Analysis of convective heat transfer at building façades in street canyons and its influence on the predictions of space cooling demand in buildings

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Abstract

An important part of the world's energy is used for space cooling of buildings. Minimization of space cooling, especially in hot urban environments, has great energy-saving potential. An important part of the heat exchange between buildings and the ambient surrounding is due to convective and radiative heat flows. The impact of these heat flows on energy consumption for cooling is much more important in urban areas compared to rural areas. This study aims at quantifying the influence of the urban radiation balance, the urban heat island effect and urban convective heat transfer coefficients (CHTC) on the space cooling demands. CHTC correlations were determined using computational fluid dynamics (CFD) for different geometries including stand-alone buildings and street canyons of different lengths. Buoyancy was accounted for by considering differences between building surface and surrounding air temperature. It was found that the building geometry has a large impact on the CHTC correlations and that the effect of buoyancy cannot be neglected when wind speeds are low. These CHTC correlations were used for Building Energy Simulation (BES) predictions of the space cooling demand. Space cooling demands for a building in a street canyon differ up to a factor of 1.8 depending on the CHTC correlations used. Therefore, for accurate predictions of the space cooling demand, adequate CHTC correlations have to be used adjusted to the actual building configuration.

Keywords:

Convective heat transfer coefficient, Computational fluid dynamics, Building energy simulation, Space cooling, Street canyon, Urban heat island

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Abbreviations

BES	building energy simulation
CFD	computational fluid dynamics
CHTC	convective heat transfer coefficient
UHI	urban heat island

1. Introduction

Roughly 25% of the final energy consumption, including all energy delivered to the final consumers (excluding deliveries for transformation and network losses) in the EU is used for residential and 15% for commercial buildings. Heating represents 70% of the residential energy consumption (European commission energy, 2009). Therefore there is a great energy saving potential by minimizing the energy demand for space heating and cooling of buildings. Today about 50% of the world population lives in urban areas, increasing to about 70% by 2050 (UN, 2007). The microclimate in urban areas differs significantly from the climate in rural areas. The air temperatures are higher due to the urban heat island effect (UHI) (Oke, 1987) and the wind speeds are lower due to wind sheltering by buildings. Measurements in London showed up to 7K higher air temperatures during the night in the city compared to measurements outside of the city (Watkins et al., 2002). In Athens the mean heat island intensity exceeds 10K which may double the energy demand for space cooling in buildings (Santamouris et al., 2001). Global warming and respective heat waves (Schär et al., 2004; Fischer and Schär, 2009) may further increase the temperatures in urban areas and can reduce the potential for night cooling significantly. The UHI not only influences the energy demand for space cooling and heating of buildings, but has also a large impact on the thermal comfort and health of the people living in urban areas.

Reasons for the urban heat island effect are the increased heat gains due to higher absorption of solar radiation on dark surfaces such as asphalt, the reduced energy losses during the night due to buildings that block thermal radiation to the cold sky, the lack of evapotranspiration as well as lower convective heat losses due to wind sheltering by buildings. Waste heat from buildings, industry and transportation further contributes to the urban warming. Besides the higher air temperatures higher radiative gains to the building and lower convective heat losses from the building also increase the space cooling. Building energy simulation (BES) models are commonly employed to predict space cooling and heating demands (Hensen and Lamberts, 2011). BES models are transient models, which solve the buildings heat balance including conduction, shortwave and longwave radiation and convection, internal heat gains and the operation of building systems. In BES, the building is commonly assumed to be stand-alone, not accounting for the influence of neighbouring buildings. The neighbouring buildings however decrease the convective heat transfer due to wind sheltering and increase the radiative gains by reflecting solar and longwave radiation and blocking the radiation exchange to the cold sky. As input air temperatures weather data from meteorological stations are commonly used, while the actual air temperature of the microclimate at the buildings location should be used. These shortcomings can lead to inaccurate predictions of space cooling and heating. A number of studies, with different degrees of complexity, have been conducted to investigate the influence of the urban microclimate on the energy demand of buildings. The most straightforward way to consider the urban microclimate is to use meteorological data measured at a specific urban location (Santamouris et al., 2001, Kolokotroni et al. 2006, Schneider and Maas 2010). A more detailed study, where the radiation exchange and the wind flow in a city quarter was explicitly modelled, was conducted by Bouyer et al. (2011). All these studies demonstrated the importance of accounting for the urban microclimate in BES.

In this study, BES results for standalone buildings and buildings forming a street canyon are compared to investigate the impact of the urban microclimate on the building cooling demand. To account for the radiation exchange with the neighbouring buildings, the BES radiation model, basically intended to model indoor space radiation, is used for modelling outdoor space radiation between the building surfaces and sky (see for more details section 3.1.2.). The UHI was accounted for by using diurnal UHI intensity schedules that are obtained from field measurements (Rotach et al., 2005). In BES, convective heat transfer coefficients (CHTCs) are used to quantify the convective flow of heat at the building façades:

$$h_c = \frac{q_{c,w}}{T_w - T_{ref}} \quad (1)$$

where h_c = convective heat transfer coefficient; $q_{c,w}$ = convective heat flux normal to the wall; T_w = surface temperature at the wall; and T_{ref} = a reference temperature.

CHTC correlations for different wind speeds are found in literature (Defraeye et al., 2011a) and are commonly based on measurements at façades of stand-alone buildings. For buildings in urban areas these CHTC relations are not sufficiently correct, since the global flow field and as such also the convective heat transfer is strongly influenced by the neighbouring buildings. Furthermore, buoyancy is important in urban areas, where façades and pavement are heated by the sun and where wind speeds are reduced due to wind sheltering. For example, in a street canyon with an aspect ratio (width versus height) of 1 and a wind flow direction perpendicular to the street axis, a vortex is formed in the centre of the street canyon. With increasing temperature difference between the air around buildings and the building façades, buoyancy will reinforce this vortex or other counter rotating vortices will be generated. These vortex structures have an important effect on the CHTC at the different surfaces of the street canyon. CHTCs were also determined by wind tunnel experiments (e.g. Kovar-Panskus et al., 2002) and CFD simulations (e.g. Xie et al., 2007) where the influence of different surface temperatures of façades and ground on the flow field was studied.

To determine CHTC by CFD, near wall modelling is needed. For the near wall modelling, two approaches exist: (1) Low Reynolds Number modelling (LRNM), which requires a high density meshing of the boundary layer and is by this computationally expensive; (2) and wall functions, where the viscous sublayer, the buffer layer and part of the logarithmic layer are not resolved but modelled. Wall functions need only a coarse meshing of the boundary layer and are computationally less expensive. Recently Defraeye et al. (2010) showed that the standard wall functions fail to predict accurately the heat transfer at the wall and consequently also the CHTC. Based on accurate LRNM simulations, Defraeye et al. (2011b) and Allegrini et al. (2012) proposed an adapted wall function approach, which provides more accurate results for the modelling of convective heat transfer at bluff bodies immersed in an atmospheric boundary layer. Recently Defraeye et al. (2012, this issue) showed that these adapted wall functions show also a much higher accuracy when buoyancy is present at stand alone buildings. Allegrini et al. (2012) came to the same conclusions when considering street canyon geometries. Therefore, we use in this paper the adapted wall function approach to derive CHTC correlations for different building geometries, ranging from stand-alone buildings to street canyons, taking into account the effect of buoyancy. The CHTC correlations are derived for stand-alone buildings and street canyons with different lengths with or without buoyancy. Only wind directions normal to the buildings are considered. In the next step, the obtained CHTC correlations are used for BES. The purpose of this paper is to analyse the influence of the used CHTC correlations on the predicted space cooling demand. The CHTC correlations depend both on wind speed and surface temperatures when buoyancy is present. However since buoyancy depends highly on the specific heating of the different surfaces forming e.g. a street canyon, the amount of different cases to be considered, and thus also the number of correlations to be determined indefinite. Another option is to directly couple BES with CFD. For each BES time step, a CFD simulation computes the CHTC for that time step. The surface temperatures used in CFD are the temperatures obtained in the BES. The resulting CHTCs are then used for the next BES. Such coupled simulations are however computationally expensive and therefore not practical for annual building energy predictions. Therefore, in this paper, we perform a study to determine the sensitivity of the BES cooling demand on the used CHTC correlations.

The structure of the paper is as follows. In section 2 the CFD model and CHTC correlations are presented. In section 3, the BES model is presented and the annual space cooling demand and peak cooling load using different CHTC correlations is studied. From these annual simulations detailed results for a two week period are selected and analysed, with the aim to quantify the sensitivity of the predicated space cooling demands on the used CHTC correlations.

2. CFD

2.1. Numerical Model

For this study, steady 2D and 3D RANS CFD simulations using ANSYS-Fluent 12.0 (ANSYS Fluent, 2009) are conducted with a realizable k-ε turbulence model. Xie et al. (2006) validated 2D RANS CFD simulations with a k-ε turbulence model for street canyons and showed the applicability of the k-ε turbulence model to predict the flow field in street canyons. For the near wall modelling, modified wall functions as presented by Defraeye et al. (2011b) are used.

Seven urban geometric configurations are considered including stand-alone buildings and street canyons. For the stand-alone buildings we consider four cases: (case i) a cubical building with side dimensions H, (case ii) a rectangular building with a height H, a width W equal to H and a length L (L=110.5m), (case iii) rectangular building with a length 2L , (case iv) an infinite long building, which is modelled as a 2D case. The street canyon is modelled as a 2D cavity with three different aspect ratios H/W: 0.5 (case v), 1 (case vi) 1 and 2 (case vii). H equals 14.6 m. The first 4 geometries were chosen to investigate the dependence of the CHTCs on building length. The last three cases of street canyons were chosen to analyse the influence of the aspect ratio. The dimensions of the 2D and 3D domains are constructed according to the guidelines of Franke et al. (2007). Figure 1 gives as an example the domain for 2D stand alone building and street canyon cavity and the meshed domain for the 3D cubical building (3D and topview).

At the inlet of the domain vertical profiles of the mean horizontal wind speed U (logarithmic law), turbulent kinetic energy (k) and rate of dissipation of turbulent kinetic energy (ε) are imposed according to Richards and Hoxey (1993). These profiles represent a neutral ABL, where the turbulence originates only from friction and shear:

$$U(y) = \frac{u^{*}_{ABL}}{\kappa} \ln\left(\frac{y+z_0}{z_0}\right)$$
$$k = \frac{u^{*2}_{ABL}}{\sqrt{C_\mu}} \qquad (2)$$
$$\varepsilon = \frac{u^{*3}_{ABL}}{\kappa(y+z_0)}$$

where u^*_{ABL} is the ABL friction velocity, y the height above the ground, z_0 is the aerodynamic roughness length. For z_0 a value of 0.03m is chosen, which corresponds to a land surface with low vegetation and isolated obstacles. The same roughness length was also used for the urban geometries in order not to influence the heat transfer by the characteristics of the approach flow, but only by the building geometries itself. . Because the street canyon is modelled as a cavity and therefore the longitudinal extensions of the domain are at the roof level, the used roughness length is assumed to be the roughness of the roof and not the roughness of the urban area. Eight different reference wind speeds at 10 m height are considered: 0.125, 0.25, 0.5, 1, 2, 3, 4 and 5m/s. The incoming air temperature equals 20°C. The wind direction for the 3D simulations is normal to the building. The following roughness heights were used for the simulations. The surfaces of the building and cavity have no roughness. Reason for this particular choice is that the wall functions used in this paper are derived from LRNM simulations, which allow only smooth surfaces (ANSYS Fluent, 2009). The surfaces of the longitudinal extension of the domain in front and behind the building or the street canyon are modelled with different roughness heights, chosen in such a way that the streamwise gradients of the vertical winds speed and turbulence profiles are minimal (Blocken et al., 2007). The surface temperatures of the building and cavity walls are assumed to be uniform. Four different surface temperatures are considered: 21, 23, 25 and 30°C to mimic different solar radiation intensities. The Richardson number is used to quantify the amount of buoyancy:

$$Ri = \frac{g\beta(T_W - T_0)h}{U^2} \qquad (3)$$

where g is the gravitational acceleration, T_w the wall temperature, h a reference height (here the building height H), U a reference velocity (here the reference velocity U_{10}) and T_0 a reference temperature (here the temperature at the inlet boundary) . The Richardson number for the cases considered in this paper varies between 0.2 and 3200. The other surfaces of the domain, with exception of the building or cavity walls, are modelled as adiabatic surfaces. Symmetry boundary conditions are imposed at the top boundary and outflow boundary conditions at the outlet. For the 3D domains symmetry boundary conditions are imposed at the lateral boundaries. No radiation is considered in the CFD simulations. To model buoyancy, the Boussinesq approximation is applied. Pressure-velocity coupling is taken care of by the SIMPLEC algorithm. The PRESTO! spatial discretization scheme is used for the pressure interpolation and a second order spatial discretization scheme for the convection of the governing equations.

2D and 3D structured grids are built based on a grid sensitivity analysis and on the guidelines of Franke et al. (2007). The 2D grids consist of 5500 to 11500 cells. The 3D grids consist of 67000 to 155000 cells. All grids are refined towards the walls. Since a wall function approach is used the y^+ values have a maximum of 500.

2.2. Importance of Buoyancy

Buoyancy plays an important role in the natural and mixed convective flow regimes. The flow field in street canyons changes significantly due to buoyancy when having high surface temperatures and low wind speeds. These weather conditions are also the critical conditions for determining the building cooling demand and peak load. In figure 2 the vector flow fields obtained by CFD are shown for cases with and without buoyancy. Different aspect ratios are considered. Without buoyancy one main vortex in the centre of the street canyon is formed. Some other small vortices in the corners of the cavity are formed. Due to the buoyancy, air rises at the heated building surfaces and two (or even more) counter rotating vortices are formed. The vorticity is higher in the buoyant case than in the forced convection case. With buoyancy, the air velocities (figure 3a) and air temperatures (figure 3b) at the building façades increase. As a result, the convective heat transfer and CHTCs increase in the buoyant case. It can be concluded, that buoyancy has to be taken into account for the determination of CHTC correlations when the temperature differences between air and surface is high and the wind speed low.

2.3. CHTC correlations

For the CHTC calculations the reference temperature in equation (1) is defined as the temperature of the incoming air at the inlet. Surface averaged CHTCs are determined for windward and leeward façade. In figure 4, the CHTC versus wind speed is shown for the 7 different geometries. Figures 4a-b show the results with buoyancy and figures 4c-d without buoyancy. The CHTC values for the leeward façade are in general smaller than the values for the windward façade (note the lower scale in ordinate axis for leeward wall), due to lower air speeds at leeward surfaces. The CHTC increases nonlinearly with the wind speed. When buoyancy is not considered, the CHTCs decrease to zero for low wind speeds, while for buoyancy they level off to a constant value. The heat flux gets constant for low wind speeds, because the flow inside the street canyon is mainly driven by buoyancy and not by the flow above the street canyon anymore. We conclude that buoyancy has to be considered for weather conditions with high surface temperatures and low wind speeds.

Different CHTC correlations are found for different geometries. We first consider the CHTCs for the windward walls. The CHTCs of standalone buildings are higher than the CHTCs in street canyons. The CHTCs for stand-alone buildings decrease with increasing building length starting from the cubic building towards the infinite long building. The Reason is that the highest air speeds and consequently convective heat transfer coefficients are found for the cubical building showing an acceleration of the 3D flow around the building. With increasing building length the air speeds and convective heat transfer coefficients further decrease. The sensitivity of the CHTC to the wind speed, represented by the slope of the correlation, is found also to depend on the building geometry. The slope of the CHTC correlation decreases with increasing building length. The CHTCs at the windward wall in the street canyon are lower compared to the infinite long stand-alone building. This decrease is due to the wind sheltering caused by the neighbouring building. The CHTCs are lower for higher aspect ratio H/W, due to the increased wind sheltering effect in narrower street canyons.

Considering the CHTCs at the leeward wall they follow the same trend as found for the windward walls. However, the CHTCs for the wider street canyons (aspect ratios 0.5 and 1) are higher than for the infinite long stand-alone building. This observation can be explained by the existence of a vortex in the street canyon, which increases the air speed at the leeward wall compared to the leeward wall in the wake of a standalone building.

The CHTC correlations derived in this study are compared to the correlations from ASHRAE (2009) in figures 4c-d. The correlations from ASHRAE are commonly used for BES and are based on measurements by Ito et al. (1972). The CHTCs determined for urban geometries studied in this paper are in general much lower than the ASHRAE correlations. Only for the windward wall of the cubical building do the ASHRAE values approximate our CHTC values, whereas for the leeward wall of all urban geometries the values are significantly lower, while the slope is higher.

Profiles of the CHTCs along the vertical centreline of the leeward and windward walls are given in figure 5a and 5b respectively for different stand-alone buildings. The profiles for these buildings are similar and the values are decreasing with increasing building length.

In figure 6a the CHTC correlations for a street canyon with an aspect ratio of 1 are shown for different façade and ground surface temperatures. With increasing surface temperatures the buoyancy effect on CHTC at low wind speeds becomes more pronounced. CHTCs are higher and become function of both air speed and temperature difference between the surface and air in the street canyon. The CHTCs for wind speeds lower than 1 m/s are almost identical for leeward and windward façade, because the flow, which is mainly driven by buoyancy, is almost equal at these two façades. For higher wind speeds the CHTC correlations for the different temperature differences collapse onto one curve, because the influence of buoyancy on the flow field becomes negligible.

In figure 6b the CHTC values for low wind speeds (box in figure 6a) are given as a function of the temperature difference between the wall and ground surfaces and the air temperature. The CHTC values are increasing in a similar way for all geometries. Theoretically, the air speed and the CHTCs at the walls should increase linearly with the temperatures difference between the surfaces in the street canyon and the air temperature. This is because the buoyancy forces are a linear function of the air density and the air density is modelled with the Boussinesq approximation, where the air density is a linear function of the air temperature. In figure 6b the increase is not linear, since the air temperature in the street canyon increases less rapidly than the façade surface temperatures. Therefore the buoyancy forces, and consequently the air speed and CHTC values, are increasing nonlinearly.

From these CFD results it becomes clear that the geometry and the temperature difference between surface and ambient air temperatures are important parameters determining the CHTC correlations. In the next section we study the influence of the different CHTC correlations on the energy demand for cooling of buildings. For this purpose, the CHTC correlations are approximated by the following functions: (i) a constant value for wind speeds below 1m/s (determined as the average CHTC in this low speed region); and (ii) with a power-law function for wind speeds above 1m/s.

3 BES

3.1. Numerical Model

TRNSYS 17.0 (2010) is used as code for BES in this study. TRNSYS is a transient 3D single building multi-zone BES software. It includes a 3D radiation model that accounts for shadowing and radiation exchange including multiple reflections for solar and long wave radiation. Heat conduction through the walls is modelled as 1D transient heat flow using wall transfer functions. TRNSYS 17 was developed for stand-alone buildings and the detailed radiation model is basically employed for interior spaces. For this study the BES model was adapted in such a way that the radiation model can also be applied for outdoor spaces between buildings (see section 3.1.2.). TRNSYS 17 uses CHTC correlations to describe the convective heat transport at the outside surface of the building. All BES are conducted with meteorological data from the Swiss city of Basel.

3.1.1. The building model

The energy demand of a three storey office building is analysed in a rural and an urban context. In the former case, the office block is considered as a stand-alone building in an open field, while in the latter case it is situated between two identical buildings (figure 7). Street canyons with different aspect ratios (H/W = 0.5, 1 and 2) are analysed.

The studied building has a length of 110.5 m to minimize lateral boundary effects in the radiation model and a total height and width of 13.5m. The building is well-insulated. Walls, roof and ground floor have U-values of respectively 0.25 W/m^{2}K, 0.15 W/m^{2}K and 0.29 W/m^{2}K. A basement is not considered. The walls have a glazing fraction of 50 % and windows with double glazing (U-value 1.4 W/m^{2}K, g-value 0.59, reflectivity 0.27) are used. Internal gains, caused by lights, devices and persons, are set according to SIA 2024 (2006). Light control is as follows: lights are on when the building is occupied and if the solar radiation on the corresponding façade is less than 70 W/m^2. External shading devices are closed when solar radiation on the corresponding façade is greater than 120 W/m^2. The lateral façades of the buildings are modelled as adiabatic. The room air temperature is controlled to remain between 21°C and 26°C. A mechanical ventilation system is used (day-time: airflow rate 30 m^3/h.person, heat recovery with 80% efficiency, ambient air is not heated to temperatures above 21°C; night-time: no mechanical ventilation). For the neighbouring buildings all walls are modelled as adiabatic except the ones adjacent to the street canyon, which are similar in construction to the building under study. At the building's façade, window and roof surfaces heat is exchanged by means of solar and long-wave radiation and forced and natural convection, which we discuss in more details below.

3.1.2. Radiative heat transfer

In classical BES of stand-alone buildings, solar irradiation on façade elements is considered as a gain, and long-wave radiation as a heat loss to the cold sky. In street canyon configurations, however, the solar direct and diffuse irradiation is characterized by multiple diffuse and specular reflections at the building surfaces. Similarly, the multiple longwave reflections and radiative exchange with neighbouring building surfaces and the sky must be considered. In TRNSYS 17, the 3D radiation model is only used for interior zones. Therefore, in this study, the outdoor space between buildings is modelled as an atrium with an open ceiling. In this way, the shadowing by the neighbouring buildings and the exchange of thermal and solar radiation between the different buildings is considered. TRNSYS 17 determines which surfaces are sunlit and which are shaded, dependent on the position of the sun and the orientation of the studied building. At opaque surfaces a part of the direct solar radiation is absorbed and the remaining part is reflected in a diffuse way. Thus, specular reflection of direct solar irradiation is not considered. If direct solar radiation hits a transparent surface (window), a part of the solar radiation is absorbed at the window panes, a second part is transmitted through the window into the building, and the rest is reflected diffusely. The sum of all diffuse shortwave radiation, consisting of diffuse solar radiation, the diffuse reflection of direct solar radiation, is distributed over all the surfaces in the street canyon (including a surface that represents the sky) using Gebhart factors. Gebhart factors are basically view factors, corrected to include the effect of multiple (diffuse) reflections. The part of the diffuse shortwave radiation that is distributed onto transparent surfaces is again reflected, absorbed and transmitted by the window panes. As for the diffuse shortwave radiation, the long wave radiation is distributed using Gebhart factors. Each surface emits long wave radiation dependent on its temperature and its emissivity. For the sky a fictive sky temperature as a function of the ambient temperature, air humidity, cloudiness factor of the sky, and the local air pressure is used for the calculations of the long wave radiation. All surfaces are considered to be opaque for long wave radiation. Therefore no long wave radiation is transmitted through the windows.

3.1.3 Surface temperatures

As an example of the presented model, the influence of the radiative exchange in an urban environment on the thermal behaviour of the street canyon is studied. We determine the surface wall temperatures for different cases: a standalone building and street canyons with different aspect ratios. Figure 8 depicts the difference between the wall surface temperature and the ambient air temperature at the 1st floor level of the office building during a summer period of two days. For reference also the air temperature is given. A building inside a street canyon with walls oriented to the North (figure 8a) and South (figure 8b) are considered. The wall surface temperatures for the buildings in an urban environment are in all cases higher than for the stand alone building. These higher temperatures are caused by multiple reflections of solar and long-wave radiation inside the street canyon (solar radiation entrapping). This effect is stronger for the north than for the south façades, because the direct solar irradiation is reflected from the south façade onto the north façade. During night, the stand-alone building cools down faster, due to the larger view factor and heat losses to the cold sky. Temperatures differences remain highest in the narrowest street canyon, due to the lower sky view factor. We remark that the highest surface temperature differences between stand-alone and street canyon buildings are found for the 1st floor. For the 2nd and 3rd floors the influence of the neighbouring buildings is decreasing.

3.2. Space Cooling Demand

3.2.1. Urban vs. rural areas

As discussed in the introduction, three phenomena may contribute importantly to the building cooling demand in an urban environment: (1) the radiation exchange between buildings, (2) the urban heat island effect and (3) wind sheltering. We compare the annual space cooling demand related to the total floor area for a stand-alone building with the energy demand of a building in a street canyon with different aspect ratios. As mentioned, all space cooling demands given here are calculated for a room air temperature threshold of 26°C. For the different geometries, TRNSYS models accounting for the detailed urban radiation exchange are developed. We used the CHTC correlation for street canyons as derived in this paper considering a temperature difference of 10K between the heated surfaces and the air inlet temperature. In these first simulations, this correlation was used for both stand-alone and street canyon building to be able to distinguish between different influencing factors. To analyse the influence of the urban heat island effect a second BES is run, where the surrounding air temperature is increased according to a diurnal urban heat island intensity schedule. Each month is characterised by a diurnal urban heat island intensity curve which is obtained by comparing air temperatures of the metrological station with air temperatures measured inside a street canyon in the city of Basel (Rotach et al. 2005). In Figure 9 important differences in space cooling demand are observed between a standalone building and a building in a street canyon. For the building in a street canyon with an aspect ratio of 0.5, the cooling demand is e.g. more than double than for the same building in a standalone configuration. The higher space cooling demand for the street canyon is caused by the different heat balance in an urban environment. Solar radiation is reflected between the buildings, adsorbed by the walls, giving rise to an increase of the surface temperatures of the buildings. Due to the higher surface temperature more longwave radiation is emitted between the buildings, resulting in higher heat gains for the buildings. During night less long wave radiation losses to the cold sky occur due to the lower sky view factors. This means that the radiation balance in an urban environment leads to higher solar gains during daytime and less radiation losses during night-time. As a consequence the cooling demand for buildings in street canyons increases. For building situated in narrower street canyons the cooling demand is lower, since less solar radiation enters and gets entrapped in the street canyons. The urban heat island intensity further increases the cooling demand, but this effect is less pronounced. However, for buildings with passive cooling by night-time ventilation, the impact of the urban heat island effect is expected to be much higher, as night ventilation becomes less effective at higher ambient temperatures (Allegrini et al., 2011).

3.2.2. Effect of CHTC correlations

Two of the three important phenomena contributing to an increase of space cooling demands of buildings in an urban context were discussed in section 3.3.1. In this section the influence of the different CHTC correlations on the space cooling demand of a building is analysed. We limit the study to one BES model of a building in an urban street canyon with an aspect ratio 1. No urban heat island effect is considered. The CHTC correlations as derived for the different geometries are used. The CHTC values are adjusted to the hourly value of the wind speed. For simplicity we did not adjust the CHTC value every time step to the surface temperature, but studied the sensitivity of the results to the CHTC correlations for different temperature differences.

In figure 10a the annual energy demand for space cooling is given using the different CHTC correlations. The space cooling demand significantly depends on the geometry. The cooling demand increase with 80% comparing a cubical building and a building situated in an infinite long narrow street canyon. Buoyancy has a less important influence on the cooling demand. The cooling demand increases with 17% comparing the CHTC correlations for the two extreme wall temperatures (21°C and 30 °C) for a street canyon with an aspect ratio of 2. BES can also be used to predict accurate peak cooling loads, as these are important for the dimensioning of HVAC systems. In figure 10b peak cooling loads are given for a building in a street canyon with an aspect ratio of 1, using different CHTC correlations. The same trend as for the annual demand can be found. The differences for the peak cooling loads are however much smaller than for the annual energy demands.

3.3.3. Effect of wind speed

In the last part of this study two typical weeks are extracted from the one year simulations for further analysis. One week is characterised by rather high wind speeds, while the other week low wind speed (figure 11a). The temperatures are comparable for the two weeks (figure 11b).

Figure 12 shows the weekly space cooling energy demand using different CHTC correlations. In general the dependencies are very similar to the annual predictions. For both weeks the influence of the geometry is lower than for the one year simulations. For the week with the high wind speeds the influence of buoyancy on energy demand is much lower than for the week with low wind speeds. This is due to the fact that for most of the time the wind speed is in a range where the influence of buoyancy is quite low (see section 2.2.). For the week with low wind speeds the impact of buoyancy on the space cooling demand is much more pronounced, because the wind speed is mostly < 1m/s were the CHTC is a function of the surface temperatures and independent on wind speed.

The results from this section show that it is important to use the appropriate CHTC correlations in order to get accurate predictions for the annual space cooling demands, weekly space cooling demands and the peak cooling loads. Most important is that the geometry and the neighbouring buildings are accounted for when choosing a CHTC correlation for BES. Also buoyancy needs to be considered for weather conditions with low wind speeds and high surface temperatures especially for buildings in urban areas.

In conclusion, the three main aspects, i.e. radiation entrapment, urban heat island effect and CHTCs for urban geometries, need to be considered for an accurate prediction of annual and weekly space cooling demand of a building in an urban area. This study was conducted for idealized stand-alone buildings and urban street canyons. Since the focus of this paper is more on the methodology, more realistic geometries like street intersections, buildings with pitched roofs or balconies etc. were not considered here, but it is possible to use the same approach presented here to other (more complex) geometries. Urban street canyons were chosen being the most generic elements a city is composed of and also critical in terms of space cooling demand, due to the wind sheltering by neighbouring buildings.

4. Conclusion

A sensitivity analysis was conducted with the aim to identify the influence of different convective heat transfer coefficient (CHTC) correlations on the space cooling demand of modern office buildings. In a first step CHTC correlations for 7 different building geometries, ranging from a stand-alone cubical building to an infinite long narrow street canyon, were derived for windward and leeward walls. For all cases, the wind direction was normal to the buildings and street canyons. For all geometries, CHTC correlations for non-buoyant flows and for buoyant flows with different temperature differences between buildings façades and air temperatures were established. It was found that the CHTC values are decreasing from a cubical to an elongated to a building in a street canyon. Further it was found that buoyancy is important for low wind speeds especially for elongated buildings and buildings in urban street canyons. Therefore convective heat transfer in urban areas is generally lower than in rural areas.

The urban heat island effect and the radiation exchange with neighbouring buildings are found to substantially contribute to the increase of cooling demand. It was also found that it is important to use correct CHTC correlations that correspond to the actual building geometry and weather conditions to get accurate predictions for the space cooling demands and peak cooling loads. For the street canyon building studied, the space cooling demand is by factor of 1.8 larger when considering CHTC correlations corresponding to an infinite long street canyon with low buoyancy, compared to the case with CHTC correlations according to a cubical stand-alone building with strong buoyancy. This study shows the importance of choosing carefully the CHTC correlations for Building Energy Simulation, especially for buildings in urban areas.

Acknowledgments

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References:

Allegrini, J., Dorer, V., Defraeye, T., Carmeliet, J., 2012. An adaptive temperature wall function for mixed convective flows at exterior surfaces of buildings in street canyons. Build. Environ. 49, 55-66.

Allegrini. J., Dorer, V., Carmeliet, J., 2011. Influence on the urban microclimate on the energy demand of buildings. Cisbat11, Lausanne Sep 14.-16. 2011.

ANSYS Fluent, 2009. Fluent 12.0 User’s Guide. Lebanon - New Hampshire.

ASHRAE, 2009. ASHRAE Handbook—Fundamentals (SI Edition). American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Blocken, B., Stathopoulos, T., Carmeliet, J., 2007. CFD simulation of the atmospheric boundary layer: wall function problems. Atmos. Environ. 41(2), 238-352.

Bouyer, J., Inard, C., Musy, M., 2011. Microclimatic coupling as a solution to improve building energy simulation in an urban context. Energy Build. 43,1549-1559.

Defraeye, T., Blocken, B., Carmeliet, J., 2012. Evaluation of a forced-convective temperature wall function for mixed convection at surfaces of bluff bodies in turbulent boundary layers. J. Wind Eng. Indust. Aerodyn., this issue.

Defraeye, T., Blocken, B., Carmeliet, J., 2011a. Convective heat transfer coefficients for exterior building surfaces: Existing correlations and CFD modelling. Energ. Convers. Manage. 52, 512–522.

Defraeye, T., Blocken, B., Carmeliet, J., 2011b. An adjusted temperature wall function for turbulent forced convective heat transfer for bluff bodies in the atmospheric boundary layer. Build. Environ. 46 (11), 2130-2141.

Defraeye, T., Blocken, B., Carmeliet, J., 2010, CFD analysis of convective heat transfer at the surfaces of a cube immersed in a turbulent boundary layer. Int. J. Heat Mass Tran. 53(1-3), 297-308.

European commission energy, 2009. Market observatory: Annual Report 2009. (http://ec.europa.eu/energy/observatory/annual_reports/annual_reports_en.htm)

Fischer, E.M., Schär, C., 2009, Future changes in daily summer temperature variability: driving processes and role for temperature extremes. Clim Dyn (2009) 33:917–935

Franke, J., Hellsten, A., Schlünzen, H., Carissimo, B., 2007. Best practice guideline for the CFD simulation of flows in the urban environment, COST Action 732: Quality assurance and improvement of microscale meteorological models. Hamburg.

Hensen, J.L.M., Lamberts, R., 2011. Building Performance Simulation for Design and Operation. Spon Press, Oxon.

Ito, N., Kimura, K., Oka, J., 1972. A field experiment study on the convective heat transfer coefficient on exterior surface of a building. ASHRAE Trans 78(1), 184-191.

Kolokotroni, M., Giannitsaris, I., Watkins, R., 2006. The effect of the London UHI on building summer cooling demand and night ventilation strategies. Sol. Energy 80, 383-392.

Kovar-Panskus, A., Moulinneuf, L., Savory, E., Abdelqari, A., Sini, J.F., Rosant, J.M., Robins, A., Toy, N., 2002. A wind tunnel investigation of the influence of solar-induced wall-heating on the flow regime within a simulated urban street canyon. Water Air Soil Pollut. Focus 2, 555-571.

Oke, T.R.,1987. Boundary Layer Climates, second ed. Methuen, London.

Richards, P.J., Hoxey, R.P., 1993. Appropriate boundary conditions for computational wind engineering models using the k-3 turbulence model. J. Wind. Eng. Ind. Aerod. 46-47, 145-153.

Rotach, M.W., Vogt, R., Bernhofer, C., Batchvarova, E., Christen, A., Clappier, A., Feddersen, B., Gryning, S.-E., Martucci, G., Mayer, H., Mitev, V., Oke, T.R., Parlow, E., Richner, H., Roth, M., Roulet, Y.-A., Ruffieux, D., Salmond, J. A., Schatzmann, M., Voogt, J. A., 2005. BUBBLE – an Urban Boundary Layer Meteorology Project. Theor. Appli. Climatol. 81, 231-226.

Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., Assimakopoulos, D.N., 2001. On the impact of urban climate on the energy consumption of buildings. Sol. Energy 70 (3), 201–216.

Schär, C., Vidale, P.L., Lüthi, D., Frei, C., Häberli, C., Liniger, M.A., Appenzeller, C., 2004. The role of increasing temperature variability in European summer heatwaves. Nature 427, 332-336.

Schneider, A., Maas, A., 2010. Einfluss des Mikroklimas auf das energetische und thermische Verhalten von Gebäuden am Beispiel des Standortes Kassel. Bauphysik 32 (6), 348-358.

SIA 2024, 2006. Guidelines for standard internal loads for energy and building services engineering. Swiss Society of Engineers and Architects (SIA), Zürich.

TRNSYS 17.0, 2010. Transient System Simulation Program, SEL, University of Wisconsin / TRANSSOLAR, Stuttgart.

UN, 2007. World Urbanization Prospects: The 2007 Revision Population Database. (http://esa.un.org/unup/)

Watkins, R., Palmer, J., Kolokotroni, M., Littlefair, P., 2002. The London Heat Island – results from summertime monitoring. BSER. & T. 23 (2), 97-106.

Xie, X., Liu, C.H., Leung, Y.C., 2007. Impact of building façades and ground heating on wind flow and pollutant transport in street canyons. Atmos. Environ. 41, 9030-9049.

Xie, X., Liu, C.H., Leung ,Y.C., Leung, K.H., 2006. Characteristics of air exchange in a street canyon with ground heating. Atmos. Environ. 40, 6396-6409.

Figure Captions

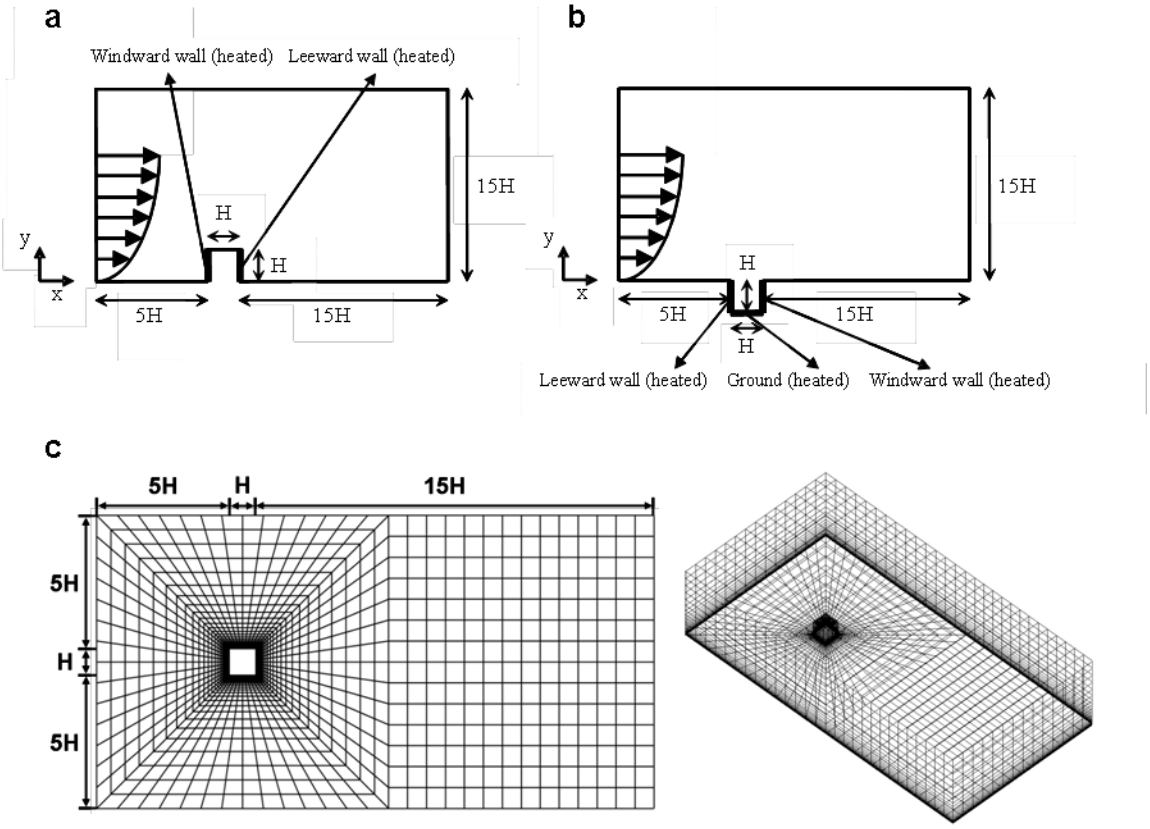

Figure 1: Computational domain for a 2D stand-alone building (a), a 2D street canyon (b) and a 3D cubical building (topview and 3D view) (c).

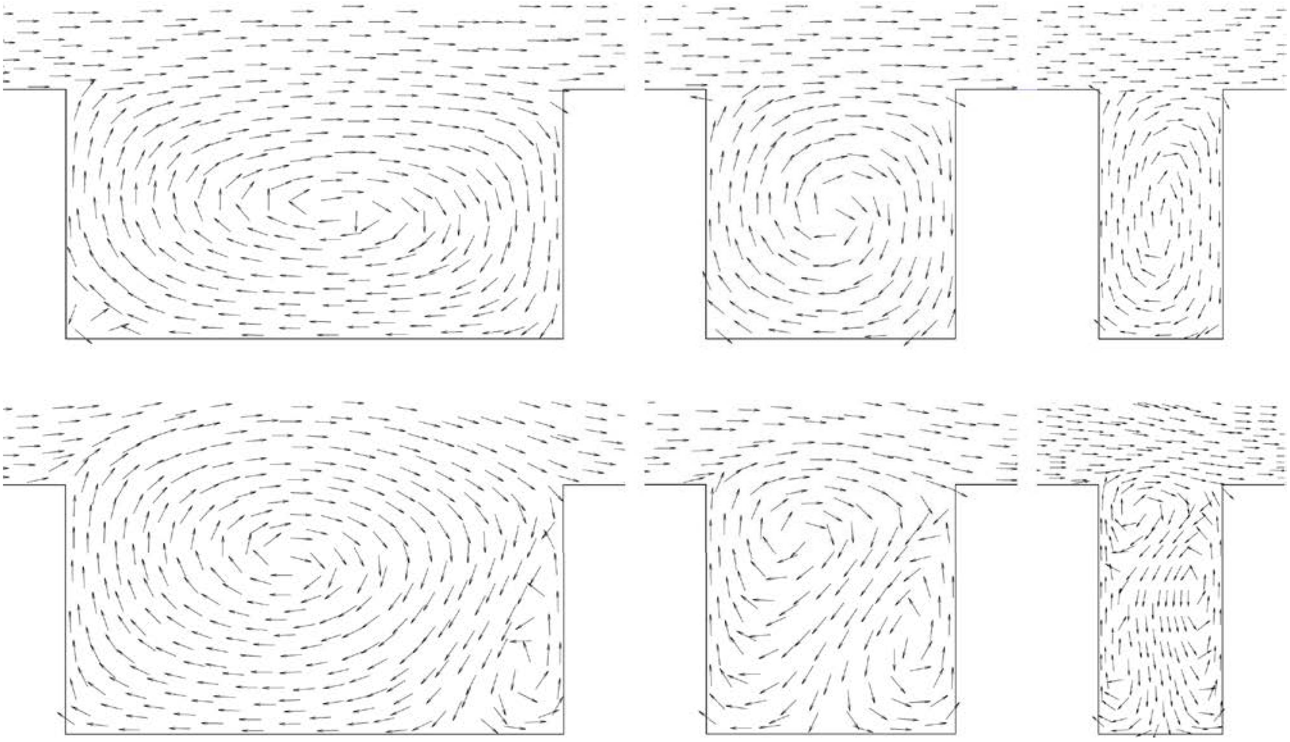

Figure 2: Flow fields neglecting buoyancy (top) and considering buoyancy (bottom) for aspect ratios of 0.5, 1 and 2 (left to right).

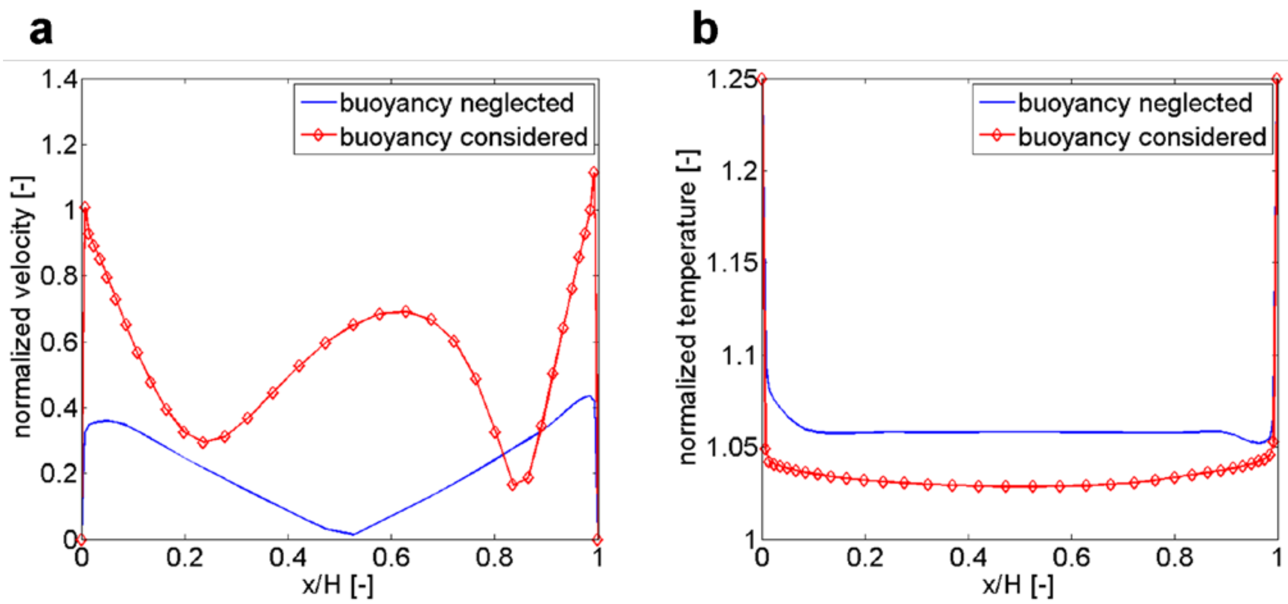

Figure 3: Velocity magnitude normalized by U_{10} (a) and temperature normalized by the inlet temperature (b) on the horizontal centreline in a street canyon with an aspect ratio of 2 , U_{10} = 0.25m/s, inlet temperature 20°C and wall and ground surface temperatures of 25°C.

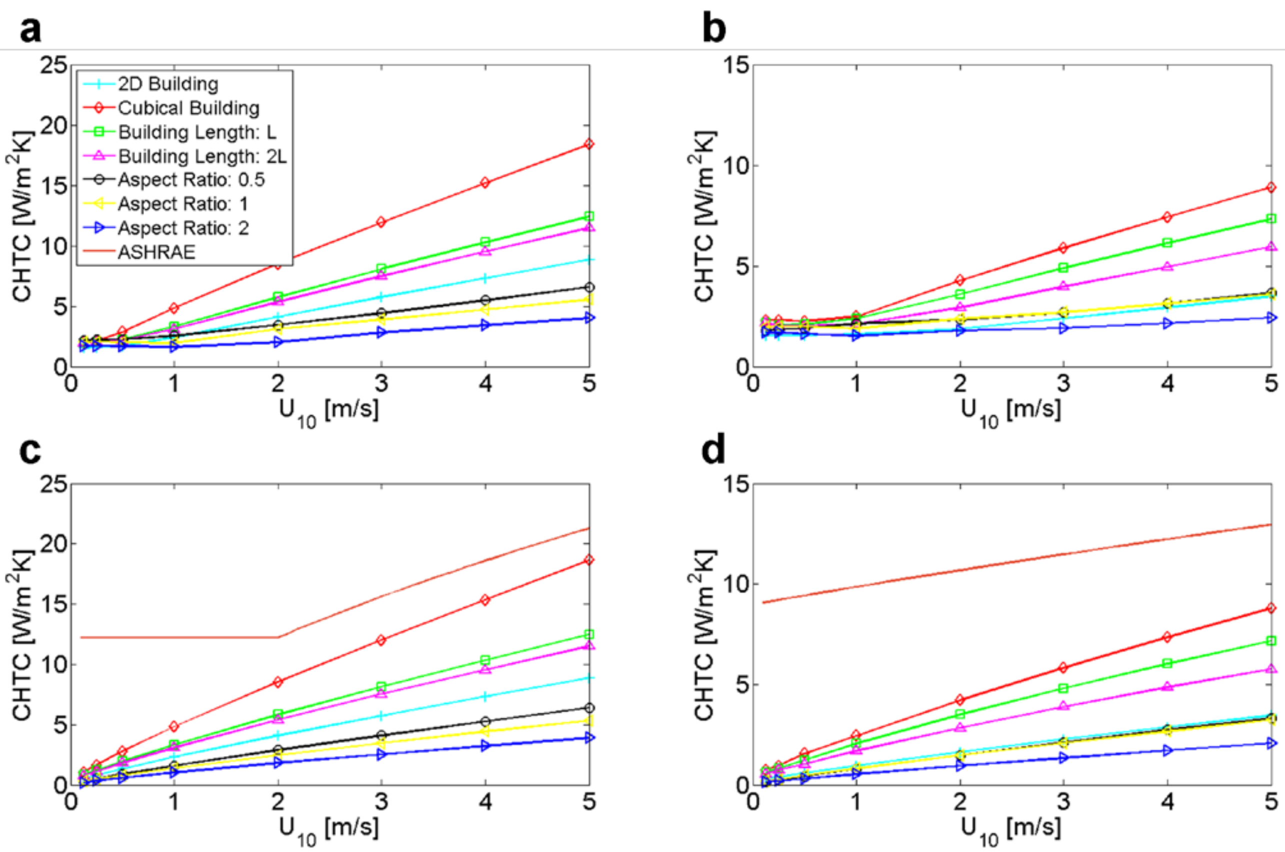

Figure 4: CHTC versus wind speed with a temperature of 30°C for the heated surfaces: (a) windward wall with buoyancy; (b) leeward wall with buoyancy; (c) windward wall without buoyancy; (b) leeward wall without buoyancy.

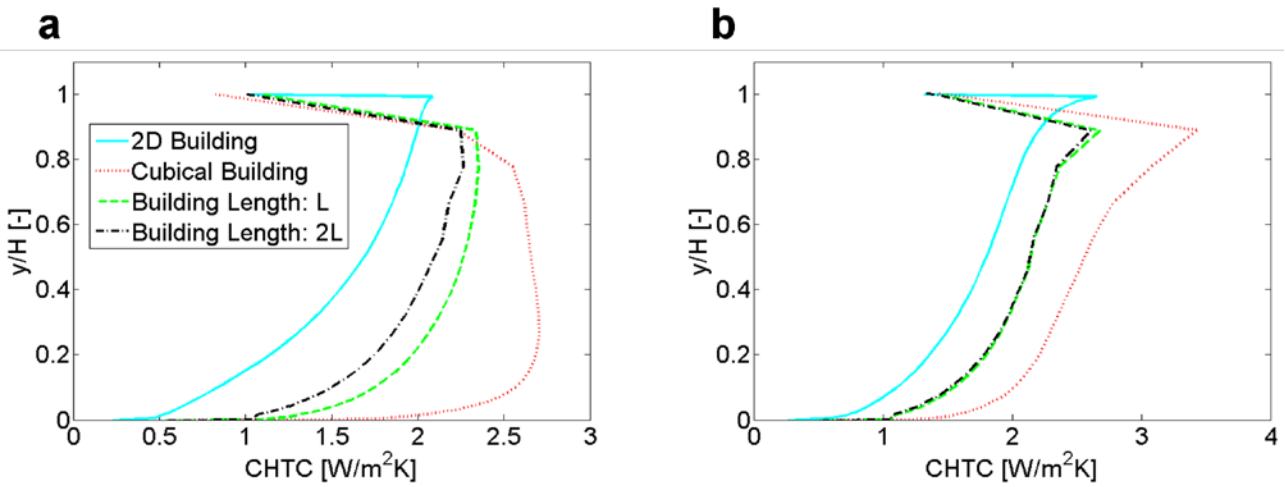

Figure 5: CHTC profiles on the vertical centreline of the leeward (a) and windward (b) walls of the 4 studied stand-alone buildings (simulations with 0.5m/s and heated surface temperatures of 30°C)

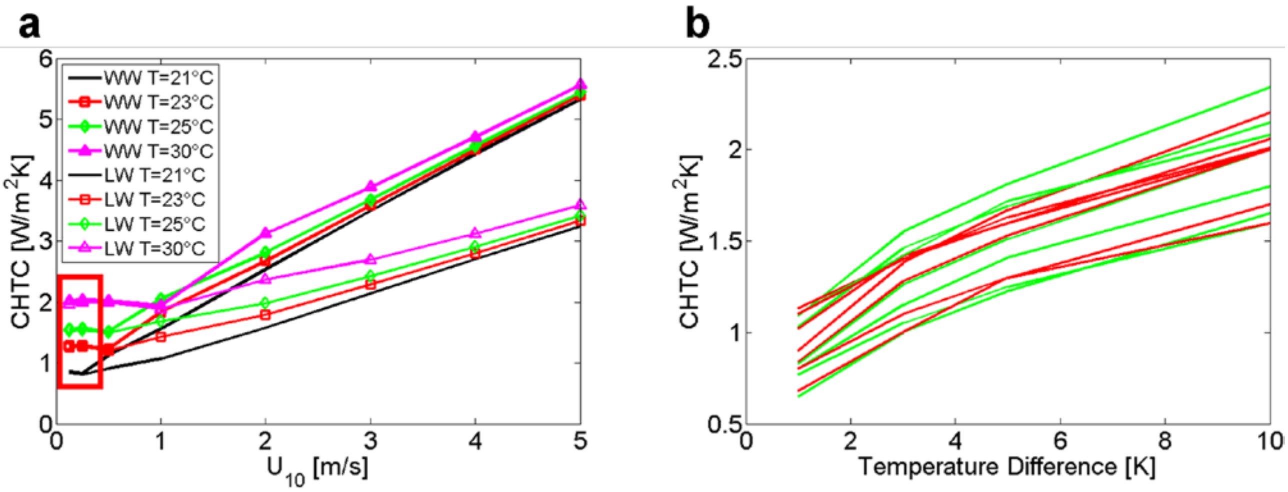

Figure 6: (a) CHTC versus wind speed for windward (WW) and leeward (LW) walls with different wall and ground surface temperatures for a street canyon with an aspect ratio of 1. (b) CHTC for low wind speeds (red box in figure 6a) versus temperature difference between air and surfaces temperatures for all 7 geometries: windward (red) and leeward (green) walls.

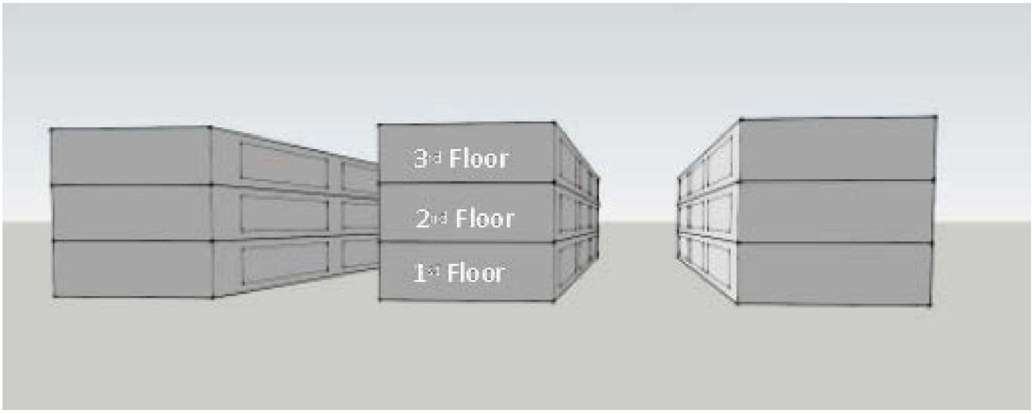

Figure 7: Three identical buildings, separated by street canyons with an aspect ratio of 1. The building of interest is the middle building.

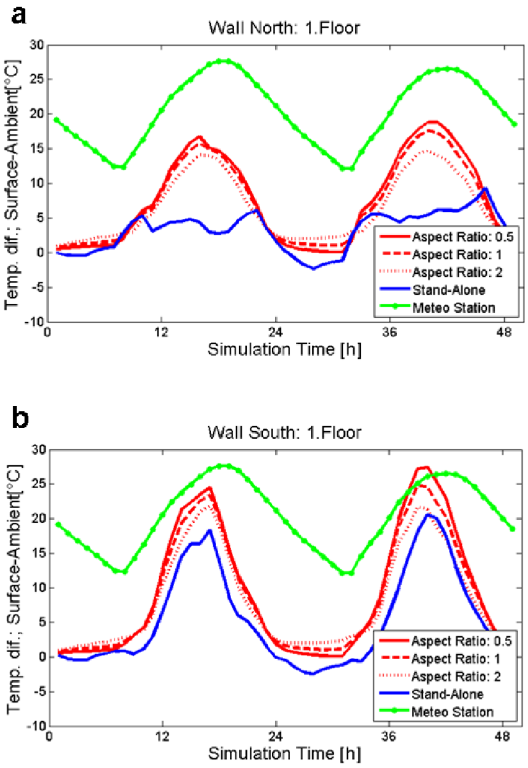

Figure 8: Ambient air temperatures and differences in wall surface temperatures for the north and south façades of the 1st floor, for a stand-alone building and for buildings surrounded by street canyons with different aspect ratios (0.5, 1 and 2).

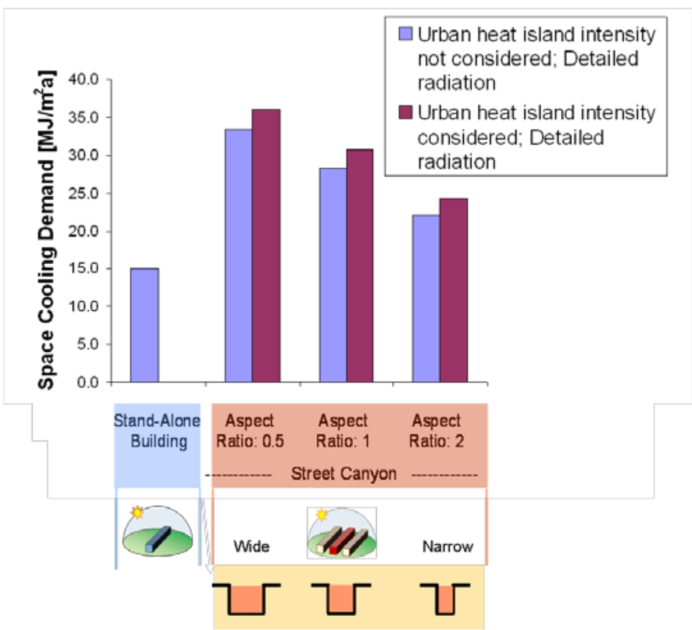

Figure 9: Annual space cooling demand for different modelling cases and different street canyon aspect ratios.

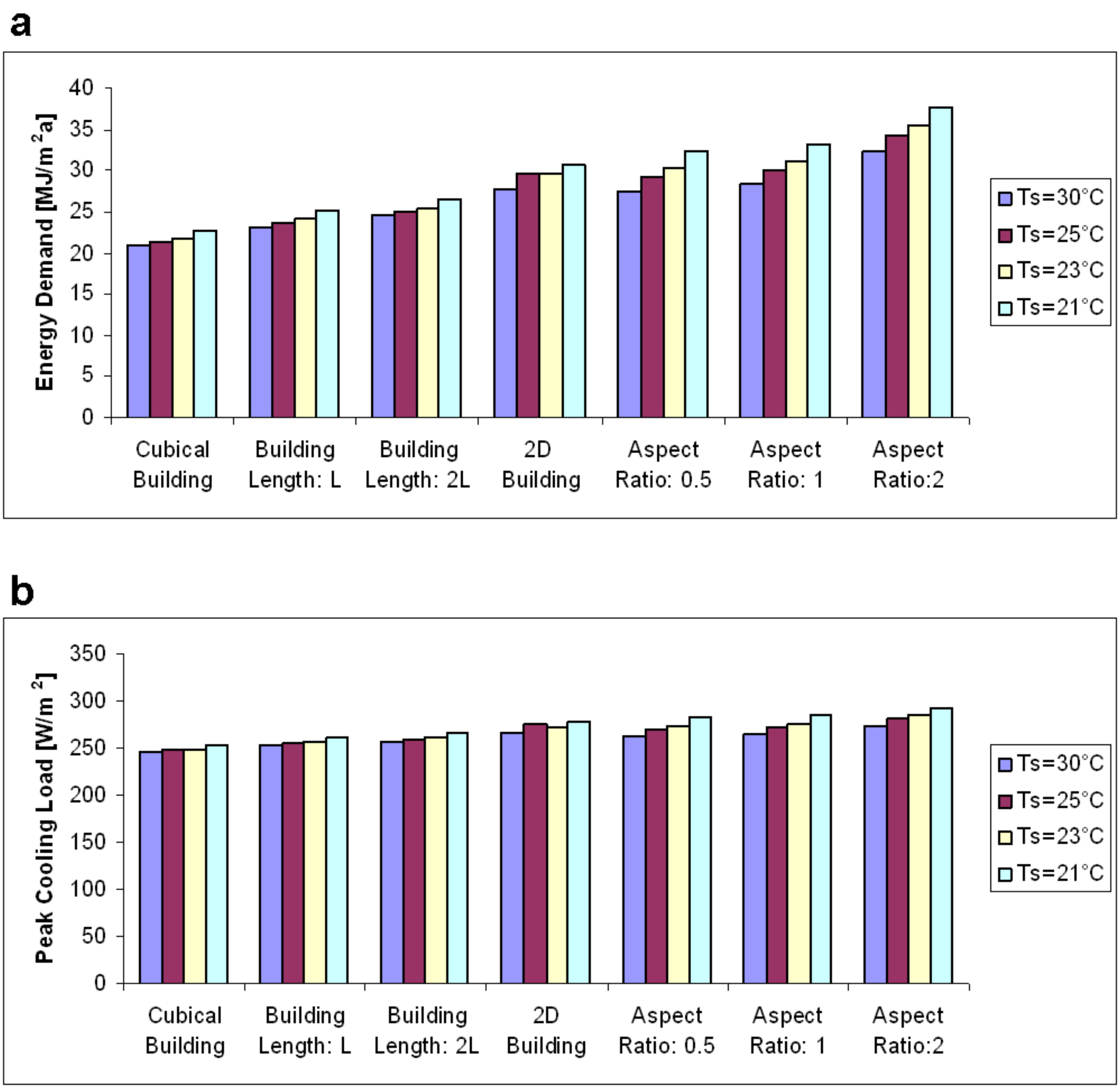

Figure 10: Total annual space cooling demands (a) and annual peak cooling loads (b) for a street canyon with an aspect ratio of 1 using CHTC correlations developed for different geometries and temperature differences between building façades (T_s) and ambient air (here 20°C).

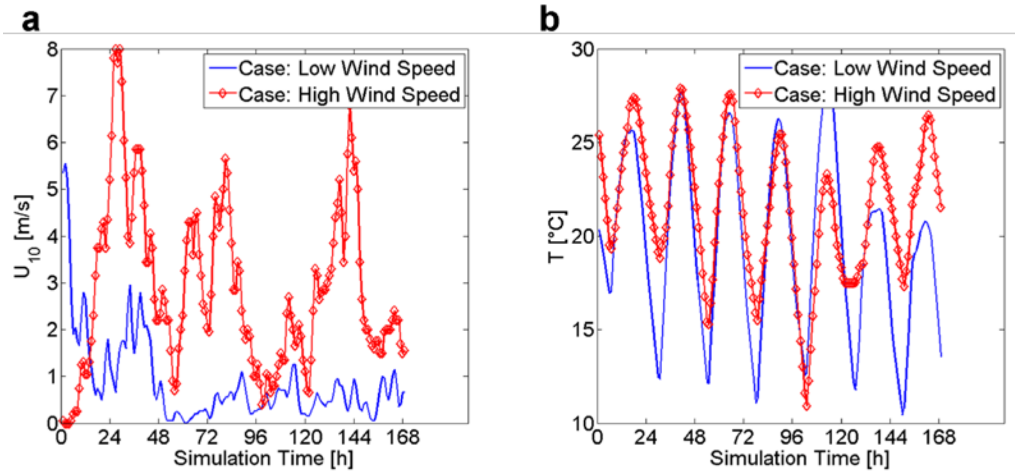

Figure 11: Wind speeds (a) and air temperatures (b) for the two studied weeks.

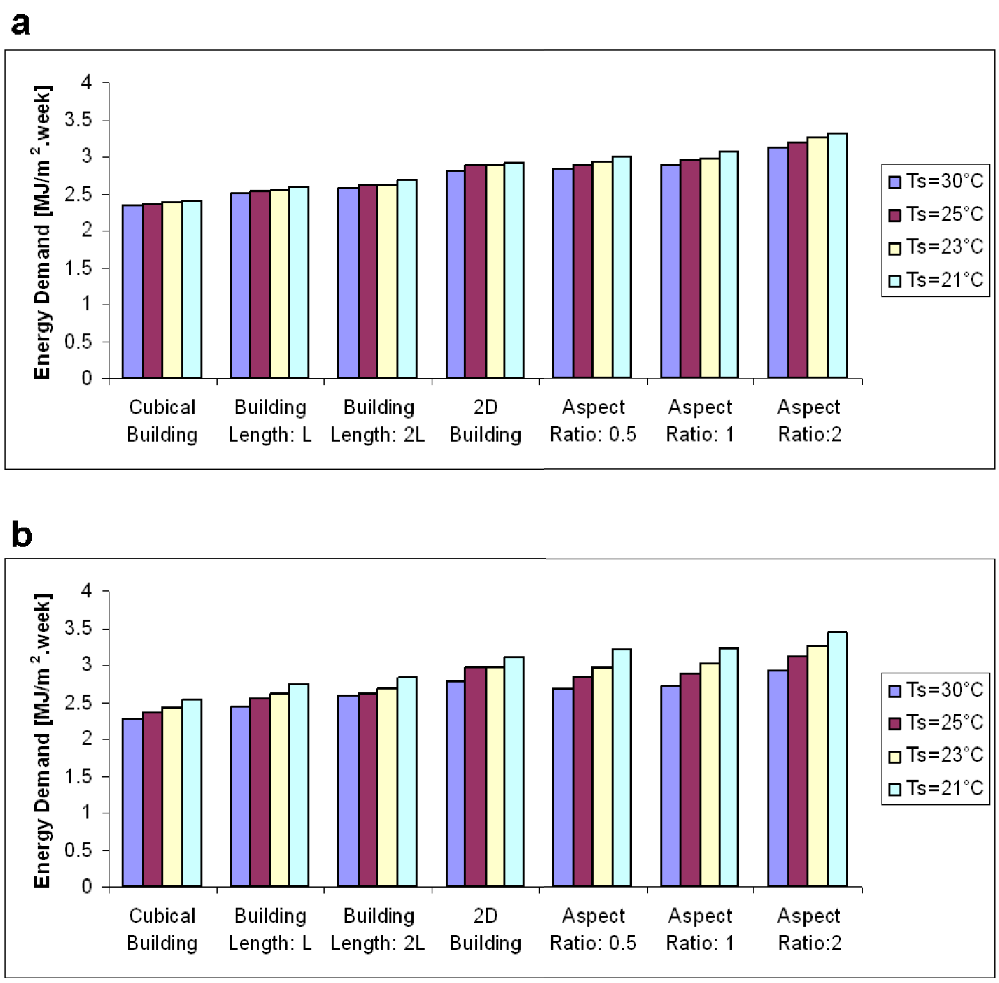

Figure 12: Weekly space cooling demands for a week with high wind speeds (a) and a week with low wind speeds (b) for a street canyon with an aspect ratio of 1 using CHTC correlations developed for different geometries and temperature differences between building façades and ambient air.