigating urban green space are Kuwait (−2.60 °C), Doha (−2.55 °C) and Riyadh (−2.53 °C). The summer climate of these cities is very hot (mean air temperature > 35 °C) and dry (mean rainfall < 50 mm/month) (Fig. 2). The mean estimated cooling effect of irrigating urban green space in arid region cities (*N* = 27) is −1.65 °C, which is greater than that from irrigating urban green space in temperate region cities (*N* = 49, −0.50 °C) and continental region cities (*N* = 23, −0.97 °C) (Fig. 6).

Urban green spaces in nine cities are predicted to experience a warming effect (mean = +0.76 °C) induced by irrigation (Supplementary Table 2). The three cities with the strongest warming potentials from green space irrigation are Pasto (+1.47 °C), Vancouver (+1.41 °C) and Glasgow (+1.31 °C) and these cities have cool summer climates (air

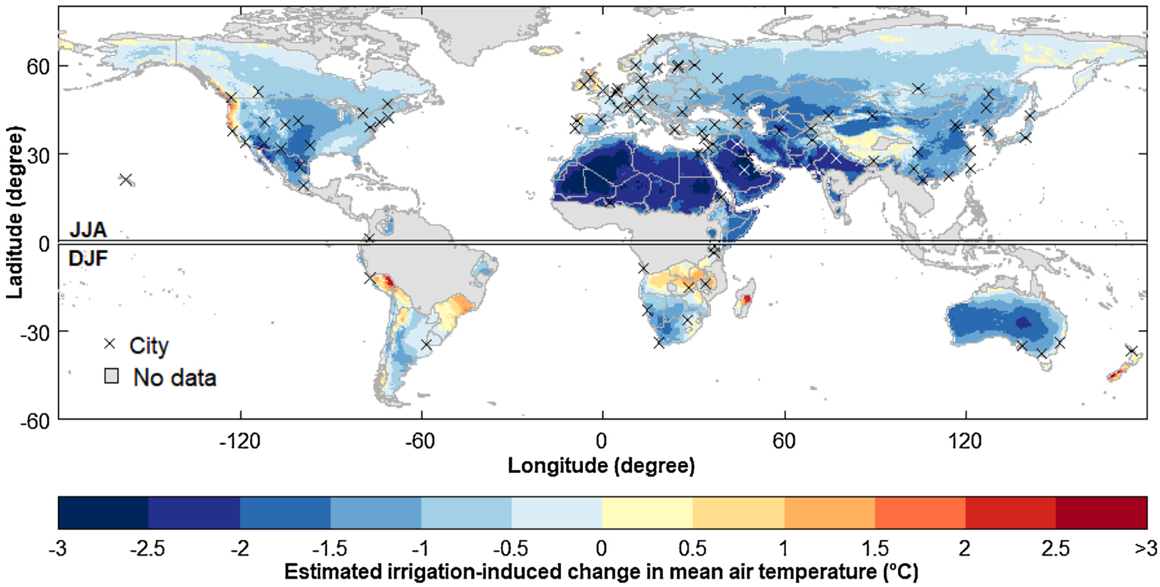


**Fig. 5.** Estimated irrigation-induced change in mean air temperature ($\Delta T_{mean}$) in JJA (northern hemisphere) and DJF (southern hemisphere). $\Delta T_{mean}$ are calculated from the 30-year (1981–2010) near surface mean air temperature and rainfall (Supplementary Fig. 2) using the regression model in Table 1. Tropical and polar regions in the updated Köppen-Geiger climate classification are greyed out and denoted by 'No data'. The locations of the 100 cities selected for further analysis (Fig. 3 and Supplementary Tables 3 and 4) are marked by (×).

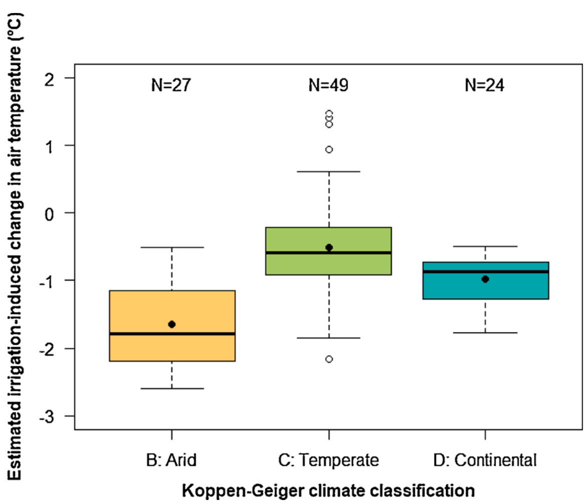


**Fig. 6.** Box-whisker plot of the estimated irrigation-induced change in mean air temperature of 100 global cities, grouped by three broad climate zones (B: Arid; C: Temperate; D: Continental). The black dots within the boxes indicate the mean.

**Table 3**
Estimated irrigation-induced change in mean air temperature of the 100 global cities by Köppen–Geiger climate classification.

| Köppen–Geiger climate classification | N | Mean | SD | Min. | Max |
|---|---|---|---|---|---|
| BWh: Arid hot desert | 8 | –2.32 | 0.27 | –2.60 | –2.15 |
| BWk: Arid cold desert | 7 | –1.59 | 0.51 | –2.29 | –1.25 |
| Dwa: Hot–summer dry–winter continental | 4 | –1.48 | 0.19 | –1.76 | –1.39 |
| BSh: Semi–arid hot steppe | 6 | –1.32 | 0.60 | –2.16 | –0.96 |
| Dsa: Hot–dry summer continental | 2 | –1.20 | 0.29 | –1.40 | –1.10 |
| BSk: Semi–arid cold steppe | 6 | –1.16 | 0.33 | –1.78 | –0.94 |
| Cwa: Dry–winter humid subtropical | 8 | –1.04 | 1.16 | –2.17 | –0.79 |
| Dfa: Hot–summer continental | 6 | –0.97 | 0.26 | –1.38 | –0.80 |
| Dwb: Warm–summer dry–winter continental | 3 | –0.92 | 0.26 | –1.14 | –0.81 |
| Dsb: Warm–dry summer continental | 1 | –0.82 | NA | –0.82 | –0.82 |
| Cfa: Humid subtropical | 9 | –0.80 | 0.35 | –1.33 | –0.61 |
| Csa: Mediterranean dry–hot summer | 7 | –0.73 | 0.31 | –1.06 | –0.51 |
| Dfb: Warm–summer continental | 8 | –0.70 | 0.18 | –1.01 | –0.58 |
| Cwb: Dry–winter subtropical highland | 6 | –0.62 | 0.32 | –1.07 | –0.50 |
| Cfb: Oceanic | 14 | –0.10 | 0.70 | –0.91 | –0.05 |
| Csc: Mediterranean dry–cold summer | 1 | –0.02 | NA | –0.02 | –0.02 |
| Csb: Mediterranean dry–warm summer | 4 | +0.30 | 0.97 | –0.90 | 0.68 |

temperature: ~15 °C) with moderate rainfall (monthly rainfall: ~60 mm).Based on the estimated cooling potentials of the 100 cities, the three climate regions with the strongest irrigation cooling potential are BWh (−2.32 °C), BWk (−1.59 °C) and Dwa (−1.48 °C) (Table 3). The three climate regions with the weakest irrigation cooling potentials are Cfb (−0.10 °C), Csc (−0.02 °C) and Csb (+0.30 °C).

## 5. Discussion

While the cooling effect of irrigation has been extensively researched from the perspective of global and regional climate change (Puma & Cook, 2010; Sugimoto et al., 2019; Thiery et al., 2017), the potential to use irrigation to mitigate heat stress in cities has yet to be evaluated in relation to the background climate of those cities. Four global studies have estimated the spatial variability of the cooling effect of agricultural irrigation (Cook et al., 2011; Puma & Cook, 2010; Sacks et al., 2009; Thiery et al., 2017) (Fig. 6). It is only possible to qualitatively compare the findings of these four global studies with our study, because they used complex climate models, whereas we used a simple regression model. In general, their findings corroborate our predictions in two irrigated regions. First, these four global studies indicate that north India and the Middle East have experienced the strongest cooling effect from agriculture irrigation (Fig. 4d in Sacks et al. (2009), Fig. 5 in Puma and Cook (2010), Fig. 6a in Cook et al. (2015) and Fig. 4a in Thiery et al. (2017)). Second, a weaker cooling effect from agriculture irrigation was predicted by these global studies for east China and the United States (same Figs. as above). The consistency between our modelling results and those in the literature suggested that our simple model can broadly capture the impact of background climate on irrigation cooling effect. Compared to the more complex and mechanistic models used in the literature, an important advantage of our model is that it was simple enough to estimate the cooling potentials for arid, continental and temperate regions using only background air temperature and rainfall data. These two types of climate data are available in most global towns and cities.

Background air temperature and rainfall were the only climate variables that remained in our model, as specific humidity, wind speed and net radiation did not have a significant relationship with air temperature reduction in this dataset of 17 irrigation studies. A significant correlation between irrigation cooling effect and background air temperature was also confirmed in a recent modelling study (Gao et al., 2020). Our model is supported by classic hydrological theory about the constraints of evapotranspiration being a function of soil moisture and energy (Budyko, 1974; Koster et al., 2009; Seneviratne et al., 2010), with soil moisture being strongly linked to rainfall and air temperature being a strong component of vapour pressure deficit which provides the 'energy' for evapotranspiration.

Frequent visits to urban green space are known to be associated with better physical and psychological health (Maas et al., 2006). Irrigating urban green spaces can improve the thermal comfort conditions, which may lead to a greater usage of the green spaces (Lin et al., 2013). However, the increase in humidity after irrigation may partially offset the air cooling benefit because a high humidity level can promote thermal discomfort (Ma et al., 2018). The overall effect of irrigation on thermal comfort is likely to also be heavily dependent on the background climate, for example the negative effect of increased humidity may be less important in dry climate regions compared to moist ones. Although tree canopy shade in urban green spaces is likely to provide a stronger and more consistent cooling effect than intermittent irrigation, there are certain places in cities where tree planting is infeasible, such as sports fields and small backyards. Therefore, it is necessary to consider using irrigation for heat mitigation in these places. Moreover, a certain level of irrigation is sometimes required for maintaining a healthy tree canopy. The potentially synergy between tree canopy shade and irrigation in urban green spaces is worthy of future research attention.

As opposed to agriculture, in which irrigation is applied regularly to meet the growth requirement of crops, irrigation of urban green spaces to provide cooling is most needed when the heat stress is strong, particularly during heatwaves. The cooling potentials predicted in this study are only representative of the mean cooling in summer (JJA for northern hemisphere or DJF for southern hemisphere). The cooling benefits of urban green space irrigation during heatwaves are yet to be determined, but there is preliminary evidence that irrigation can induce an even stronger cooling benefit during heatwaves as compared to during non-heatwave periods (Gao et al., 2020). The landscape and surface characteristics of urban green spaces are often more complex than in agricultural landscapes as they can possess multiple vegetation layers, and as such the microclimatic response of irrigating urban green spaces may also be different. A well recognised cooling benefit provided by urban green spaces is the shade cast by urban trees as well as their transpiration, and irrigation or misting are likely to enhance these existing cooling benefits (Crum & Jenerette, 2017; Santamouris et al., 2018). An urban green space with turfgrass, shrubs and tall trees will have greater aerodynamic roughness and lower reflectance to shortwave radiation (Allen et al., 2005). The presence of trees in urban green space can provide a significant cooling effect because of shading (Brown et al., 2015; Shashua-Bar et al., 2009) and the increased surface roughness can enhance the convective cooling efficiency (Gunawardena et al., 2017). Nevertheless, irrigation of urban green spaces has been recognised as an important factor in mitigating urban heat stress and promoting the park cool island effect (Bowler et al., 2010; Crum & Jenerette, 2017; Ziter et al., 2019). Furthermore, since urban trees can experience significant leaf loss during a heatwave or drought (Sanusi & Livesley, 2020), leading to a reduced shading and cooling effect (Rahman et al., 2020), irrigating urban green space may create a synergistic cooling benefit by maintaining tree canopy cover and grass cover whilst promoting evapotranspiration cooling benefits of both.

The cooling and health benefits of green space irrigation are dependent on the available area of green space in these cities as well as the accessibility and ownership of those green spaces. The proportion of a city that is green space can vary from 11 % in Birmingham, UK (Angold et al., 2006), to 34 % in Beijing, China (Yao et al., 2015) and to nearly 50 % in Stockholm and some other European cities (Fuller & Gaston, 2009). The ownership of urban green space dictates the potential for irrigation and who the beneficiaries of the irrigation cooling benefits are likely to be. For example, the fraction of open space that is privately-owned in Hong Kong is 15 % (Jim & Chan, 2016), while 60 % of the green space in Brisbane, Australia, is private (Rupprecht & Byrne, 2014).

The cultural practice of irrigation also determines the feasibility of the promotion and expansion of green space irrigation. Although we predicted that the cooling benefits of green space irrigation would be the highest in arid cities, e.g. Kuwait, Doha and Riyadh, these cities are already irrigating many urban green spaces to support the survival of the vegetation in these arid cities. The cooling benefits from urban green space irrigation predicted by our model assume that these urban green spaces are not currently irrigated, which will apply to many cities in temperate and continental regions, as well as lower socio-economic cities in arid regions. Ultimately, the feasibility, benefits and costs of urban green space irrigation will depend on the actual conditions of individual cities. In a world with increasingly limited freshwater supply (Rodell et al., 2018) and a need to protect and conserve drinking water for potable uses only, integrated water management in modern cities can increase irrigation water supply through rainwater and stormwater collection, greywater use and recycling of sewage (Griggs, 2013; Howells et al., 2013; Wong & Brown, 2009). It was estimated that over 600 kL/year/ha of stormwater can be collected from a 42 % impervious catchment in Melbourne for a storage capacity of 20 kL/ha (Mitchell et al., 2007). The collected stormwater will allow an additional 0.16 mm/day of irrigation for the same area, assuming that the water is applied evenly across that area. The additional water may be enough to meet the water demand for all vegetated area because not all surfaces are vegetated and require irrigation.

If irrigation is infeasible due to limited water availability, other heat mitigation strategies, such as expanding the size of urban green spaces and changing the vegetation composition, may be considered. Xiao et al. (2018) measured the air temperature in small ($<$ 4 ha) and large ($>$10 ha) parks in a humid subtropical region (Köppen climate classification: Cfa) in China. They found that the cooling effect of large parks (3.32 °C) was much higher than the small ones (1.75 °C). Cheung and Jim (2019) measured the air temperature impacts of three different types of vegetation (tree, shrub and grass) in a similar climate region (Cwa). They showed that an 50 % increase in tree cover can lead to a reduction in daytime mean air temperature by 0.4 °C, whereas the same increase in shrub cover can only lead to a 0.2 °C reduction and the impact of grass on air temperature is insignificant. However, similar to irrigating urban green space, the cooling potentials of these strategies are likely to be dependent on background climate. A recent review study showed that urban greening is more effective in reducing air temperature in arid climate (monthly rainfall $<$ 80 mm) than humid climate (monthly rainfall $>$ 80 mm) (Lai et al., 2019). More studies are needed to compare the cooling effect of different strategies in different climate regions. Although our predictions of cooling effect using a simple model are somewhat consistent with the results from more complex earth system models, such simplification has several major limitations. First, we were unable to include irrigation rate as an independent variable in the model because only seven cases have reported their irrigation rates (Table 1). This severely restricts the implications of the model as we do not know how much water is required to achieve the predicted cooling potentials. We estimate that the required irrigation rate should be comparable to the median (3.6 mm/day) or mean (4.5 mm/day) of the seven reported irrigation rates in the dataset, assuming that the unreported irrigation rates followed a similar distribution as the reported ones. Second, the spatial and climatic coverage of the dataset were highly limited. All but four studies were undertaken outside China or the

United States (Table 1). The small variability of the dataset prevents us from predicting the cooling potential in the tropics, where cooling is much appreciated (Matzarakis & Amelung, 2008). The accuracy of the model is also uncertain due to the limited sample size ($N = 19$). Third, the linear assumption of this simple model may generate somewhat unrealistic predictions, particularly in regions with large amounts of rainfall. The model predicted that irrigation would produce a warming effect of over 2 °C in south Peru and Madagascar mainly because of their high rainfall (>200 mm/month). However, a global modelling study showed that historic irrigation in these regions did not induce a notable warming (<0.5 °C) in air temperature (Puma & Cook, 2010). It is unlikely that the addition of a few more millimeters of moisture through irrigation will result in a strong warming effect in these relatively wet climates.

## 6. Conclusion

We showed that background climate, namely air temperature and rainfall, had a strong impact on irrigation cooling potentials in arid, temperate and continental climates. The cooling potentials were greatest in the Middle East and north India; an apparent irrigation cooling effect was also plausible for most areas in Australia, China, Europe and the United States. The cooling potentials in arid climates were much higher than temperate and continental climates, because irrigation can unleash the huge evaporative cooling potentials in soils that are otherwise moisture-limited. Our model predicted that irrigation would help mitigate heat stress in green spaces in the majority cities in the arid, temperate and continental climates.

This study has assessed the impact of irrigation on air temperature in different climate regions. The results can be useful for identifying and prioritising urban heat mitigation strategies. In contrast to urban greening, the impact of irrigating urban green spaces on air temperature has rarely been investigated explicitly (Broadbent et al., 2017; Daniel et al., 2018; Yang & Wang, 2015). While urban greening strategies, particularly tree planting, are often limited by the availability of space (Jim & Chan, 2016), irrigation can enhance the cooling effect of existing urban green space in both the public and private realm. Sufficient irrigation is also beneficial for the health of urban vegetation and the sustained delivery of their ecosystem services. Although irrigation water supply may be restricted in the dry regions, innovative water sensitive urban design can be used to increase irrigation water supply by harvesting stormwater, with subsequent irrigation and redistribution to enhance soil moisture (Coutts et al., 2013). Such water sensitive urban designs can support cities to develop climate sensitive urban design (Oke et al., 2017) to mediate extreme urban climates in a warming world. However, more irrigation studies are required across those climate zones where few or no studies have been performed, to assess the cooling potentials of irrigating green spaces in cities across a wider range of climate zones more accurately. In addition, more city-scale studies are also needed to assess the irrigation cooling potentials of specific cities according to their urban configuration, climate and water supply.

## Declaration of Competing Interest

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.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.scs.2021.102974.

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