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Quantifying the Potential of Photonic Cooling to Improve Urban Microclimate

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1 ABSTRACT

The observed warming trend in regional climate is expected to continue in the future, aggravating urban heat load as extreme temperatures are amplified in cities due to the urban heat island (UHI) effect. Beside causing negative health effects and reducing human comfort, this development results in an increase in urban air conditioning (AC) usage, again negatively influencing the outdoor urban microclimate due to AC waste heat emission. As cities are continiously growing (the population of e.g. Vienna increased more than 10% over the past 10 years), more and more people are affected by this additional anthropogenic heating of the urban canyon. The Viennese trend away from individual motorized traffic such as cars and towards the use of public transport, walking and cycling further leaves increased numbers of inhabitants directly exposed to excessive heat loads, highlighting the need for innovative solutions to counteract this problem. The exploratory project 'Photonic Cooling', funded by the Austrian Research Promotion Agency through the 'City of the Future' program, aims at evaluating the potential of practical and cost-effective photonic cooling techniques for the cooling of buildings. The use of the photonic cooling technology instead of conventional AC systems minimizes anthropogenic heat emissions resulting from building cooling, hence minimizing the UHI development due to AC heat release and improving the quality of life of the urban population as a result.

This paper focusses on the quantification of the potential of photonic cooling to improve the urban microclimate using Vienna as a case study. To estimate the future development of the UHI, the resulting changes in cooling demand and its effect on urban temperatures, a modelling approach is used. Simulations with the MUKLIMO_3 urban climate model are performed for the city of Vienna to determine changes in urban temperature for the 2021-2050 period relative to the 1971-2000 period. These results are then used as input for an empirical model to determine future cooling demand in terms of AC electricity use in buildings. Based on existing studies for other cities a relation between AC heat release and city temperature increase is established. Combining this with the modelled future cooling demand quantifies the influence from conventional AC systems on the urban microclimate, illustrating the benefit of using passive photonic cooling techniques to cover cooling demands instead.

Keywords: Cooling Load Modelling, Commuter Comfort, Urban Heat Island, Urban Climate, Photonic Cooling

2 INTRODUCTION

As a result of climate change, extreme heat events are occurring more frequently over large parts of Europe including Austria, and this trend is expected to continue in the future (Fischer and Schär, 2010; IPCC, 2013; ACCP, 2014). The excess in heat is further amplified in cities due to the urban heat island (UHI) effect caused by modifications in land use through urbanization and respective changes in the surface energy balance (e.g. Landsberg, 1981; Oke, 1987). The UHI effect is generally evident as a temperature increase in urban areas compared to the nearby rural environments and is superposed on the regional warming trend. This increase in heat load not only results in a decrease in thermal comfort for the urban population, but has in recent years been recognized as a severe threat to the environment and society. Increase in frequency, intensity and duration of heat events with reduced nocturnal cooling, decreased ventilation and consequent air pollution can have significant impacts on morbidity and mortality (e.g. Souch and Grimmond 2004; Son et al. 2012).

Beside causing negative health effects and reducing human comfort, these changes likely also result in an increase in urban air conditioning (AC) usage. Although improving indoor conditions, AC systems can negatively influence the outdoor urban microclimate due to their emission of waste heat in the urban canyon and thereby increasing the already high temperatures in the city. Continued city growth over the next decades (e.g. Referat für Statistik, 2012) together with the Viennese trend away from individual motorized traffic such as cars and towards the use of public transport, walking and cycling (Referat für Statistik, 2016) leaves more and more people exposed to this additional anthropogenic heating.

These developments highlight the need for innovative solutions to counteract this problem. One such innovative solution is the use of photonic cooling to cool buildings, as the use of this technology instead of conventional AC systems would minimize the anthropogenic heat emission resulting from building cooling. Photonic cooling is based on the concept of materials having a high reflectivity in the visible and near infrared wavelength range (0.35-2 µm) as well as a high emissivity in the atmospheric window wavelength range (8-13 µm). These properties allow for a direct radiative cooling to space, and by using this technique surfaces can be cooled to temperatures below the ambient temperature. A recent study by Raman et al. (2014) has shown that, even for a surface under direct solar radiation during daytime, a cooling of up to 7°C can be reached when suitable photonic materials are used. However, the materials used in the Raman et al. (2014) study are too expensive to be used for the cooling of buildings. The exploratory project 'Photonic Cooling', funded by the Austrian Research Promotion Agency through the 'City of the Future' program, aims at evaluating the potential of practical and cost-effective photonic cooling techniques for the cooling of buildings. As can be seen in Fig 1, first results are very promising for a photonic device comprising mainly of polymer foils. In particular, the investigated photonic device has a very high reflectance (>95 %) for solar radiation (0.35 – 2 µm) and a decent emission coefficient in a wavelength range between 8 to 13 µm. Consequently, almost no solar radiation is absorbed, while thermal radiation is emitted into the clear sky. The temperature difference between ambient and device temperature was found to be in the range between 3 to 7°C. In order to check the impact of the photonic cooling effect, a polycarbonate cover was put on the device, blocking the thermal emission into the sky, while sun light in the visible and near-infrared can surpass the cover. As it is shown in Fig. 1, cooling beyond ambience is clearly related to that effect.

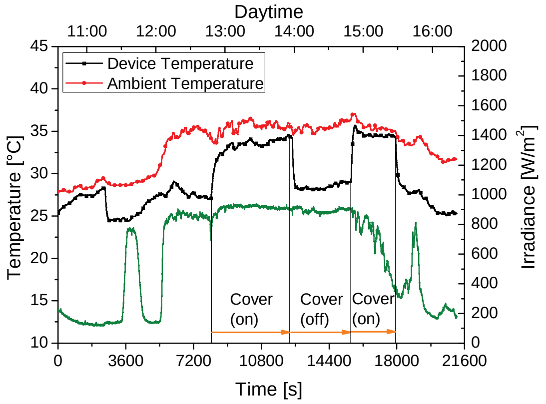

Fig. 1: First results on outdoor measurements of cost efficient photonic cooling devices. In particular the ambient temperature, the device temperature and the global irradiance is plotted over the course of a day (30th May 2017, Weiz / Austria). Due to photonic cooling effects the device was measured to have a temperature of 3-7 °C below the ambience. For cross-checking a transparent polycarbonate cover was put on the device in order to maintain the solar irradiation and block the thermal emission into the sky

Another part of the project focusses on the development of these materials and their implementation in the cooling of buildings. The focus of this paper is on the final project part where the potential of photonic cooling to improve urban microclimate is evaluated.

A method to estimate the potential of photonic cooling to improve urban microclimate, using Vienna as a case study, is presented. This approach consists of three steps. The projected increase in urban heat load as a result of climate change and UHI effect are determined in the first step based on existing simulations with the urban climate model MUKLIMO_3. Based on these simulations, the future urban climate for Vienna can be estimated, and serve as an input to determine the resulting changes in AC cooling demand in step 2. Finally, a linear model describing maximum urban outdoor temperature increase as a result of AC cooling demand (if covered by conventional AC systems) is developed in step 3. This then provides an estimate of the advantage of the use of photonic cooling techniques for the cooling of buildings over that of conventional AC systems in terms of urban microclimate. These steps as well as their results are outlined in detail in Section 3.1, 3.2 and 3.3. A discussion and summary are found in Section 4.

3 METHODS AND RESULTS

3.1 Urban Climate Change in Vienna

Observations have shown that the urban heat load in Vienna has been increasing over the past decades. This positive trend could be assigned to both the observed warming in the regional climate (Auer et al., 2007) and changes in urban environment (Böhm, 1998). Global and regional climate projections show this warming trend will likely continue in the future. According to IPCC climate projections (IPCC, 2013), the maximum temperature in the summer period in South and Central Europe is very likely to increase by the end of the 21st century. Furthermore, the analysis of climate scenarios from regional multi-model ensembles (Schär et al., 2004; Fischer and Schär, 2010) shows an increase in both intensity and frequency of heat waves.

Although global and regional models provide key information on the climate in the 21st century, they are limited in their capacity to represent the relatively small scales such as urban areas. Therefore, it is necessary to apply further downscaling methods to provide information on the local level. In this study, the urban climate model MUKLIMO_3 (Sievers and Zdunkowski, 1983) and the dynamical-statistical cuboid method (Früh et al., 2011) are used for the downscaling of 15 EURO-CORDEX (Coordinated Regional Climate Downscaling Experiment, European domain; Jacob et al., 2014) regional climate model simulations. These simulations are driven by three Representative Concentration Pathways (RCPs) defined in the International Panel on Climate Change (IPCC) Fifth Assessment Report (Moss et al., 2010; IPCC, 2013). RCPs are not based on socioeconomic scenarios, but rather prescribe the development of the radiative forcing, and are named according to their 2100 forcing levels. The simulations used in this study consider the RCP scenarios corresponding to a stabilization of radiative forcing at 4.5 W/m2 in 2100 (RCP4.5), a rising radiative forcing crossing 8.5 W/m2 in 2100 (RCP8.5), and peaking radiative forcing within the 21st century at 3.0 W/m² and declining afterwards (RCP2.6; van Vuuren et al., 2007).

In order to calculate climatic indices, such as the mean annual number of summer days (SU, defined as days with maximum temperatures over 25°C) which are used in order to assess the heat load, the dynamical modeling approach is combined with the cuboid method (Früh et al. 2011; Žuvela-Aloise et al. 2014). The cuboid method refers to a tri-linear interpolation of meteorological fields derived by single-day simulations from an urban climate model. The simulations are performed for a set of idealized weather patterns for potential situations where extreme heat load in the urban center could occur. Eight simulations with a duration of 24 hours for two prevailing wind directions are calculated, representing the cuboid corners. The calculation of climatic indices for 30-year climatic periods is based on the maximum temperature fields from the eight single-day simulations using daily time series of the mean air temperature, relative humidity and wind speed, including hourly wind direction. The climatological data driving the model are obtained from the EURO-CORDEX regional climate model simulations, and reference simulations are performed for the periods 1971-2000 and 1981-2010 using observations as well as climate model runs.

3.1.1 Results

Fig. 2 shows simulations based on observational data for the time periods 1971-2000 and 1981-2010 (top left and right panel, respectively) and future climate scenarios (bottom panels) for Vienna for the time period 2021-2050. The reference simulations show a typical spatial distribution with the maximum heat load in densely built-up areas in the city center and in residential areas in the flat terrain to the north and east of the Danube. Both orography and land use distribution influence the thermal characteristics. Due to the orography and prevailing winds from the northwest and southeast, the heat load in the residential areas located on the hill slopes in the west is lower than the heat load in the same type of built-up terrain in the flat areas located southward and eastward of the city center. Although the spatial pattern in the simulations for the periods 1971-2000 and 1981-2010 based on observational data is similar, an increase in SU can be seen between 1971-2000 and 1981-2010, in line with observational time series (Žuvela-Aloise et al., 2014). Furthermore, in order to check the performance of the regional climate model simulations used as an input, the simulations for the time period 1971-2000 driven by observational data and climate model data were compared (not shown) and it was found that both simulations show similar results.

The model results for the time period 2021-2050 (Fig. 2, bottom panels) show a moderate increase in SU compared to the reference simulation (Fig. 2, top left panel). The intensity of warming and the spatial pattern do not vary much between different climate scenarios for this period. However, as shown by Bokwa et al. (2015), the increase in number of summer days is substantially different for each RCP scenario for the end of the century (2071-2100). This behavior is not surprising, as the spread in radiative forcing for the different RCP scenarios is largest towards the end of the century (Moss et al., 2010).

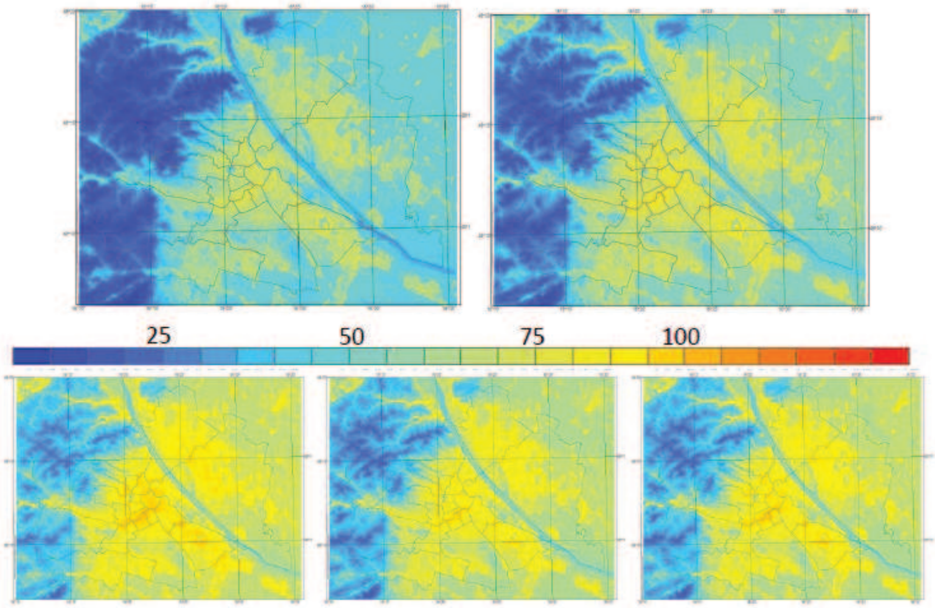

Fig. 2: Mean annual number of SU in Vienna determined with the MUKLIMO_3 model combined with the cuboid method based on the observational time series for 1971-2000 (top left) and 1981-2010 (top right), and IPCC scenarios RCP2.6 (bottom left), RCP4.5 (bottom middle) and RCP8.5 (bottom right) for 2021-2050 using ensembles of EURO-CORDEX RCM model simulations as input. Adapted from Bokwa et al. (2015).

In Table 1, the evaluation of the heat load is expressed as mean annual number of SU for different IPCC scenarios. The analysis is performed for the stations Hohe Warte (HW, in a residential area to the northwest of the city center) and Innere Stadt (IS, located in the city center). The results show a difference in heat load in the city center (IS) compared to the residential districts (HW), with higher heat loads in the city center. Furhtermore, the future climate projections show an increase in heat load of about 20 SU in annual mean in both the city center and residential area when comparing the time period 2021-2050 to the reference period 1971-2000. The variation between different IPCC scenarios is relatively small (less than 5 SU in the annual mean).

SU (days)	Time period	Observations	Reference simulation	RCP2.6	RCP4.5	RCP8.5
HW	1971-2000	56.4	53.1			
	1981-2010	64.1	-			
	2021-2050	-	-	75.0	70.7	72.4
IS	1971-2000	67.6	71.0			
	1981-2010	72.3	-			
	2021-2050	-	-	91.7	87.8	90.0

Table 1: Mean annual summer days (SU) for the climatic periods 1971-2000; 1981-2010; and 2021-2050 based on observations and climate projections for Hohe Warte (residential area) and Innere Stadt (city center). The results shown for RCP2.6 are based on a single run with EUR-11_ICHEC-EC-EARTH_rcp26_SMHI-RCA4, the other model results are based on ensemble averages.

Based on this analysis, it is to be expected that Vienna will experience an increase in SU. How this temperature change might influence the market penetration rate of AC systems and AC electricity use is explored in Section 3.2.

3.2 Estimating the Potential Increase in AC Demand

3.2.1 Data, Methods and Results

To translate the projected change in urban climate for the middle of the 21st century to AC cooling demand, a model was developed to estimate the AC market penetration rate based on the projected temperature changes. The model is based on daily average temperatures in 2015 and 2016 (NOAA, 2017) for 55 cities in 16 european countries from NOAA online database (NOAA, 2017). These are combined to create an population weighted average temperature for each country which is compared to the daily national electricity consumption (ENTSO-E, 2017).

Damm et al. (2016) showed that a country's electricity consumption in the course of a year is dependent on outdoor air temperature, as illustrated in Fig. 3 . Two regimes can be distinguished. For temperatures below about 18-20°C in the first regime, electricity consumption can be seen to increase with decreasing temperatures as a result of heating. Above 18-20°C (this minimum will be denoted by T0) a linear increase of electricity consumption is present, which can be explained by the use of AC systems above these temperatures. The remainder of this paper will focus on this second regime.

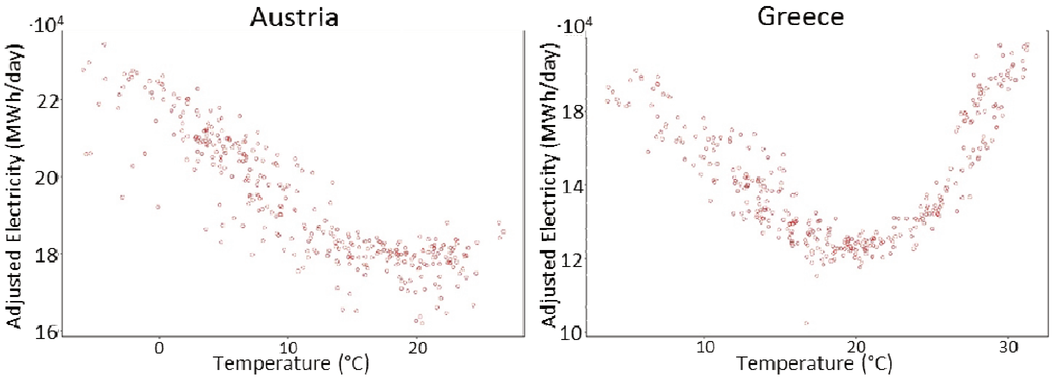

Fig. 3: Daily population weighted electricity consumption versus average temperature for Austria and Greece in 2016. The electricity data are normalised for day of week and national holidays and weekends have been excluded.

The slope of the line in the second regime (ΔE/ΔT) divided by floor area of housing and commercial buildings, calculated from the floor area per capita (ENTRANZE, 2017) and population, is roughly linearly dependent on the market penetration rate of AC systems, as can be seen from Fig. 4. Disregarding the outlier Spain, it is clear that ΔE/ΔT/Afloor (with Afloor denoting floor area) increases for increasing AC market penetration rates, meaning that the electricity consumption in countries where more people have AC systems increases more per 1°C temperature increase than in countries where less households have AC systems.

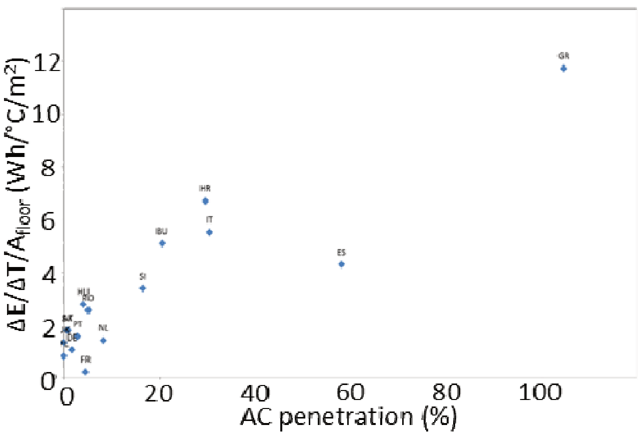

Fig. 4: $\Delta E/\Delta T/A_{floor}$ (Wh/°C/m2) as a function of AC penetration rate (%) in 2010 for several European countries. AC penetration rate is from Odyssee (2017).

We assume that the total electricity consumption for the second regime can be expressed as:

$$E_{tot} = a_0 + A_{floor} \cdot P_{AC} \cdot a_1 \cdot (T - T_o) \qquad \text{Eq. 1}$$

Here, E_{tot} and T are the daily electricity consumption and mean temperature, respectively. a_0 denotes that part of the electricity consumption not related to building cooling (e.g. lighting), P_{AC} is the AC market penetration rate, and a_1 is a coefficient related to the thermal properties of buildings such as their insolation, design and floor area. Eq. 1 can be rewritten to focus on the increase in cooling demand per °C temperature change ($\Delta E/\Delta T$) related to AC market penetration (P_{AC}), resulting in:

$$\Delta E/\Delta T = A_{floor} \cdot P_{AC} \cdot a_1. \qquad \text{Eq. 2}$$

Hence, if the future AC market penetration rate and floor area are known, the future AC cooling demand for a certain outdoor temperature can be determined.

To estimate the market penetration rate of AC systems, cooling degree days are often used. Cooling degree days (CDD) are a measure of how much the outdoor temperature is above a certain threshold (T_o, taken to be 18.3°C in this study) and for how long (in days), with CDD defined as CDD = $\Sigma(T-T_o)$ over all days in a single year on which $T>T_o$. Several relationships between CDD and P_{AC} have been suggested (e.g. Sailor and Pavlova, 2003; Jakubcions and Carlsson, 2017). However, these cannot be applied to the current analysis, as the study by Sailor and Pavolova (2003) is representative of the situation in the USA and cannot directly be applied to the European case, and the relation in Jakubcions and Carlsson (2017) suggests a decline in P_{AC} when CDD decreases. The latter situation seems unlikely, as it suggests already installed AC systems are removed again in years with colder summers. Therefore, we introduce the term CDD_{max}, where the last maximum of CDD as a function of time is taken as the current CDD value. Hence, CDD_{max} is a step function, which never decreases.

The current situation in Europe is used to derive a relationship between market penetration rate and CDD_{max}. If it is assumed that the relation between $\Delta E/\Delta T$ and market penetration rate remains valid, even under a warmer climate, and assuming factor a_1 remains constant (i.e.: no significant changes in building design or insolation) this relationship can then be used to estimate AC cooling demand based on the projected future CDD_{max}. By assuming a_1 to largely remain constant, a change in cooling demand is therefore only caused by a change in AC market penetration rate.

To this end, $\Delta E/\Delta T/A_{floor}$ (which is directly related to the market penetration rate, see Eq. 2) as shown in Fig. 3 was determined for the second regime for all European countries separately. In addition, the CDD_{max} per country was determined. $\Delta E/\Delta T/A_{floor}$ as a function of CDD_{max} per country is shown in Fig. 5 for current climatic conditions. Based on a linear regression, the following relation is found:

$$\Delta E/\Delta T/A_{floor}\ (\text{Wh/d/°C/m}^2) = -1.206 + 0.00868\ CDD_{max}. \qquad \text{Eq. 3}$$

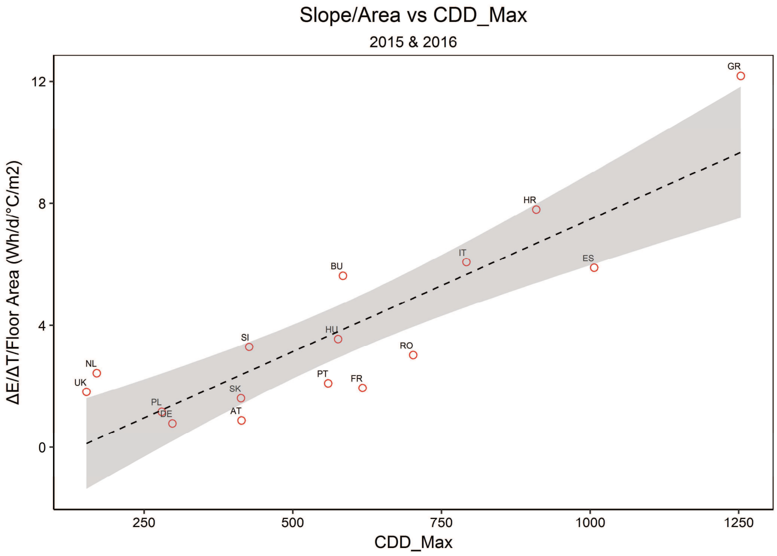

Fig. 5: Slope ($\Delta E/\Delta T/A_{floor}$, which is directly related to AC market penetration rate) as a function of CDD_{max} for current climatic conditions in Europe.

It should be noted that although the market penetration rate is no longer visible in Eq. 3, it is still present as it determines the slope of the daily AC electricity consumption as a function of daily outdoor temperature. For larger CDD_{max}, AC penetration rates will be larger and as a result the increase in AC electricity consumption for a 1°C increase in temperature will be larger.

Combining Eq. 1 and Eq. 3, it is now possible to determine the future AC energy consumption for a given outdoor temperature based on the projected CDD_{max}, illustrating the possibility to determine AC energy consumption based on climate projections:

$$E_{AC} = (-1.206 + 0.00868\ CDD_{max}) \cdot A_{floor} \cdot (T-T_o). \qquad \text{Eq. 4}$$

3.3 Estimating the Effect of AC Heat Release on Urban Climate

3.3.1 Data and Methods

In this section, the effect of AC heat release, which is directly related to AC energy consumption, on urban climate is investigated based on literature research. In the studies examined, the influence of building structure and anthropogenic heat emissions on the atmospheric circulation was studied using urban parameterizations coupled to regional climate and weather models. Common urban parameterizatino schemes are the Town Energy Balance (TEB) model (Masson, 2000) and the Building Effect Parameterization (BEP; Martilli et al., 2002). The BEP scheme has been integrated in the Weather & Forecasting (WRF) model together with the Building Energy Model (BEM; Salamanca et al., 2010), and is widely used. The TEB scheme is combined with a soil and vegetation scheme and is integrated in the ALADIN model group. These models enable the estimation of the change of urban air temperature caused by additional heat release through AC systems.

The modelling studies considered here investigated the effect of AC heat release on urban temperatures for European (de Munck et al., 2013; Salamanca et al., 2012), American (Salamanca et al., 2011; Salamanca et al., 2014) and Asian (Kikegawa et al., 2003; Ohashi et al., 2007) cities, all showing maximum temperature increases between 1.0°C and 3.0°C. The temperature effect of anthropogenic heat emissions from AC systems in Paris (France) during the 2003 heat wave using actual AC system data and the TEB model was studied by de Munck et al. (2013). This time period was chosen, as global climate model projections suggest these heat wave temperatures to be representative of mean summer temperatures during the second half of the 21st century. Under currently present AC cooling loads, with a total heat release power of 5.16 GW and AC heat being released as both sensible and latent heat, maximum local temperature increases between 0.25°C and 1°C were found, and the UHI was increased by +0.3°C. Keeping the heat release the same as in the previous case, but converting all latent heat releases to sensible heat, maximum local temperature impacts range from 0.25°C to 2°C and an increase in UHI effect of 0.8°C. The future scenario, in which the heat release is doubled and solely emitted as dry (sensible) heat, results in maximum local temperature increases of 0.25°C to 3°C. In terms of UHI, it was observed that the future scenario would result in an UHI increase of almost 2°C. Another European case was studied by Salamanca et al. (2012), who simulated the increase in air temperature due to AC heat fluxes for Madrid, Spain. Using the BEP-BEM scheme integrated in the WRF model and assuming an internal building target temperature of 25±1°C and coefficient of performance (COP) of 3.5 of the AC systems, the effect of anthropogenic heat release due to AC heat fluxes was found to be 1.5°C-2°C in the densest urban areas. Studies for the US have shown similar results, with local maximum temperature increases up to 1°C (Houston, TX) to 2°C (Phoenix, AZ) in the densest urban areas during the nighttime (Salamanca et al., 2011; 2014). Simulations for Tokyo (Japan), are in line with these results, and show an increase in air temperature of 1.0°C to 2.0°C due to AC heat release (Kikegawa et al, 2003; Ohashi et al., 2007).

Due to the wide range of meteorological conditions as well as urban structures represented in these studies, generalizing these results for other cities is not trivial. Here, the relation between peak AC heat emission per unit urban area and maximum local temperature effect is derived in an attempt to generalize the impact of AC use on urban temperature. For consistency, only the results determined where waste heat was solely emitted as sensible heat (as opposed to a combination of sensible and latent heat) are taken into account. Anthropogenic heat emissions were either mentioned in the studies or determined using the COP and energy or electricity consumption (EC) through

$$Q_{ant} = EC + CL \qquad \text{Eq. 4}$$

and

$$EC = CL / COP \qquad \text{Eq. 5}$$

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with Q_{ant} the anthropogenic heat emission, EC the AC energy consumption and CL the cooling load (Ohashi et al., 2007). Using the COPs reported in the studies, energy consumption can now be converted to anthropogenic heat emission and vice versa.

3.3.2 Results

Based on the studies that not only reported temperature effects but also gave information related to the AC energy consumption or heat release, a relation between the maximum local temperature effect and the peak AC heat release can be derived (Fig. 6). As expected, the temperature effect increases with increasing AC heat release, and although hard to estimate based on the limited amount of data, the two parameters appear to be linearly related. The linear best-fit forced through the origin, as for a non-existent AC heat flux the temperature effect has to be zero as well, is indicated with a dotted line. The relation between maximum local temperature (MLT) and peak AC heat release (Q_p) is:

$$MLT = 0.08 \cdot Q_p. \qquad \text{Eq. 6}$$

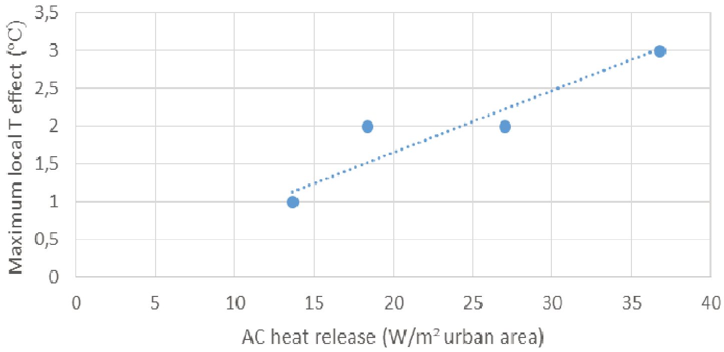

Fig. 6: The maximum local temperature effect as a function of peak AC heat release for the studies by de Munck et al. (2013) and Salamanca et al. (2011; 2014) (dots), and the linear best-fit going through the origin.

It should be noted, however, that this result is based on the assumption that anthropogenic heat is only released as sensible heat. Based on the results from de Munck et al. (2013), this relation might therefore be viewed as an upper limit. Another caveat is that the peak AC heat release, which occur during daytime, are compared to the maximum temperature increases, which are found during nighttime when the boundary layer is shallower. Ideally, the two nighttime values would be compared to obtain a more direct relationship. However, the nighttime AC heat release could not be determined for all studies. Therefore, a more comprehensive analysis is not feasible at this time.

4 DISCUSSION AND SUMMARY

In the framework of the exploratory project ‘Photonic Cooling’, funded by the Austrian Research Promotion Agency through the ‘City of the Future’ program, the potential for the use of photonic cooling over conventional AC systems in terms of urban microclimate was investigated. In this study, relations allowing for a quantitative estimate of the maximum local temperature increase as a result of increased future AC cooling demand were derived. As the approach is based on several steps, all associated with uncertainties and assumptions, it was chosen to focus on the methodology rather than the numerical result.

Based on urban climate projections for the city of Vienna it was shown that the observed trend of warmer summers is expected to continue in the future. An increase of about 20 SU for the 2021-2050 time period relative to the reference period 1971-2000 is expected, both for dense urban areas as well as residential areas. In these projections, the effect of AC systems on urban climate is not incorporated, and the projected changes are solely due to climate change. In Section 3.2, a model to estimate the relation between CCDs and AC market penetration rate was developed, which showed that AC market penetration and hence AC energy consumption increases for increasing temperatures. If this increased cooling demand is covered by conventional AC systems, AC anthropogenic heat release will increase as a result. From results shown in recent studies, the maximum local temperature effect was shown to be lineraly related to anthropogenic AC heat release, suggesting increased urban temperatures as a result of increased AC market penetration.

In summary, a feedback cycle, where increased temperatures lead to an increase in AC market penetration resulting in – if conventional AC systems are used – increased anthropogenic heat release and hence temperatures, develops. If the increased cooling demand under a changing climate, however, could (partially) be covered by the photonic cooling technology, the increase in anthropogenic heat release would be limited. As such, photonic cooling has the potential to keep further urban temperature increase as a result of anthropogenic heat emissions at bay.

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