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ORIGINAL PAPER

# The effect of urban geometry on mean radiant temperature under future climate change: a study of three European cities

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**Abstract** Future anthropogenic climate change is likely to increase the air temperature ($T_a$) across Europe and increase the frequency, duration and magnitude of severe heat stress events. Heat stress events are generally associated with clear-sky conditions and high $T_a$, which give rise to high radiant heat load, i.e. mean radiant temperature ($T_{mrt}$). In urban environments, $T_{mrt}$ is strongly influenced by urban geometry. The present study examines the effect of urban geometry on daytime heat stress in three European cities (Gothenburg in Sweden, Frankfurt in Germany and Porto in Portugal) under present and future climates, using $T_{mrt}$ as an indicator of heat stress. It is found that severe heat stress occurs in all three cities. Similar maximum daytime $T_{mrt}$ is found in open areas in all three cities despite of the latitudinal differences in average daytime $T_{mrt}$. In contrast, dense urban structures like narrow street canyons are able to mitigate heat stress in the summer, without causing substantial changes in $T_{mrt}$ in the winter. Although the $T_{mrt}$ averages are similar for the north–south and east–west street canyons in each city, the number of hours when $T_{mrt}$ exceeds the threshold values of 55.5 and 59.4 °C—used as indicators of moderate and severe heat stress—in the north–south canyons is much higher than that in the east–west canyons. Using statistically downscaled data from a regional climate model, it is found that the study sites were generally warmer in the future scenario, especially Porto, which would further exacerbate heat stress in urban areas. However, a decrease in solar radiation in Gothenburg and Frankfurt reduces $T_{mrt}$ in the spring, while the reduction in $T_{mrt}$ is somewhat offset by increasing $T_a$ in other seasons. It suggests that changes in the $T_{mrt}$ under the future scenario are dominated by variations in $T_a$. Nonetheless, the intra-urban differences remain relatively stable in the future. These findings suggest that dense urban structure can reduce daytime heat stress since it reduces the number of hours of high $T_{mrt}$ in the summer and does not cause substantial changes in average and minimum $T_{mrt}$ in the winter. In dense urban settings, a more diverse urban thermal environment is also preferred to compensate for reduced solar access in the winter. The extent to which the urban geometry can be optimized for the future climate is also influenced by local urban characteristics.

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## Introduction

Air temperature ($T_a$) is likely to increase in Europe due to the effect of human-induced climate change. According to the Intergovernmental Panel on Climate Change, global mean surface temperature is projected to increase between 1.4 and 4.8 °C by the end of the 21st century (Stocker et al. 2013). This is likely to increase the frequency, duration and magnitude of heat stress events, such as the European heat waves in 2003 and 2006, which had substantial impacts and caused heat-related health issues (D'Ippoliti et al. 2010). Watkiss et al. (2009) suggested that the heat-related death rate in Europe could double by the 2040s and potentially increase by ten times by the end of this century under the Special Report on Emissions Scenarios (SRES) A2, an emission scenario characterized by intensive energy use and a continuous increase in greenhouse-gas emission. It is important to note that the projected increases in $T_a$ across Europe are not uniform and exhibit strong seasonal differences. The largest increases in the summer are expected to be experienced in southern Europe, while the northern part of Europe is expected to experience the highest warming in the winter (Christensen et al. 2007).

The effect of urban geometry on thermal comfort has been widely addressed for different climates (Masmoudi and Mazouz 2004; Ali-Toudert and Mayer 2006; Pearlmutter et al. 2007a, b; Andrade and Alcoforado 2008; Holst and Mayer 2011; Krüger et al. 2011; Lindberg and Grimmond 2011; Thorsson et al. 2011). However, the thermal comfort performance of urban geometry across different climates has rarely been studied (Katzschner 2010). As a result of differences in climatic conditions and urban geometry, the effect of future climate change on outdoor thermal comfort varies across climatic regions. Thorsson et al. (2011) found that open built structure leads to a larger increase in numbers of hours with strong or extreme heat stress, while street canyons shaded by surrounding buildings are more comfortable. Mitigating heat stress in urban areas requires a better understanding of the optimal urban geometry for the particular climatic region.

Mean radiant temperature ($T_{mrt}$), as one of the most important meteorological parameters that governs human energy balance and outdoor thermal comfort during warm and clear weather, has been widely adopted for urban thermal comfort studies (Masmoudi and Mazouz 2004; Thorsson et al. 2004, 2007; Emmanuel et al. 2007). The spatial variation of $T_{mrt}$ within urban environments is primarily determined by the shadow patterns generated by vegetation, buildings and topography and also by surface materials (Lindberg and Grimmond 2011). $T_{mrt}$ shows spatial variations over short distances, especially within a complex urban environment (Lindberg et al. 2013). Thorsson et al. (2014) found that daily maximum $T_{mrt}$ was a better predictor of heat-related mortality for people aged 80 years and above than maximum $T_a$, implying that $T_{mrt}$ better describes the weather conditions that generate daytime heat stress. This makes $T_{mrt}$ a good measure for identifying urban hot spots.

Global climate models (GCMs) are the best tools available for estimating future global climate changes. However, their spatial resolution is currently in the range of 150–300 km. This resolution is too coarse to study the impacts of climate change on societies at the urban scale. Various 'downscaling' techniques have therefore been developed in order to provide information on finer spatial scales. These methods are generally divided into dynamical and statistical techniques. In statistical downscaling, observed term series are used to establish an empirical relationship between local variables and large-scale atmospheric features such as the regional wind or pressure patterns, which GCMs can skilfully simulate (Benestad et al. 2008). Once these relationships are established from observations, they may be used to obtain local climate information from the large-scale GCMs.

Another way to generate higher resolution climate change scenarios is by dynamical downscaling, where a high-resolution regional climate model (RCM) is forced by GCM outputs. Recently, regional climate change scenarios for Europe have been created within the ENSEMBLES project (Van Der Linden and Mitchell 2009) using dynamic downscaling. The RCMs used had a resolution of 25–50 km which, for many local applications such as urban design, is still too coarse. Another problem with using RCMs for climate change impact assessments is that their outputs are biased compared to the observed, real-world climate, so bias correction is often required (e.g. Teutschbein and Seibert 2010). For example, Rivington (2008) found that HadRM3 systematically overestimated solar radiation. As a result, it is becoming more common to apply statistical downscaling/bias correction algorithms to dynamically downscaled outputs from RCMs (e.g. Yang et al. 2010).

The aim of the present study is to investigate the effect of urban geometry on daytime $T_{mrt}$—the radiant component of outdoor thermal comfort—in three European cities (Gothenburg in Sweden, Frankfurt in Germany and Porto in Portugal) under present and future climatic conditions. $T_{mrt}$ was simulated by using the solar and longwave environmental irradiance geometry (SOLWEIG) model (Lindberg et al. 2008; Lindberg and Grimmond 2011) for designated study sites in the three cities The implications of future climate change on outdoor heat stress are also discussed. The study concludes with urban planning and design recommendations for minimizing heat stress in the three cities. This study is part of the Urban-NET project, entitled 'Potential impact of climate trends and weather extremes on outdoor thermal comfort in European cities—implications for sustainable urban design', which examines the effects of urban morphology and vegetation on outdoor heat stress at urban and street levels and also incorporates the effects of regional climate change. It aims to develop a set of policies and design guidelines for maintaining health and thermal comfort under changing climate conditions and extreme weather events for European cities.

## Materials and methods

### Study areas

Three European cities, namely Gothenburg in Sweden (57.7° N, 12.0° E), Frankfurt in Germany (50.1° N, 8.7° E) and Porto in Portugal (41.2° N, 8.6° E), were selected to represent northern, central and southern European climates in this study. As the present paper aims to compare the effect of large-scale climatic conditions on $T_{mrt}$ in the three cities under different urban settings, they are selected due to the difference in large-scale climatic conditions. For example, the difference in $T_a$ is due to latitudinal difference and solar elevation, which leads to more intense incoming solar radiation. Such a difference in $T_a$ affects the modelling of longwave radiation in a complex urban area. However, regional cloudiness also affects the simulation of radiant fluxes and subsequently $T_{mrt}$. Figure 1 shows the monthly average of mean $T_a$, water vapour pressure and global, diffuse and direct solar radiation for the three cities. Gothenburg has a marine west-coast climate with milder winters and cooler summers compared to other places with similar latitude. Mean $T_a$ is 15.9 °C in the summer (June to August) and 0.8 °C in the winter (December to February). The driest months are observed in the spring and summer. Solar radiation peaks in late spring and summer, with the highest diffuse radiation observed in the summer due to high cloudiness in the region. Frankfurt has a temperate oceanic climate with slightly warmer winters than Gothenburg. It is generally drier than Gothenburg due to its more inland location. Summer and winter mean $T_a$ is 19.7 and 2.1 °C, respectively. Solar radiation is slightly higher than that in Gothenburg except in April when direct radiation is lower. Porto has a Mediterranean climate with dry summers and wet winters. Mean $T_a$ is 19.6 °C in the summer and 10.0 °C in the winter. Porto has the highest solar radiation of the three cities (all three components) due to the high sun altitude.

The study areas are located in the central parts of the three cities (Fig. 2). They are generally characterized by relatively flat topography, high building densities and average building heights (Table 1). Four point locations with different urban settings were selected in each city in order to examine the effect of urban geometry on $T_{mrt}$, including a north–south (N-S) orientated street canyon, an east–west (E-W) orientated street canyon, a large open square and a courtyard. These locations are selected to represent the typical urban settings in the three cities, and they are generally comparable despite of the higher sky view factor (SVF) of the open square in Gothenburg (SVF=0.95) and the lower SVF of the courtyard in Frankfurt (SVF=0.53).

## Meteorological data

Two sets of meteorological data are used. The first set is composed of hourly meteorological data, including $T_a$, solar radiation (global and diffuse components) and relative humidity, recorded in each city. Meteorological information of Gothenburg was obtained from the meteorological station operated by the Swedish Meteorological and Hydrological Institute (SMHI). It is located within the city of Gothenburg approximately 1.5 km east of the city centre. In Frankfurt, the meteorological station is operated by the Hessische

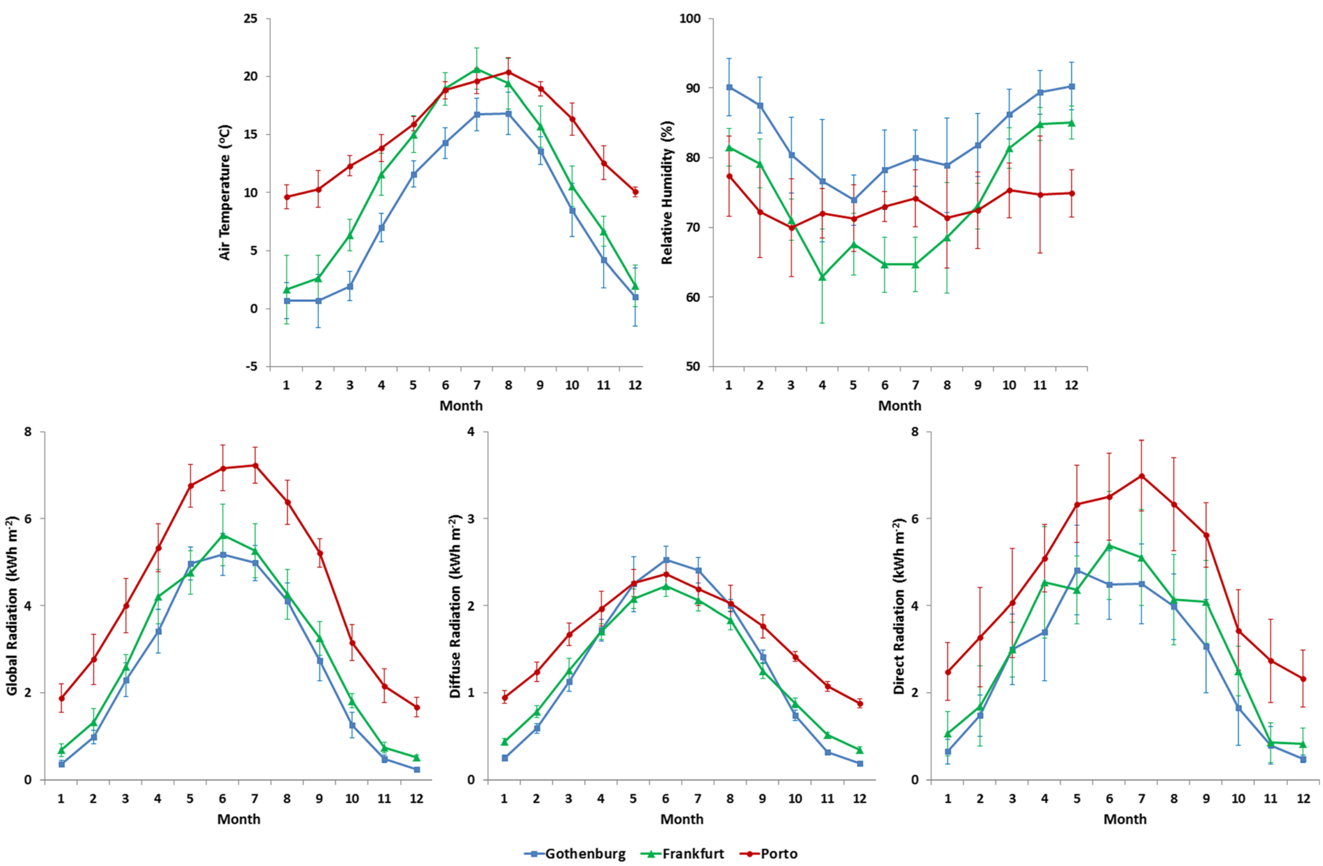


**Fig. 1** Monthly average of daily mean air temperature, water vapour pressure and global, diffuse and direct solar radiation in Gothenburg, Frankfurt and Porto, with error bars denoting the standard deviation. The reference period is 2003–2010 except for solar radiation data of Gothenburg due to the closing down of the meteorological station

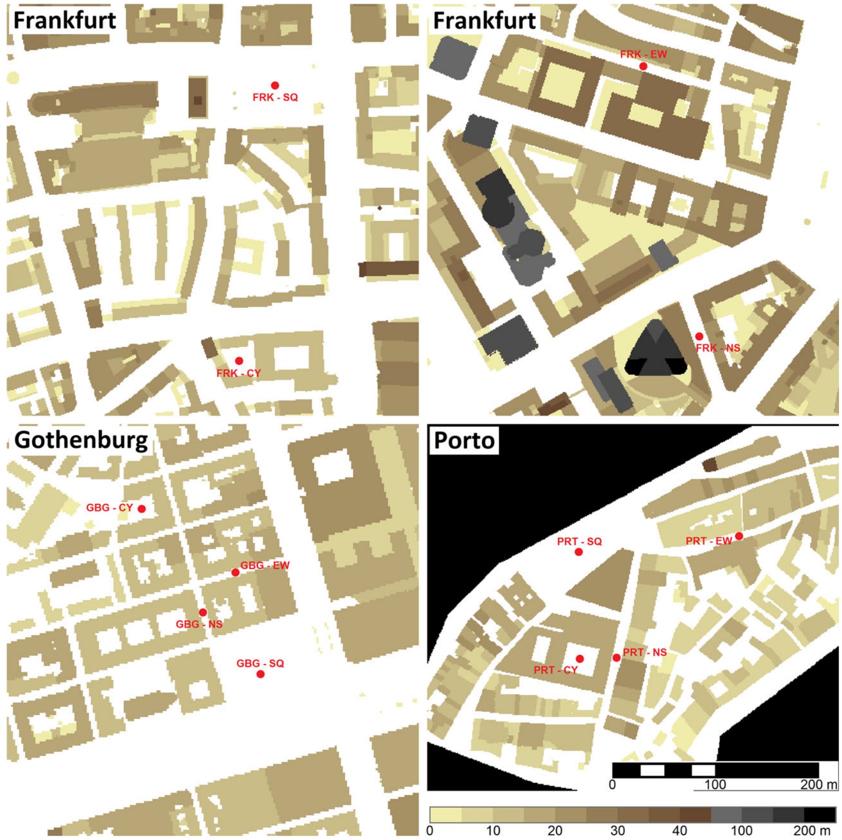


**Fig. 2** Location of the study sites which are denoted in *red dots* in the figure

Landesanstalt für Umwelt und Geologie (HLUG). It is situated in Höchst, an industrial district located about 10.2 km west of the city centre. In Porto, the meteorological station is located at the airport (Pedras Rubras), about 15 km north-west of the city centre. It is operated by the Instituto Português do Mar e da Atmosfera (IPMA). The observation periods are 1998–2005 for Gothenburg and 2003–2010 for Frankfurt and Porto. These records are used to simulate the spatial variation of $T_{mrt}$ for the present-day climate. It is noted that the earlier period for Gothenburg is due to the closing down of the meteorological station in Gothenburg, which leads to the lack of solar radiation data from 2005 onwards. Therefore, the latest 8 years (1998–2005) of the record is chosen to represent the present-day climate of Gothenburg and for the input of the

**Table 1** Information about the study areas and sky view factor of the study locations

| | Study area | | | | Street canyon | |
|---|---|---|---|---|---|---|
| City | Built-up fraction (%) | Average building height (m) | Average street width (m) | Location | SVF | H/W ratio |
| Gothenburg | 49.8 | 15.3 | 23.7 | N-S street | 0.26 | 1.36 |
| | | | | E-W street | 0.29 | 1.06 |
| | | | | Open square | 0.95 | |
| | | | | Courtyard | 0.60 | |
| Frankfurt | 43.9 | 17.4 | 22.8 | N-S street | 0.26 | 1.55 |
| | | | | E-W street | 0.30 | 1.36 |
| | 57.6 | 30.8 | 23.0 | Open square | 0.88 | |
| | | | | Courtyard | 0.53 | |
| Porto | 49.9 | 12.7 | 12.1 | N-S street | 0.28 | 1.64 |
| | | | | E-W street | 0.29 | 1.68 |
| | | | | Open square | 0.88 | |
| | | | | Courtyard | 0.59 | |

SOLWEIG model. The second set of meteorological data is obtained by statistical downscaling of future climate scenarios as described in the following section. The entire observation periods are then used for subsequent statistical downscaling and spatial modelling of $T_{mrt}$ as well as the analysis of the effect of urban geometry on urban thermal environment at different temporal scales.

## Future climate scenarios

A future climate scenario was created for each city by combining change factors derived from RCM outputs with meteorological observations of $T_a$ and three-component solar radiation (global, diffuse and direct), using the method of Rayner et al. (2014). With this method, change factors are first calculated from differences in ranked daily RCM outputs for a future period (2070–2098) and a present-day period (the period of the historical record). Changes consistent with these daily factors are then applied to historical hourly meteorological observations to create hourly future scenarios. A summary of the method is given below. The scenarios are based on outputs from the European Centre for Medium-Range Weather Forecasts, Hamburg (ECHAM) 5/Max Planck Institute ocean model (MPI-OM) GCM (Roeckner et al. 2003) forced with the SRES A1B greenhouse-gas emission scenario, downscaled to 25-km resolution with the Rossby Centre Regional Atmospheric Climate Model (RCA) (Kjellström et al. 2005). The SRES A1 scenario describes rapid, global economic development. Summer temperature in northern Europe is expected to increase by at least 2 °C by 2100 if greenhouse-gas emissions follow the SRES A1B scenario (Meehl et al. 2007). The A1B scenario corresponds to a ‘mid-range’ reference scenario (that is, a scenario without deliberate greenhouse-gas mitigation actions) in the context of more recent scenario modelling (Moss et al. 2010).

For $T_a$, the hourly scenarios were created by interpolating the change factors for daily maximum and minimum $T_a$. That is, for each day in the historical record, a change factor for the daily maximum $T_a$ was determined from the ranked changes in the RCM maximum $T_a$ outputs. Change factors for the minimum $T_a$ for each day were similarly determined. These series of change factors were then combined, and change factors for every hourly temperature value in the historical record were derived using linear interpolation.

For three-component radiation, the procedure was more complicated. This was firstly because the RCM outputs do not separate solar radiation into direct and diffuse components and secondly because change factors need to be derived in such a way that the modified global, diffuse and direct radiation remains self-consistent. In summary, change factors for daily global radiation were first calculated for each day in the historical record based on differences in ranked daily incoming shortwave radiation for RCM present-day and future outputs. The global radiation change factor for a given day was applied to all hourly global radiation values for that day. To calculate change factors for the hourly diffuse radiation values, the diffuse radiation was estimated from the global radiation using the method of Reindl et al. (1990), for both the observed and modified (future) hourly global radiation. The ratio of these estimates is the change factor that is applied to the observed historical diffuse radiation. Finally, the direct radiation component for the future scenario was determined from the future global and diffuse radiation components. In addition, estimation of $T_{mrt}$ in SOLWEIG (see below) is most sensitive to $T_a$ and shortwave radiation, whereas it is almost unaffected by air humidity (Onomura et al. 2014). Thus, the climate scenarios use the unmodified observed hourly relative humidity.

## Numerical modelling

The study areas are 400×400 m for Gothenburg and Frankfurt and 370×400 m for Porto. The SOLWEIG model (version 2013a) used in this study simulates spatial variations of three-dimensional radiation fluxes and $T_{mrt}$ as well as shadow patterns and SVFs in complex urban settings. It was previously evaluated in Lindberg et al. (2008) and Lindberg and Grimmond (2011) for a number of locations in Gothenburg and also in Germany (Freiburg and Kassel). The model requires hourly weather time series for variables $T_a$, relative humidity and global and diffuse solar radiation together with a 1-m-resolution digital surface model (DSM) and geographical location (i.e. latitude, longitude and altitude). $T_{mrt}$ is calculated for a standing person, with the factors specifying the proportion of radiation received from each direction set to 0.22 for east, west, north and south and 0.06 for radiation fluxes from above and below. Absorption coefficients for shortwave and longwave radiation are 0.7 and 0.97, respectively (Höppe 1992). Albedo and emissivity for buildings and vegetation are 0.20 and 0.95, respectively (Oke 1987). The transmissivity of shortwave and longwave radiation through vegetation is 5 and 0 %, respectively (Lindberg and Grimmond 2011). Neither wind field nor variations in ground or building wall materials are considered in the current version of the model. For a detailed description of the SOLWEIG model, see Lindberg et al. (2008) and Lindberg and Grimmond (2011).

## Quantification of heat stress in terms of mean radiant temperature

Thorsson et al. (2014) showed that high daily maximum $T_{mrt}$ values for a generic urban location are associated with an increased relative risk of mortality in Stockholm, Sweden. There is an increase of 5 % in relative risk of mortality when daily maximum $T_{mrt}$ exceeds 55.5 °C for the eldest population

(80+). When daily maximum $T_{mrt}$ exceeds 59.4 °C, the relative risk of mortality increases to 10 %. Similar thresholds were also reported for Porto, Portugal (Monteiro et al. 2012). In the present study, $T_{mrt} \geq 55$ °C at a study site is taken to indicate moderate heat stress at that site and $T_{mrt} \geq 60$ °C to indicate severe heat stress, and we report the number of hours per year when $T_{mrt}$ exceeds these two thresholds for the present and future climate scenario.

In addition, we introduce the metric overheating degree–hours (ODH), which is calculated with respect to thresholds for moderate and extreme heat stress by using the equation

$$ODH = \sum_{i=1}^{N} \begin{cases} T_i - T_b, & T_i > T_b \\ 0, & T_i \leq T_b \end{cases}$$

where $T_i$ is the hourly $T_{mrt}$, $T_b$ the $T_{mrt}$ threshold and $N$ the total number of hours in the study period. Results are expressed as overheating degree–hours per year.

Finally, the frequency of occurrence per year of five consecutive days when $T_{mrt}$ is higher than the two thresholds of $T_{mrt}$ is also recorded to indicate the possible occurrence of heat waves under present and future climates.

## Results

### Intra-urban differences in mean radiant temperature

The seasonal statistics of daytime average (from sunrise to sunset) $T_{mrt}$ for the 12 study locations under clear-sky conditions are shown in Table 2. The squares generally have the highest $T_{mrt}$ across all seasons, followed by courtyards except for the winter in Frankfurt and Porto. These two locations also have larger standard deviation (SD) than the street canyons, implying that very different thermal conditions occur in more open locations during the day. There are no considerable differences in daytime $T_{mrt}$ between two street canyons. However, daytime maximum $T_{mrt}$ of the N-S canyons is higher than that of the E-W canyons in all seasons, with the greatest difference (14.7 °C) observed in the winter in Porto.

In Gothenburg, the highest daily daytime mean $T_{mrt}$ is observed in the open square in the summer, which is 10.7 and 10.1 °C higher than the N-S and E-W canyons, and the mean $T_{mrt}$ of the courtyard is higher than those of the street canyons (28.5 °C). It is primarily due to the longer exposure to incoming shortwave radiation and longwave radiation from the ground surface. A similar pattern is observed in the other three seasons despite that mean $T_{mrt}$ is higher in the N-S canyon than in the E-W canyon in autumn and winter. It is notable that the daily daytime maximum $T_{mrt}$ observed in the N-S canyon is considerably higher (3.8 °C) than that in the E-W canyon in the winter, which is a result of the lower sun altitude in the winter, so incoming solar radiation is blocked by buildings to the south of the E-W canyon.

In Frankfurt, the spatial pattern is similar to that in Gothenburg with the highest daily daytime mean $T_{mrt}$ observed in the square (35.5 °C) in the summer and lower mean $T_{mrt}$ observed in N-S and E-W canyons (24.8 and 25.4 °C, respectively). Mean $T_{mrt}$ of the E-W canyon is slightly higher than that of the N-S canyon (0.6 °C) due to the reflected shortwave radiation during most of the daytime period. The courtyard exhibits lower mean $T_{mrt}$ than the street canyons in the winter (−1.0 °C) due to the lower sun altitude. In addition, the N-S canyon has higher daily daytime maximum $T_{mrt}$ than the E-W canyon throughout the year since it is sunlit when the sun is at its highest altitude at noon, resulting in a large amount of both direct and reflected shortwave radiation reaching the street canyon. In contrast, the southern side of the E-W canyon is permanently under shading, leading to lower daily daytime maximum $T_{mrt}$.

In Porto, the square has the highest daily daytime mean $T_{mrt}$ among the three cities. In the summer, mean $T_{mrt}$ observed in the square is 43.5 °C, about 15 °C higher than that in both street canyons. SD of the open square is lower than those observed in Gothenburg and Frankfurt. It is possibly due to the higher $T_a$ in Porto, which prevents the release of longwave radiation from the canyon surface even when they are not sunlit. The N-S canyon has higher daily daytime maximum and mean $T_{mrt}$ than the E-W canyon throughout the year except in the summer. It also has a larger swing of $T_{mrt}$ than the E-W canyon since the E-W canyon is shaded by the tall buildings in the south. Nonetheless, SD of the street canyons is lower than that of more open locations, suggesting that denser urban structures are able to mitigate the swing of $T_{mrt}$ during daytime.

### Diurnal variation of mean radiant temperature

Figure 3 shows the diurnal variation of $T_{mrt}$ at selected study sites during daytime on a clear summer day. In Gothenburg, the large open square generally has higher $T_{mrt}$ than the street canyons during daytime since it is sun-exposed. $T_{mrt}$ of the courtyard starts to increase when it is sunlit at 8 h and becomes slightly higher than that observed in the square due to the longwave radiation emitted from surrounding building walls. The N-S canyon only receives solar radiation when it is sunlit at midday. For the E-W canyon, high $T_{mrt}$ is observed in the afternoon due to high $T_a$ and sun exposure. It is notable that $T_{mrt}$ is similar in all four locations when it is sun-exposed.

In Frankfurt, the diurnal variation and magnitude of $T_{mrt}$ observed in the open square are similar to that observed in Gothenburg. The courtyard has higher $T_{mrt}$ than the square at midday due to the multiple reflection of shortwave and

**Table 2** Seasonal average of daily daytime (from sunrise to sunset) maximum, mean, minimum and standard deviation of $T_{mrt}$ (°C) of four urban settings (NS, north–south-orientated street; EW, east–west-orientated street; SQ, open square; CY, courtyard) under clear sky conditions in Gothenburg, Frankfurt and Porto

| | Gothenburg | | | | Frankfurt | | | | Porto | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NS | EW | SQ | CY | NS | EW | SQ | CY | NS | EW | SQ | CY |
| Spring | | | | | | | | | | | | |
| Max | 25.1 | 20.8 | 36.8 | 26.4 | 30.8 | 25.1 | 42.0 | 32.7 | 41.5 | 33.2 | 48.0 | 44.9 |
| Mean | 10.6 | 10.7 | 22.8 | 13.1 | 16.8 | 16.4 | 29.3 | 19.0 | 21.5 | 20.6 | 34.4 | 27.7 |
| Min | 3.0 | 2.7 | −1.5 | 0.0 | 8.2 | 8.1 | 6.8 | 6.1 | 10.4 | 10.2 | 8.9 | 8.3 |
| SD | 10.5 | 11.1 | 19.2 | 16.5 | 12.2 | 10.7 | 18.2 | 16.9 | 11.7 | 9.8 | 16.5 | 17.1 |
| Summer | | | | | | | | | | | | |
| Max | 33.1 | 34.0 | 46.4 | 40.9 | 39.3 | 37.8 | 50.0 | 45.0 | 50.8 | 46.2 | 55.0 | 53.3 |
| Mean | 19.7 | 20.7 | 31.3 | 25.5 | 24.8 | 25.4 | 35.5 | 28.5 | 28.8 | 28.9 | 43.5 | 36.4 |
| Min | 11.5 | 11.3 | 6.4 | 8.5 | 15.1 | 14.8 | 12.1 | 12.8 | 15.8 | 15.8 | 15.0 | 13.6 |
| SD | 9.5 | 10.1 | 18.7 | 16.3 | 11.6 | 10.7 | 17.9 | 16.9 | 11.5 | 9.9 | 14.0 | 16.4 |
| Autumn | | | | | | | | | | | | |
| Max | 16.5 | 12.2 | 24.6 | 13.2 | 24.6 | 16.4 | 30.6 | 19.3 | 39.2 | 25.8 | 44.9 | 34.5 |
| Mean | 9.7 | 8.9 | 14.9 | 7.8 | 14.6 | 13.2 | 21.7 | 13.1 | 21.3 | 19.2 | 29.8 | 22.6 |
| Min | 5.7 | 5.4 | 0.4 | 2.4 | 9.4 | 9.0 | 6.3 | 7.1 | 12.1 | 12.0 | 9.3 | 9.6 |
| SD | 9.1 | 8.1 | 18.6 | 11.3 | 10.2 | 7.8 | 18.4 | 11.5 | 11.3 | 7.5 | 16.6 | 14.6 |
| Winter | | | | | | | | | | | | |
| Max | 3.6 | −0.2 | 7.9 | −1.9 | 8.1 | 1.9 | 4.1 | 0.9 | 28.6 | 13.9 | 33.3 | 14.8 |
| Mean | −0.6 | −1.3 | −0.3 | −3.7 | 2.1 | 0.7 | −0.7 | −1.0 | 12.7 | 10.9 | 17.7 | 10.7 |
| Min | −2.7 | −3.0 | −9.3 | −6.2 | −0.5 | −1.1 | −6.4 | −3.4 | 5.9 | 5.8 | 3.5 | 3.7 |
| SD | 7.1 | 5.1 | 15.4 | 5.6 | 8.4 | 5.1 | 14.4 | 5.9 | 8.8 | 4.5 | 13.6 | 5.4 |

longwave radiation. High $T_{mrt}$ is observed in the E-W canyon in the morning when it receives incoming solar radiation. Similar to Gothenburg, high $T_{mrt}$ is only observed at midday when it is sunlit. $T_{mrt}$ of the street canyons and courtyard is found to be higher than that observed in the square when these locations are sunlit.

In Porto, the highest $T_{mrt}$ is observed (over 60 °C) in the N-S canyon at 13 h due to the intense solar radiation reaching the canyon surface. The street canyons generally exhibit lower $T_{mrt}$, which is approximately 20 °C lower than that of the square, when it is shaded, especially for the E-W canyon due to the tall buildings in the south. The courtyard has higher $T_{mrt}$ than the square from 10 to 14 h due to the longwave radiation emitted from the sunlit surface. On a clear summer day, longwave radiation from sunlit building walls and ground surface plays an important role in such high $T_{mrt}$.

Figure 4 compares the diurnal variation of both sides of the N-S and E-W canyons in the three cities. For the N-S canyons, high $T_{mrt}$ (near 60 °C in Frankfurt and Porto) is observed on the western side when it is sunlit in the morning. As sun altitude increases, the eastern side of the N-S canyons receives sunlight at 11 and 13 h in Gothenburg and Porto, respectively. The earlier peak in $T_{mrt}$ in Gothenburg is due to the slightly north-west–south-east orientation which allows solar radiation reaching the eastern side before noon. In contrast, the slightly north-east–south-west orientated canyon in Porto results in the later peak in $T_{mrt}$. In Frankfurt, the eastern side of the N-S canyon is shaded by the tall buildings in the west. Therefore, no obvious peak in $T_{mrt}$ is observed despite of the slight increase due to higher $T_a$ at noon.

For the E-W canyon, the northern side is sunlit throughout the day in Gothenburg and Porto, resulting in high $T_{mrt}$ up to 64.6 °C in Porto. In Frankfurt, the tall buildings on the southern side only allow solar radiation reaching the canyon surface in the morning since it is slightly orientated towards north-west. Incoming solar radiation is then blocked from 11 h, leading to a drop in $T_{mrt}$ under 40 °C. The southern side of the E-W canyon receives 1 hour of sunlight (2 hours in Porto) since the street canyons are slightly orientated to either north-west–south-east (Frankfurt) or north-east–south-west (Gothenburg and Porto). It implies that the southern side of the E-W canyon is free of heat stress for most of the day, especially in Porto where a reduction of 20 °C in $T_{mrt}$ is observed when it is shaded.

## Effect of future climate change

Under the future climate scenario, $T_a$ increases in all three cities throughout the year. The changes in $T_a$ exhibit substantial seasonality in Frankfurt and Porto (Fig. 5). Higher increases are observed in December and January (4.1 and 3.6 °C, respectively) in Frankfurt, while warming is higher during summer months in Porto (approximately 3.3 °C). The warming in Frankfurt is anomalously low in April (about

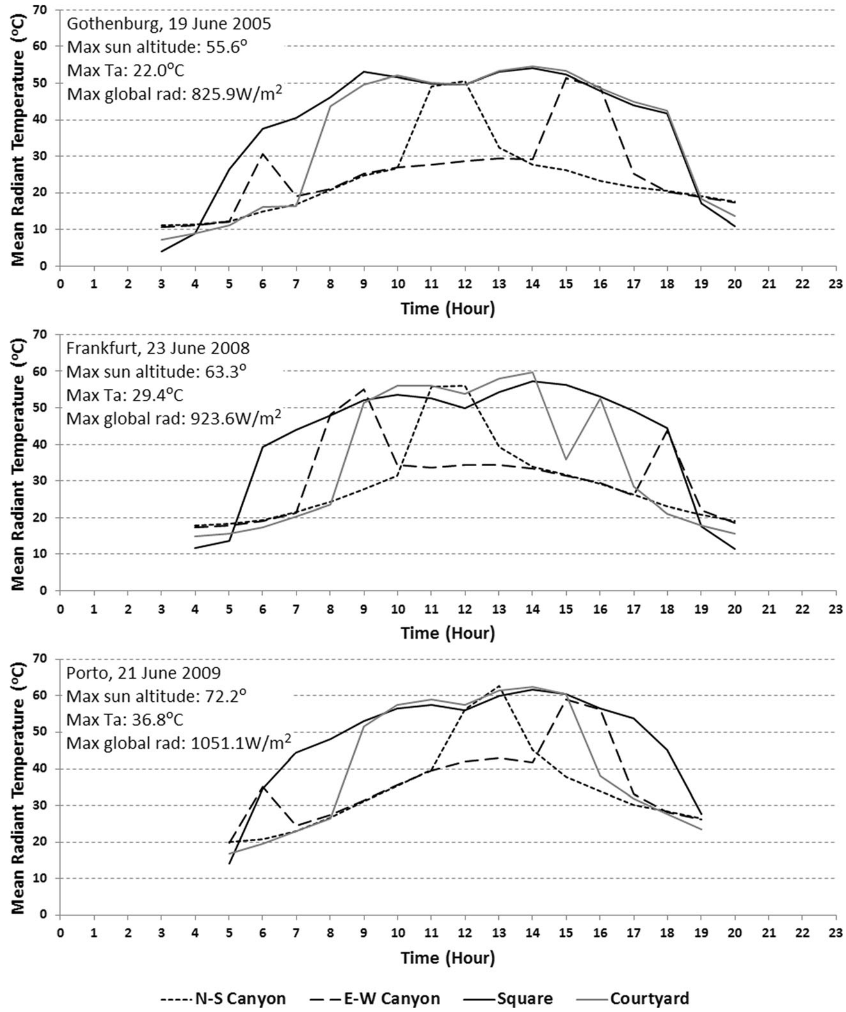


**Fig. 3** Mean radiant temperature of N-S and E-W-orientated street canyons, square and courtyard of the three cities from sunrise to sunset on a clear summer day

1 °C). On the other hand, warming is relatively constant throughout the year in Gothenburg with slightly higher increases in January, February and March (2.6–2.7 °C). There is a reduction in global radiation in Gothenburg and Frankfurt in the RCA scenario, likely due to the increase in regional cloudiness on both cloudy and clear days under the downscaled scenario. Because diffuse radiation is low on clear days, the effect of increasing cloudiness is that diffuse radiation increases in the spring and summer months in Gothenburg (0.4–2.5 W $m^{-2}$), while increases occur in the spring in Frankfurt (up to 3.4 W $m^{-2}$). The changes in direct radiation are quantitatively similar to the changes in global radiation. In contrast, global radiation increases in Porto, with increases by almost 10 W $m^{-2}$ in May–June. A more detailed investigation of the RCA outputs revealed that this increase represents a large decrease in cloudiness on cloudy days, which more than compensates for a small increase in cloudiness on clear days. As a result of these changes, there is a substantial decrease in diffuse radiation from April to June and from October to November in the downscaled scenario.

Climate change does not considerably change the intra-urban differences in $T_{mrt}$ among four study sites of each city (except for the square in Gothenburg). However, the effect of climate change on $T_{mrt}$ is unevenly distributed across cities as well as seasons in the downscaled scenario (Fig. 6). In Gothenburg, under the downscaled scenario, the street canyons and courtyard experience increases in $T_{mrt}$ ranging from 0.4 to 2.5 °C, with lower increases observed in late spring and summer. No large changes in $T_{mrt}$ are observed for the square despite of the increases in the winter (about 2 °C) as well as in June and September (about 1 °C). In Frankfurt, there are no notable differences between four study sites, despite the relatively higher $T_{mrt}$ in the E-W canyon in March and October (1.1 and 2.2 °C, respectively). $T_{mrt}$ increases in the summer, fall and winter but decreases in the spring. In Porto, $T_{mrt}$ increases throughout the year. No notable differences in changes in $T_{mrt}$ are found between two street canyons in Porto, while the square has higher increases in the summer and autumn. A smaller $T_{mrt}$ increase is observed in the courtyard in late summer and autumn (1.8 to 2.8 °C).

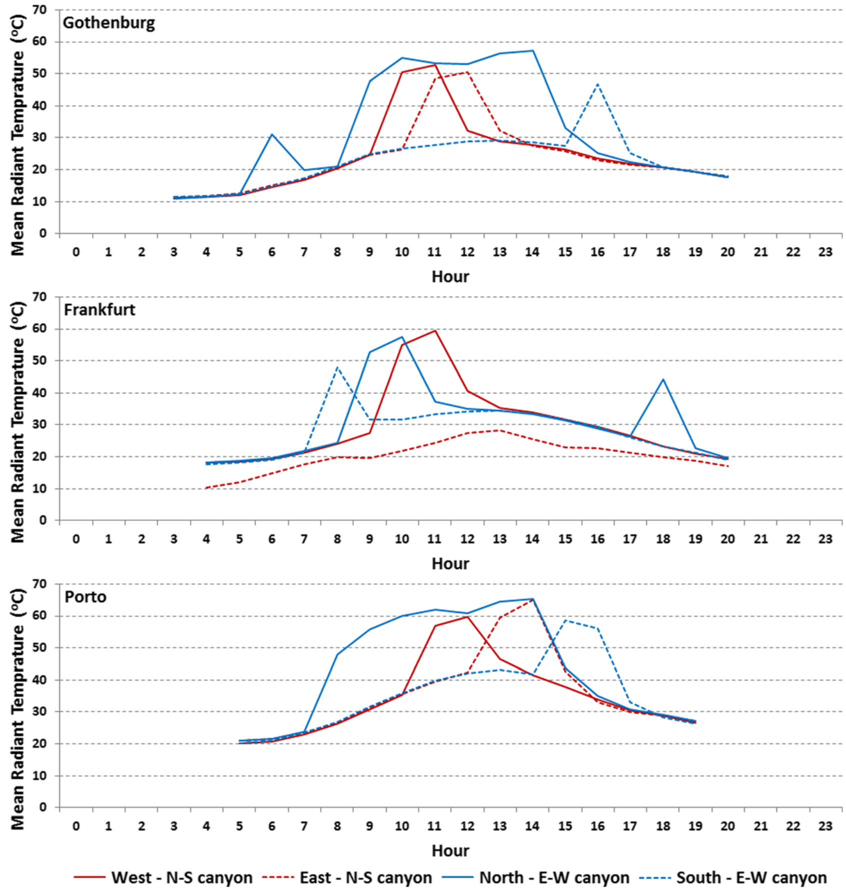


**Fig. 4** Mean radiant temperature of both sidewalks of the N-S and E-W-orientated street canyons of the three cities from sunrise to sunset on a clear summer day

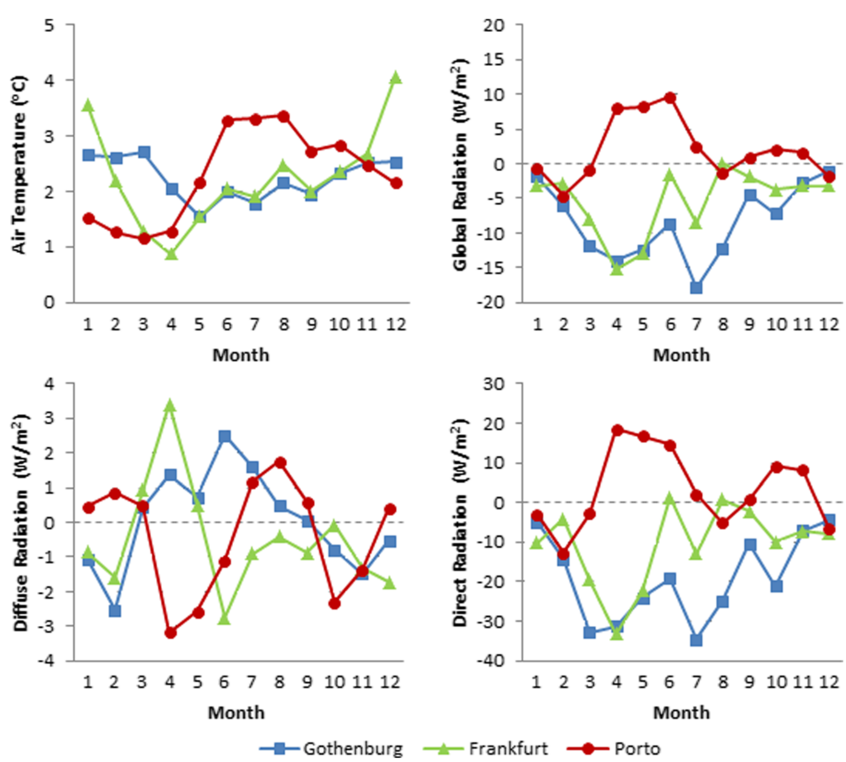


**Fig. 5** Changes in air temperature and global, diffuse and direct radiation from observation to future (2070–2098) period in Gothenburg, Frankfurt and Porto. Downscaled scenarios are based on ECHAM5 GCM run 3 forced with an SRES A1B scenario, downscaled using the RCA3 RCM

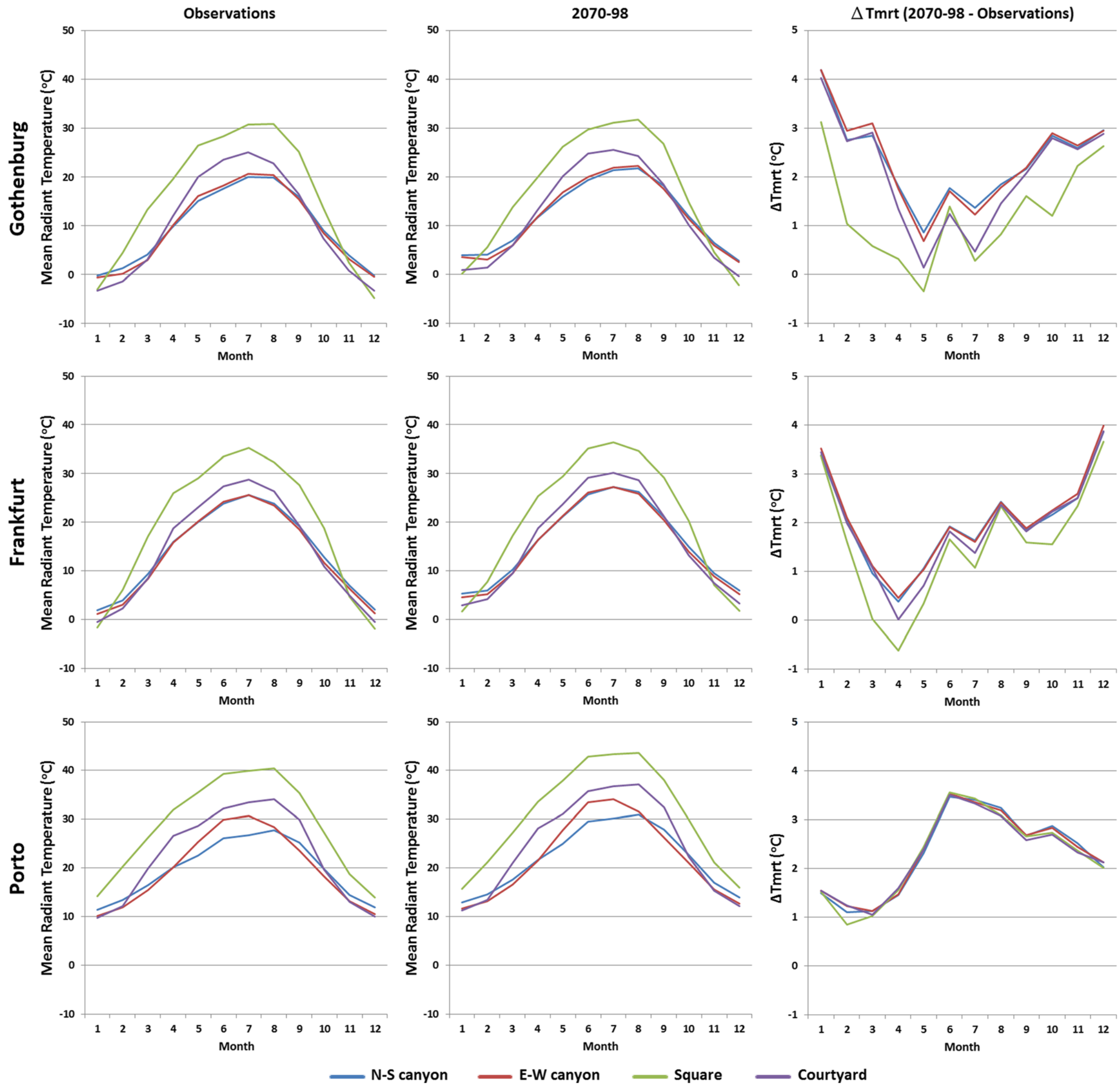


**Fig. 6** Monthly average of daytime $T_{mrt}$ of four urban settings under present and future climates. Differences between the two periods are shown in the *third column*

In order to examine the sensitivity of $T_{mrt}$ to future climatic conditions, the difference in daytime $T_{mrt}$ between observed climate and future $T_a$ and/or shortwave radiation ($R$) is compared (Fig. 7). It is clearly shown that the $T_{mrt}$ obtained from future $T_a$ and observed $R$ ($T_{2070}R_{obs}$) is generally higher than the observed climate throughout the year, while the $T_{mrt}$ calculated using observed $T_a$ and future $R$ ($T_{obs}R_{2070}$) is lower in Gothenburg and Frankfurt, and slight increase is observed in Porto. The changes in the $T_{mrt}$ calculated using future climate for both $T_a$ and $R$ ($T_{2070}R_{2070}$) closely resemble those obtained by future $T_a$ and observed $R$ ($T_{2070}R_{obs}$), except for the open squares in Gothenburg and Frankfurt, for which changes in future solar radiation are also important. $T_{mrt}$ calculated from $T_{obs}R_{2070}$ is lower than that from $T_{2070}R_{2070}$ (by up to 3.5 °C) for three cities.

## Heat stress conditions under future climate

Table 3 shows the number of hours per year with $T_{mrt}$ above 55.5 °C (moderate heat stress) and 59.4 °C (severe heat stress) under present and future climates. The squares and courtyards in Gothenburg and Frankfurt would experience over 40 % increase in the number of hours of moderate heat stress. It is notable that the percentage increase in the number of hours of severe heat stress is doubled (except the negligible increase in the courtyard in Gothenburg). For the square and courtyard in Porto, the increases in the numbers of hours of moderate and severe heat stress are about 160 and 300 %, respectively. In comparison to more open locations, the number of hours of heat stress in the street canyons in Gothenburg is negligible, suggesting that narrow street canyons are not affected by heat stress in the future. In Frankfurt, there are 20 and 5 h of moderate heat stress in the N-S and E-W canyons under the

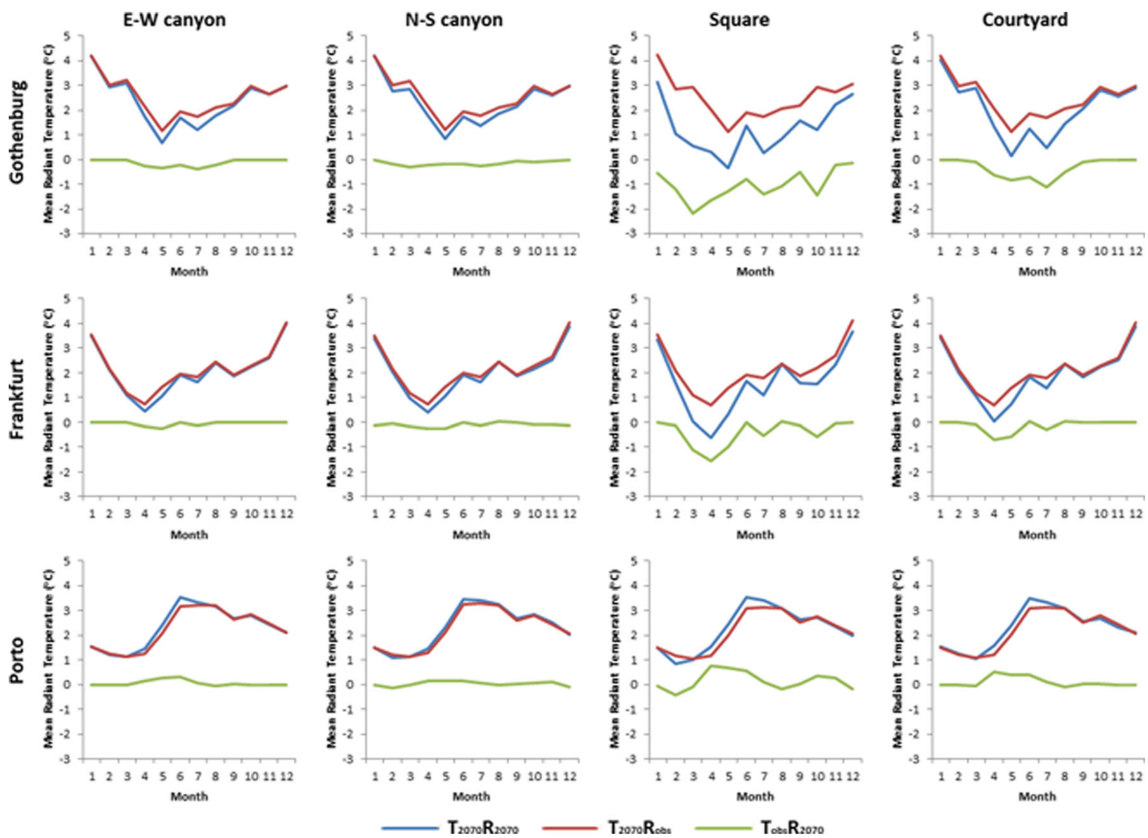

**Fig. 7** Sensitivity test using the difference between observed daytime $T_{mrt}$ and $T_{mrt}$ calculated from future $T_a$ with observed shortwave radiation ($T_{2070}R_{obs}$, *red line*), observed $T_a$ with future shortwave radiation ($T_{obs}R_{2070}$, *green line*) and both future $T_a$ and shortwave radiation ($T_{2070}R_{2070}$, *blue line*)

present climate, which increase by 18 and 7 h, respectively. A similar situation is seen for Porto, but it is notable that there is also a considerable increase in the number of hours of severe heat stress in the N-S canyon (13 h).

ODH per year, calculated with respect to the two thresholds, is shown in Table 4 for the present and future climates. The pattern is similar to the number of hours when heat stress occurs. However, the magnitude is slightly different. For example, the number of hours when $T_{mrt}$ is over 55.5 °C in the square of Frankfurt under future climate is 2.5 times higher than that observed in Gothenburg. However, the ODH values are nearly 3.5 times higher, compared to the number of hours. The increases in ODH values of the N-S canyons are higher in Frankfurt and Porto, indicating that these locations are more prone to heat stress under future climate due to the increase in $T_a$.

**Table 3** The number of hours per year when $T_{mrt}$ of the study locations over 55.5 °C (moderate heat stress) and 59.4 °C (severe heat stress) under present and future climates

| | Present | | | | 2070–2098 | | | | Changes | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NS | EW | SQ | CY | NS | EW | SQ | CY | NS | EW | SQ | CY |
| $T_{mrt}$ over 55.5 °C (moderate heat stress) | | | | | | | | | | | | |
| GBG | 0 | 0 | 67 | 7 | 1 | 0 | 95 | 10 | 0 | 0 | 28 | 3 |
| FRK | 20 | 5 | 154 | 87 | 38 | 12 | 231 | 127 | 18 | 7 | 77 | 40 |
| PRT | 26 | 4 | 150 | 97 | 71 | 18 | 402 | 257 | 45 | 14 | 252 | 160 |
| $T_{mrt}$ over 59.4 °C (severe heat stress) | | | | | | | | | | | | |
| GBG | 0 | 0 | 11 | 0 | 0 | 0 | 22 | 0 | 0 | 0 | 11 | 0 |
| FRK | 1 | 0 | 38 | 21 | 10 | 2 | 87 | 50 | 9 | 2 | 49 | 29 |
| PRT | 5 | 0 | 29 | 16 | 18 | 3 | 112 | 68 | 13 | 3 | 83 | 52 |

*GBG* Gothenburg, *FRK* Frankfurt, *PRT* Porto

**Table 4** Overheating degree–hour per year over the two thresholds (55.5 and 59.4 °C) in the three cities under present and future climates

| | Present | | | | 2070–2098 | | | | Changes | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NS | EW | SQ | CY | NS | EW | SQ | CY | NS | EW | SQ | CY |
| $T_{mrt}$ over 55.5 °C (moderate heat stress) | | | | | | | | | | | | |
| GBG | 0 | 0 | 143 | 9 | 0 | 0 | 246 | 16 | 0 | 0 | 103 | 7 |
| FRK | 37 | 6 | 404 | 228 | 103 | 24 | 814 | 459 | 66 | 18 | 410 | 231 |
| PRT | 61 | 6 | 338 | 217 | 192 | 38 | 1167 | 705 | 131 | 32 | 829 | 488 |
| $T_{mrt}$ over 59.4 °C (severe heat stress) | | | | | | | | | | | | |
| GBG | 0 | 0 | 20 | 0 | 0 | 0 | 43 | 0 | 0 | 0 | 23 | 0 |
| FRK | 1 | 0 | 66 | 34 | 17 | 2 | 225 | 121 | 16 | 2 | 159 | 87 |
| PRT | 8 | 0 | 42 | 20 | 41 | 4 | 254 | 141 | 33 | 4 | 212 | 121 |

*GBG* Gothenburg, *FRK* Frankfurt, *PRT* Porto

The frequency of occurrence of five consecutive days per year with $T_{mrt}$ over the two thresholds under present and future climates is shown in Table 5. For moderate heat stress ($T_{mrt}$ over 55.5 °C), such conditions occur only in the square in Gothenburg, with an increase of two times per year under future climate. In Frankfurt, increases of three and two times are recorded in the square and courtyard, respectively, under future climate. The frequency of the N-S canyon is also tripled in the future. In Porto, there is a substantial increase in the N-S canyon, the square and the courtyard, with increases in frequency of 12, 50 and 25, respectively. It suggests that open locations would experience a prolonged period of heat stress in the future, especially in Porto where there is an increase in direct radiation due to the reduction in cloudiness. In terms of the prolonged period of severe heat stress ($T_{mrt}$ over 59.4 °C), the changes in all locations in Gothenburg are negligible, while the increases in frequency in Frankfurt and Porto are similar. It is worth noting that prolonged periods of severe heat stress occur in the N-S canyon in Porto in the future climate scenario, whereas with this index, the E-W canyons are less affected by climate change.

## Discussion

### The role of urban geometry in mean radiant temperature

According to the results of the present-day climate study, there are large spatial variations in daytime $T_{mrt}$ within the study areas, and they are primarily due to the amount of solar radiation reaching the ground and building surfaces. These variations are, in turn, controlled by urban geometry, which includes street orientations, building height and spacing of individual street canyons. The hourly average of daytime $T_{mrt}$ of the square in the high-latitude city of Gothenburg can be up to 30 °C higher than the $T_{mrt}$ observed in street canyons

**Table 5** The frequency of occurrence per year of five consecutive days with $T_{mrt}$ over the two thresholds (55.5 and 59.4 °C) in the three cities under present and future climates

| | Present | | | | 2070–2098 | | | | Changes | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NS | EW | SQ | CY | NS | EW | SQ | CY | NS | EW | SQ | CY |
| $T_{mrt}$ over 55.5 °C (moderate heat stress) | | | | | | | | | | | | |
| GBG | 0 | 0 | 4 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 2 | 0 |
| FRK | 1 | 0 | 14 | 6 | 3 | 0 | 17 | 8 | 2 | 0 | 3 | 2 |
| PRT | 2 | 0 | 10 | 5 | 14 | 2 | 60 | 30 | 12 | 2 | 50 | 25 |
| $T_{mrt}$ over 59.4 °C (severe heat stress) | | | | | | | | | | | | |
| GBG | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| FRK | 0 | 0 | 2 | 1 | 1 | 0 | 5 | 3 | 1 | 0 | 3 | 2 |
| PRT | 0 | 0 | 1 | 1 | 1 | 0 | 4 | 2 | 1 | 0 | 3 | 1 |

*GBG* Gothenburg, *FRK* Frankfurt, *PRT* Porto since they are only sunlit for several hours of the day. When street canyons are sun-exposed (11–12 h and 15–16 h for N-S and E-W canyons, respectively), their $T_{mrt}$ becomes slightly higher than the square's due to longwave and shortwave radiations reflected by surrounding building walls. It should be noted that the N-S canyon in the present study is slightly orientated towards north-west–south-east, leading to earlier sun exposure than a pure N-S orientation. Nonetheless, the results agree with those obtained in a previous study (Thorsson et al. 2011) except for the lower $T_{mrt}$ in the courtyard and N-S canyon at midday. The differences are mainly due to the improvements in the SOLWEIG model, in particular, the inclusion of ground-view factors which measure the fraction of sunlit surfaces, influencing outgoing shortwave and longwave radiation (Fig. 6in Lindberg and Grimmond 2011). The different weather conditions of the selected days are also a reason for this reduced $T_{mrt}$ since both $T_a$ and direct incoming solar radiation are higher on the day selected in the previous study.

In Porto, the higher $T_{mrt}$ in N-S canyon is more prominent due to the higher longwave radiation from the canyon surface after the exposure to intense solar irradiance at midday. The effect of the reflection of shortwave and longwave radiation by surrounding building walls is further demonstrated by the high $T_{mrt}$ in the courtyard when the building walls are sunlit. The prolonged period of high daytime $T_{mrt}$ in the open square agrees with previous studies that open urban structures tend to result in daytime heat stress (Andreou 2013; Müller et al. 2014).

The present study shows that a dense urban structure is able to mitigate heat stress during daytime. It is particularly prominent in cooler climates where open areas are exposed to intense heating during daytime, while narrow street canyons are only sunlit for 2 h on a clear summer day. The range of daytime $T_{mrt}$ is also reduced, preventing the occurrence of extremely high and low temperature. Shashua-Bar and Hoffman (2000) reported that an increase (0.24) in height–width (H-W) ratio results in a reduction of up to 5 °C in physiological equivalent temperature (PET) based on a numerical simulation study in Athens, Greece. The effect of such a dense structure persists in Porto as street canyons are apparently cooler than the open square. However, higher sun altitude increases the amount of shortwave radiation trapped entering within street canyons, and a dense urban structure may prevent re-radiation of such intense heat in the form of longwave radiation, even when the street canyon is shadowed, and cause thermal discomfort at night (Johansson and Emmanuel 2006). For open areas or sunlit surfaces such as the northern sidewalk of the E-W canyons, shading can be provided by vegetation, which is widely accepted as a mitigation measure to outdoor heat stress (Gulyás et al. 2006; Oliveira et al. 2011; Cohen et al. 2012). Therefore, the effect of vegetation can be included in future studies in order to determine the appropriate locations as well as the type of vegetation with regard to mitigating outdoor heat stress.

Street orientation also plays an important role in mitigating heat stress. Although there are no considerable differences in average $T_{mrt}$, the number of hours with moderate and severe heat stress in the E-W canyon is much less than that in the N-S canyon. It suggests that the E-W orientation is more preferred in terms of reducing radiant heat load in the urban environment. However, it should be noted that the E-W canyons in the present study are generally deep canyons, which are in line with Andreou (2013) that E-W canyons are able to achieve satisfactory levels of thermal comfort with high H-W ratio. It is demonstrated in the northern side of the E-W canyon in Frankfurt and Porto where high-rise buildings to the south block incoming solar radiation from reaching the canyon surface. It results in the highest difference between maximum and minimum $T_{mrt}$ observed in the E-W canyon in Porto, especially when the sun altitude is lower in the spring, autumn and winter. The different angles of street orientation in the three cities affect the time of the day when the canyons are sunlit, but overall conditions of radiant heat load are comparable. Findings of the present study confirm that urban geometry has a great potential in mitigating heat stress in the urban environment (Ali-Toudert and Mayer 2006; Emmanuel et al. 2007; Andrade and Alcoforado 2008; Krüger et al. 2011; Thorsson et al. 2011).

High solar irradiance, in the form of longwave and shortwave radiation, contributes to high outdoor $T_{mrt}$, the indicator of heat stress used in the present study. The implications on internal temperature of buildings should not be neglected since the high radiant heating is an important component of the heat load on buildings, causing the increase in indoor $T_a$ if the buildings are not air-conditioned. For naturally or fan-controlled ventilated buildings, the relatively cooler indoor air is replaced by warmer outdoor air through the ventilation system. People living in non-air-conditioned buildings are exposed to higher risks of heat stress. Therefore, the mitigation to higher radiant heat gains (i.e. $T_{mrt}$) would help to reduce the internal temperature of the buildings.

## Regional differences of mean radiant temperature

There are considerable variations in summer daytime hourly $T_{mrt}$ cities. In Gothenburg, lower $T_{mrt}$ is primarily associated with lower solar angle, which limits sunlight reaching the ground and building surfaces. Narrow street canyons are sheltered from direct solar radiation, so intense summer heat stress is ameliorated. As sun altitude increases, more ground and building surfaces are exposed to direct solar radiation. As a result, the highest $T_{mrt}$ values generally occur in Frankfurt and Porto in street canyons (Fig. 3). Similar magnitude was found between the two cities because the effect of higher $T_a$ in Porto is offset by the smaller angle of solar radiation being received by a standing person (of which $T_{mrt}$ is calculated for in the present study). Urban geometry plays an important role in the radiant heat load of the two cities.

Regional differences in winter daytime $T_{mrt}$ are similar to those in the summer (Table 2). Lower maximum daytime $T_{mrt}$ is observed when the study locations are sunlit (e.g. N-S canyons and open squares), which is a result of regional differences in $T_a$. The lowest $T_{mrt}$ observed in the E-W canyon is the result of incoming shortwave radiation being blocked by tall buildings in surrounding areas, especially in Gothenburg and Frankfurt where lower sun altitude is experienced. The higher sun altitude in Porto allows solar radiation reaching the canyon surface through the reflected shortwave component by building walls. The highest daytime maximum $T_{mrt}$ is observed in Porto in open environments where solar radiation reaches pedestrian height. Although the range of daytime $T_{mrt}$ is similar in Gothenburg and Frankfurt, high $T_{mrt}$ likely occurs during sunlit hours.

### The implications of future climate change on mean radiant temperature

For the future climate scenarios used in this study, changes in $T_{mrt}$ are dominated by changes in $T_a$, but changes in solar radiation also play a role in more open, sun-exposed areas. In times of higher increase in cloudiness, like spring in Frankfurt and Gothenburg, the reduced direct solar radiation lowers $T_{mrt}$ in sunlit open squares, and thus, the difference between street canyons and open areas is reduced (Lindberg et al. 2013). Such a finding is different from the previous study which employed PET to assess the effect of climate change on outdoor thermal comfort in Gothenburg (Thorsson et al. 2011). The incorporation of wind conditions in calculating PET is one possible reason for such a difference. The effect of $T_a$ on $T_{mrt}$, as illustrated by Onomura et al. (2014), is also the reason for future changes in $T_{mrt}$. It suggests that although the urban environment may become warmer in the future, a dense urban structure could reduce the range of $T_{mrt}$ so that extreme conditions can be alleviated.

An increase in $T_{mrt}$ in Porto is shown to be stronger in the summer, while in Frankfurt, $T_{mrt}$ increases at a higher rate in the winter, suggesting that measures to reduce radiant heat load are most needed in Porto. However, there are no considerable differences between four study locations in Porto, and mitigation measures can be provided according to local urban characteristics. For example, street canyons are generally narrower in Porto, so vegetation on sidewalks is virtually impractical. Projected features from buildings to provide additional shading would be effective since the sun altitude is much higher in Porto. At higher latitude cities, an increase in $T_{mrt}$ is found to be at a higher rate in street canyons, particularly in autumn and winter, which is likely due to increasing $T_a$. It may reduce cold stress in the winter but cause potential overheating in autumn. On the other hand, the increase in $T_{mrt}$ is at a lower rate (up to 1.6 °C less) in open squares. Therefore, it is particularly important to offer a diversity of thermal comfort conditions within short distances in order to allow urban dwellers to easily seek shading in the urban environment.

Thorsson et al. (2014) reported a 5 % increase in relative risk of mortality in Stockholm, Sweden, when daily $T_{mrt}$ for a generic urban location is higher than 55.5 °C, and the increase is doubled if $T_{mrt}$ exceeds 59.4 °C. In the present study, these two values are considered as the thresholds for moderate and severe heat stress, respectively, for the study locations. Our results show that the number of hours of heat stress is substantially higher in the squares than in the other three locations. Moreover, the frequency of occurrence of consecutive days with heat stress is also lower in narrow street canyons under the future climate scenario. This suggests that narrow street canyons are able to mitigate the negative effects due to future climate change in terms of reducing the radiant heat load in the urban environment. In northern Europe, warmer future climate does not cause substantial increases in heat stress in the narrow street canyons, and they may benefit somewhat from the reduced cold stress due to the increasing $T_a$. However, in southern Europe, the number of hours of heat stress increases considerably in the N-S canyon, though to a lesser extent than that in the square. This implies that the design of urban geometry has to be considered differently according to the climatic conditions and local characteristics of the city. For example, street canyons are generally narrower in Porto, so vegetation on sidewalks is virtually impractical. Projected features from buildings to provide additional shading would be effective since the sun altitude is much higher in Porto.

The sensitivity test of $T_{mrt}$ to future climatic conditions shows that $T_a$ is the dominant factor of future changes in $T_{mrt}$. $T_a$ affects surface temperatures, sky emissivity and temperature and thus longwave radiation fluxes from each direction. It is best demonstrated by the sites located in the street canyon since they are occasionally shaded throughout the day, and shortwave radiation only affects $T_{mrt}$ during sunlit hours. Therefore, future $T_a$ depends on the reliability of numerical modelling, which is fundamentally dependent on the accuracy of the RCM, which is driven by the outputs of the ECHAM5/MPI-OM GCM. Nonetheless, the importance of direct shortwave solar radiation is clearly shown in more open sites where $T_{mrt}$ is considerably affected by the reduced solar radiation in the future.

## Conclusions and final remarks

The present study models the intra-urban differences in daytime $T_{mrt}$ in three European cities, using both historical observations and a climate change scenario. In general, almost all study sites experience daily maximum $T_{mrt}$ over 60 °C in the summer, except street canyons in Gothenburg and Frankfurt. Similar maximum $T_{mrt}$ is observed in squares in all three cities, which implies that people in open areas in all three cities experience daytime heat stress. In the winter, the highest daytime $T_{mrt}$ is still observed in squares, but the courtyards exhibit the lowest daytime $T_{mrt}$ due to the reduced sun altitude. It may result in cold stress in the courtyards in the winter.

Daily maximum $T_{mrt}$ is higher in N-S canyons than in E-W canyons since they are exposed to intense solar radiation at midday, especially in Porto. However, there are no considerable differences in average $T_{mrt}$ between N-S and E-W canyons. High $T_{mrt}$ only occurs for a few hours around midday in E-W canyons, and the shaded E-W canyon in Frankfurt suggests that E-W canyons with high H-W ratio are capable of reducing radiant heat load. $T_{mrt}$ observed on the southern sidewalk is considerably lower than that on the northern sidewalk, with the highest difference observed in Porto (up to 20 °C). Such deep canyons may only be common in dense urban cores and not typical in less dense suburban areas. Regional differences are lower in the winter, except for the square and courtyard in Porto, where high $T_{mrt}$ is observed. Our results support the assertion that dense urban structures can reduce daytime heat stress since this reduces high $T_{mrt}$ in the summer and does not cause substantial changes in thermal comfort in the winter. Solar access may be hampered in the winter, however, and this would need to be addressed by designing a diverse urban environment which offers a wide range of thermal comfort requirements.

The effect of future anthropogenic climate change on $T_{mrt}$ is also investigated using statistically downscaled data to simulate the radiant heat load in the urban environment for a future scenario. Most of the study sites show increases in $T_{mrt}$ in the future climate scenario, except in Frankfurt during spring months, which is possibly due to increased cloudiness. Warming is relatively lower in Gothenburg with the highest increase in $T_{mrt}$ found in the winter. The largest increases in average $T_{mrt}$ were found in Porto in the summer and in Frankfurt in the winter (near 4 °C). These changes are accompanied by substantial increases in the number of hours over the two $T_{mrt}$ threshold values, with the largest increases in heat stress hours in Porto, where heat stress is common already. The present-day intra-urban variations of monthly $T_{mrt}$ persist in the future. No significant differences between $T_{mrt}$ changes for the four study locations were observed in any city, except for the open square in Gothenburg where increases were at most 3 °C lower than the other three sites in spring.

Limitations of the present study are twofold. First, the effects of wind speed and surface materials are not included in the numerical model. For example, using sea breezes to improve outdoor thermal comfort in coastal areas has been widely discussed (Emmanuel and Johansson 2006; Papanastasiou et al. 2010). However, the effect of sea breezes is rather limited in the study areas since the selected city centres are situated inland and the urban settlements reduce the inland penetration of sea breezes due to the increased surface roughness (Khan and Simpson 2001; Ryu and Baik 2013). Although reducing radiant heat load is the concern in the present study, the importance of wind components should be respected, especially in places where coastal sea breezes are abundant.

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