F: Physical responses & physiology
F.2. Health assessment (incl. Thermal comfort)

ASSESSMENT OF OVERHEATING RISK IN DWELLINGS

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SUMMARY

Overheating in buildings is identified as an essential cause of several problems ranging from thermal-discomfort and productivity reduction to illness and death. The aim of this study is to assess the overheating risk in dwellings considering the diversity in dwelling designs and operations as well as the expected changes in climate. The overheating risk in thousands dwelling cases is assessed for current and future climate scenarios by using high-resolution dynamic thermal modelling and a new-defined performance indicator called indoor overheating degree (IOD). The dwelling cases represent 9,216 possible combinations of archetypes, orientations, fabric-characteristics, shading options, ventilation rates, internal-heat gains, and adaptation opportunities consistent with the characteristics of the Dutch dwelling stock from 1964 to 2012. The results show that for a given climate scenario, there is a significant difference in overheating risk in dwellings. The difference will increase in the future as global warming continues mainly because of the reduction in natural cooling potential. Dwellings with high solar-heat gains (e.g., detached houses with a large inefficient-shaded glazing area) and/or with low-heat transmissions (e.g., highly-insulated/small-facade apartments) are at higher risk of overheating than others. Adaptation interventions should be taken quickly for protecting those more sensitive dwelling to climate change.

INTRODUCTION

Over 35,000 people across Europe died from heat-related causes in the sweltering summer of 2003 (Brücker, G., 2005). If the heat-trapping emissions continue to rise at current rates, a summer like the one in 2003 could be considered ordinary by the end of the century (Stott et al., 2004). Although there is only limited and indirect epidemiological evidence concerning the conditions of indoor temperature exposure that give rise to adverse health effects (Department for Communities and Local Government 2012), it is reasonable to assume that the heat-related illness and death cases resulted not only from unusually high peak outdoor temperatures and a reduction in the diurnal temperature swing, but also from a failure of buildings to successfully modify the external environment (Coley and Kershaw, 2010). High indoor temperature impairs the ability to recover from outdoor heat stress (Kovats and Hajat 2008). Furthermore, it allows growth and propagation of pathogenic ecosystems (Bernstein, et al., 2008). Increased sleep fragmentation because of high temperatures was directly linked to poor health (Buysee et al., 2010), and heat-related mortality is pronounced among the elderly in nursing homes (Garssen et al.,2005). The projected rise in both average and extreme temperatures, due to the global warming, will make dwellings more uncomfortable and potentially dangerous to the occupant's health due to the high internal temperatures. In order to protect existing and new dwellings from the ever-increasing risk of overheating, policy decisions and adaptation interventions should be taken quickly if the dwelling already at a higher overheating risk. The aim of this study is to assess the overheating risk in a wide range of dwelling types for supporting better understating and optimal decision for mitigating the overheating risks.

METHODOLOGIES

Considering the wide diversity in dwelling designs and operations as well as the expected change in the current climate, the overheating risk in a wide range of dwelling cases is quantified under four climate scenarios using a detailed building performance simulation program (IDA-ICE 4.6) assisted by an ancillary post-processing calculation model. The IDA-ICE 4.6 is used to calculated the free-running hourly indoor operative temperature in all the addressed dwellings. The calculations considered the radiative, conductive and convective heat exchange between building elements and the internal and external environment, as well as dynamic representations of occupancy densities, solar gains, air densities, and air flow. The ancillary calculation model is developed using MATLAB-2013b for quantifying and comparing the overheating risk in the studied dwelling cases considering not only the intensity and frequency of the overheating conditions but also the particular occupant behaviour and adaptation opportunity in each dwellings zone identified. Different thermal comfort criteria are applied for different zones of the dwelling. Adaptive comfort temperature limits according to (Boerstra et al., 2013) and (Peeters et al.,2009) are considered for living rooms and bedrooms, respectively. The studied dwelling cases, climate scenarios, and thermal comfort criteria as well as overheating indices are described below.

Studied dwelling cases

The overheating risk in dwellings is investigated considering 9,216 possible combinations of dwelling archetype, orientation, fabric characteristics, shading option, ventilation rate, internal heat gain, adaptation opportunities, as well as occupancy time consistent with the characteristics of the Dutch dwelling stock from 1964 to 2012 (Table 1). The maximum ventilation rate is assumed to vary according to the available potential of ventilative cooling. The maximum ventilation is emulated by proposing a virtual VAV system in the simulation model. The outdoor air is used to cool down the dwelling if the indoor temperature is higher than 25^{o}C in living rooms and 23^{o}C in bedrooms. Shading control is assumed to apply shading when the schedule is 'on' and the incident light exceeds 100 W/m^2 on the inside of the glass.

Climate scenarios

The overheating risks in the 9,216 studied dwelling cases are assessed for four climate scenarios resulting in 36,864 (9216 x 4) studied cases. The climate scenarios are selected to represent historical and future outdoor conditions according to historical measurements and global-warming projections made by the Dutch metrological institute (KNMI, 2006). The climate scenarios (Table 2) include moderate climate (De Bilt 1964/1965) considering the average summer of the Netherlands, extreme weather (De Bilt 2003) considering the 2003 long-term heatwave, warm climate (De Bilt 2100 GH) assuming the 2100, 2^{o}C degree, global warming scenario (G_H), and hot climate (De Bilt 2100 WH*) assuming the 2100, 4^{o}C degree, global warming scenario (W_H) as well as 1.4^{o}C temperature rise due to the urban heat island effect in accordance with (Heijden et al., 2013).The warming degrees of the aforementioned climates are shown in Table 2 using traditional indicators (e.g., mean ambient temperature ''T_m'' and cooling Degree days ''CDD'') as well as a newly defined indicator called ambient warmness degree (AWD) that is defined by Equation 1. The AWD is defined to quantify the warmness of a given climate considering both the amplitude and timespan of warmness conditions.

$$AWD = \left(\frac{\sum_{i=1}^{N.} (T_a - T_b)_i \, dt}{\sum_{i}^{N} dt} \right) \qquad \text{Equation 1}$$

where T_a is ambient temperature, T_b is base temperature (18^{o}C) and N is the number of hours provided that $T_a \geq T_b$ in the summer season. dt is the time step (one hour).

Table 1 Parameters of the 9216 dwelling design and operation cases

Parameters		No. options	description
Design parameters	Archetype	8	detached house, semi-detached house, as well as six flat typologies (corner/middle x ground/middle/top floor)
	Fabric characteristics (e.g., U-value, WWR, etc.) according to dwelling construction age	6	According to six construction period (before 1964, 1965-1974, 1975-1991, 1992-2005, 2005-2012, post 2013) representing the Dutch building stock
	Orientation	4	South/North or West/ East
	Shading option	3	No shading, internal shading or external shading with control.
Operation Parameters	adaptation opportunity	2	Fixed and adaptive temperature limits are assumed if ''there is no'' and if ''there is yes'' adaptation opportunity, respectively.
	Ventilation Rate	2	Minimum (0.9 l/sm^2) or maximum (5 and 8 ACH variant acc. to natural cooing potential for bedrooms and living room respectively)
	Internal heat gain from lighting and appliances	2	Standard or a bit higher, about 4.3 or 5 W/m^2 for houses and about 5 or 5.3 W/m^2 for flat apartments considering realistic occupant behavior patterns according to ISSO32, 2010i.
	Occupancy profile	2	Attendant at home during working hours ? (Yes or NO)
Number of parameters combinations		9,216	dwelling designs & operations

Table 2 The investigated climate scenarios

Climates		T_m [°C]	CDD-18°C	AWD 18°C	Direct Radiation [W/m²]	Diffuse radiation [W/m²]
Histo-ric	DeBilt 1964/1965 *(Average summer)*	14.9	0.0	0.6	125.7	105.9
	DeBilt 2003 *(extreme weather)*	16.6	10.7	1.5	153.0	106.1
Future	DeBilt 2100 G_H *(future scenario)*	19.4	30.0	3.0	162.7	101.3
	DeBilt2100 W_H**(worst future scenario)*	23.7	101.4	6.0	158.6	101.1

Overheating risk assessments

The indoor overheating risk is quantified using traditional indicators like maximum temperature (T_{max}) and number of indoor overheating hours (*IOH*) as well as a newly defined indicator called indoor overheating degree (*IOD*, see Equation 2). The *IOD* is defined to quantify the overheating risk in all the dwelling zones, taking into consideration the intensity/amplitude and frequency of the indoor overheating conditions as well as the particular occupant behaviour and adaptation opportunity in each zone identified. The intensity is quantified by the temperature difference (ΔT) between the free running indoor temperature (T_{fr}) and the thermal comfort temperature limit (TL_{comf}). The frequency is calculated by integrating the amplitudes of overheating during the occupied period (occ.t) at the different dwelling rooms/zones (no.Z) to present the overall overheating in the dwelling

$$IOD = \frac{\sum_{z=1}^{no.Z} \sum_{t=1}^{occ.t(z)} \left(\max\{\Delta T(z,t), 0\} \times dt\right)}{\sum_{z=1}^{no.Z} \sum_{t=1}^{occ.t(z)} dt} \qquad \text{Equation 2}$$

Where: $\Delta T(z,t) = T_{fr}(z,t) - TL_{comf}(z,t)$

t: time step (hour***),*** ***z:*** zone (room)***,*** ***occ.t:*** occupied time.

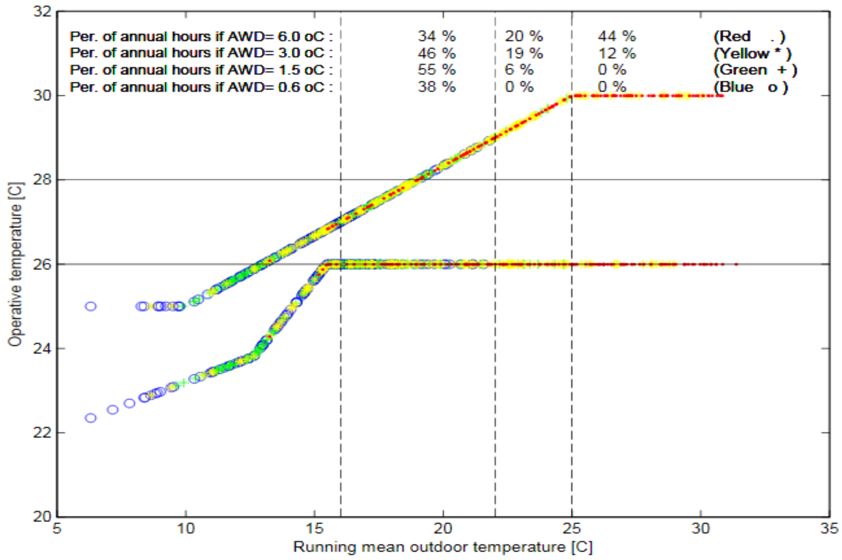

Figure 1 The implemented fixed and adaptive temperature limits for overheating risk assessments

Fixed and adaptive comfort temperature limits are used to assess the overheating risk in terms of IOHs and IOD considering the particular occupant behaviour and adaptation opportunity in each zone identified. The temperature limits are shown in Figure 1 as functions of the running mean outdoor temperature. In the same figure the annual hours are divided by percentage according to the AWD as well as the summer thresholds. The figure shows that 20% and 44% of the annual hours of the hot climate (De Bilt 2100 W_H*) are classified as warm and hot summer, respectively.

RESULTS AND DISCUSSION

This section presents the simulation results of the predefined 36,864 studied cases (9,216 dwelling cases x 4 climate scenarios). Figure 2 presents the ranges of maximum and mean free-running indoor operative temperatures in living rooms (the most overheated during the occupied hours) in all the studied dwelling cases (Table 1) versus the four given climate scenarios (Table 2) presented by their AWD 0.6 ^{o}C, 1.6 ^{o}C, 3 ^{o}C, and 6 ^{o}C, respectively. The figures on the left and right hand side present the temperature ranges in the dwelling cases with minimum (~1.5 AHC) and maximum (up to 8 ACH) ventilation rates, respectively. It is reasonable to assume that there will be a fairly wide distribution of indoor temperatures at a given ambient temperature. Firth et al. 2007 highlighted large variations (up to 5^{o}C temperature difference) in the maximum internal temperatures of 62 houses in Leicester during the 2006 heat wave. In this study up to 13 ^{o}C and 7 ^{o}C maximum indoor temperature difference is observed (Figure 2). between minimally and maximally ventilated dwelling cases, respectively, for climate scenario 2 (2003 extreme weather, AWD = 1.6^{o}C). According to the dwelling designs and/or operations (Table 1) the lowest maximum indoor temperature for climate scenario 2 is 34^{o}C. However, the greatest maximum indoor temperature for the same climate scenario is 47^{o}C. It is worth mentioning that, for a given climate scenario, the temperature differences during the night time are smaller than the differences during the daytime, particularly in well-ventilated dwellings.

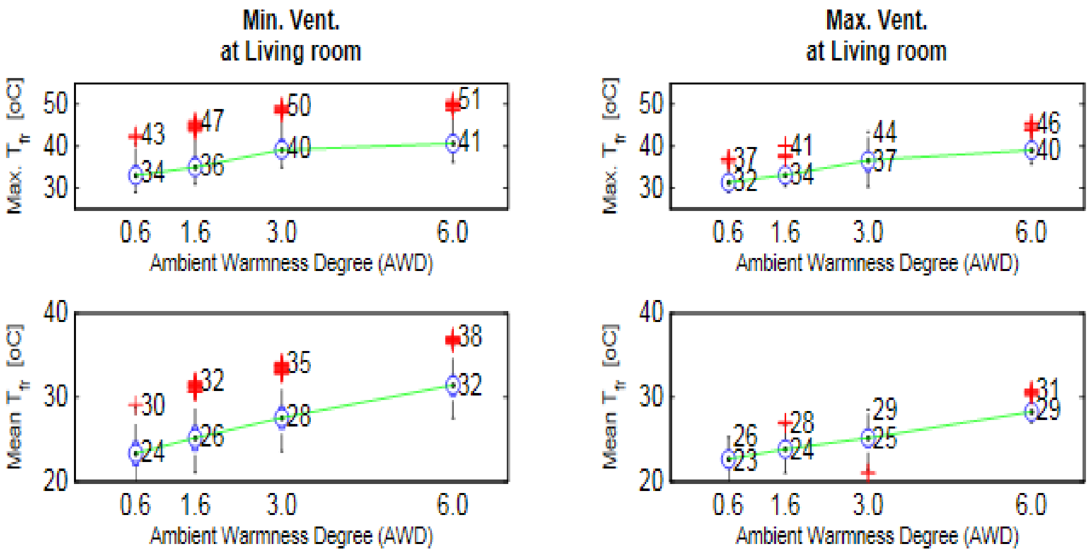

Figure 2 Boxplots present the ranges of maximum and mean, indoor operative temperatures in living rooms during the occupied hours (from 1st May to 30th September) considering all the studied dwelling cases (Table 1) as well as the four climate scenarios (AWD = 0.6, 1.5, 3, and 6 ^{o}C, respectively). The left and right columns present the temperature ranges when minimum (~1.5 ACH) and maximum (up to 5 ACH for bedrooms and 8 ACH for living room) ventilation rates are implemented, respectively. (The red points presents the outlier more/less than 3/2 times of upper/lower quartile).

It is also worth mentioning that in extreme weather like 2003 (AWD = 1.6°C), the daily mean temperature in most of dwelling cases would exceed the safe limit (24.7 °C) identified by epidemiological studies which have shown that mortality begins to rise above a heat threshold of around 24.7°C maximum daily temperature. The results also show that in the studied dwelling cases the minimum temperature will increase significantly as the global worming continues. The minimum temperature will increase from 14°C to 20°C on average when the AWD increases from 0.6 to 6 °C.

Figure 3 and Figure 4 present the overheating risk in the studied dwelling cases in terms of indoor overheating hours (*IOHs*) and indoor overheating degree (*IOD)* assuming FTL and ATL as comfort criteria (Figure 1), respectively. The figures show that the Dutch dwellings with minimum ventilation rate (0.9l/sm^2) are already vulnerable to overheating and that this is likely to get worse as global warming continues. For a given climate scenario, there is a significant difference in overheating risks in dwellings. This difference will increase in the future as the ambient is going to get warmer with the ventilation rate and the solar shading being the main causes of this difference. The archetype has a significant influence on the overheating degree in dwellings with minimum ventilation rate. However, it has insignificant influence on the well-ventilated dwellings. Flats in middle-floor middle-location of apartment buildings, flats in top-floor middle-location of apartment buildings as well as detached houses are the dwelling archetypes most sensitive to global warming. They are at a higher overheating risk than other archetypes (e.g., semi-detached houses, and flats in ground floors) in the current climate (De Bilt 1964/1965) and they will continue to be at a higher risk in the future. Old dwellings (post-1964) with little or no mechanical ventilation and insufficient solar protection will be at a significant risk of overheating. However, the risk will be significantly higher in new dwellings (from 2005 to 2012) with high insulation levels and improper solar protection, Figure 5. Such new buildings are already at a significant risk (up to *IOD* = 2 °C) of overheating in the current climate. Figure 5 shows the maximum, mean, standard deviation, and minimum of IOD of all the studied dwelling cases classifying them according to their archetypes, ages, and comfort criteria (Table 1).

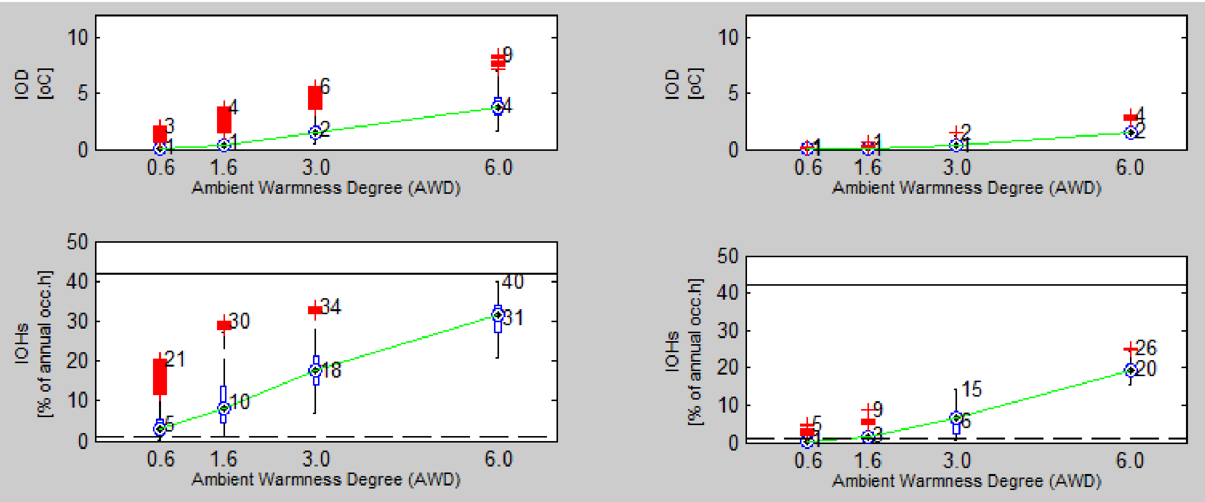

Figure 3 The indoor overheating degree (IOD) and the percentage of the indoor overheating hours (IOHs) at the four given climate scenarios presented by their AWD (0.6, 1.6, 3, and 6 °C). Where fixed temperature limits (28 and 26 °C) are applied as thermal comfort criteria for living spaces and bedrooms, respectively. The figures on the left and right hand sides show the overheating risk in the

dwellings with minimum and maximum ventilation rate, respectively. (The red points ''+'' present the outlier more/less than 3/2 times of upper/lower quartile).

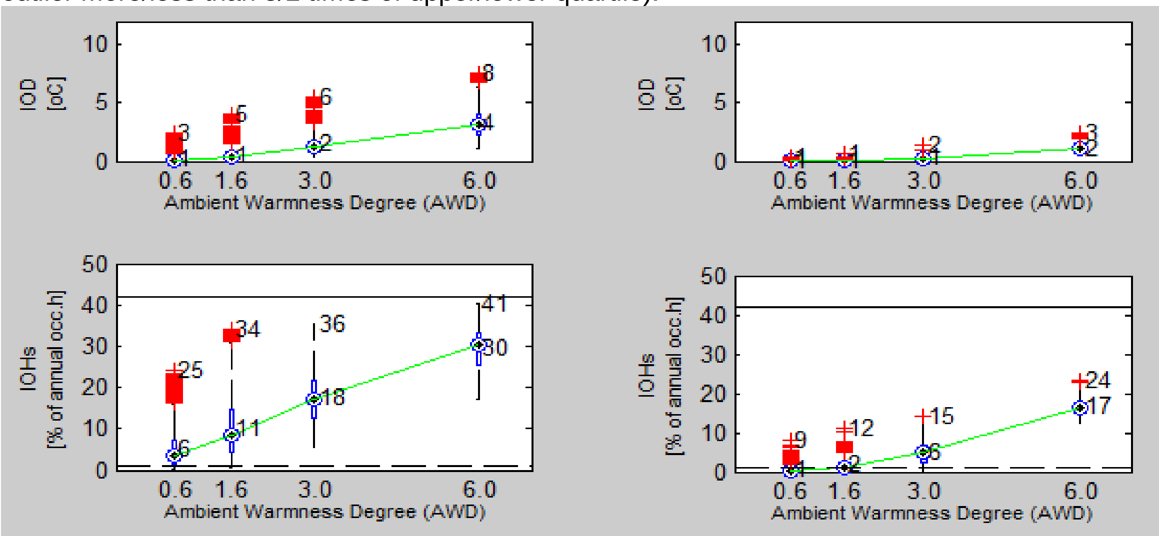

Figure 4 The indoor overheating degree (IOD) and the percentage of the indoor overheating hours (IOHs) at the four given climate scenarios presented by their AWD (0.6, 1.6, 3, and 6 ^{o}C). Where adaptive temperature limits (Figure 1) are applied as thermal comfort criteria for living spaces and bedrooms, respectively. The figures on the left and right hand sides show the overheating risk in the dwellings with minimum and maximum ventilation rate, respectively. (The red points ''+'' present the outlier more/less than 3/2 times of upper/lower quartile).

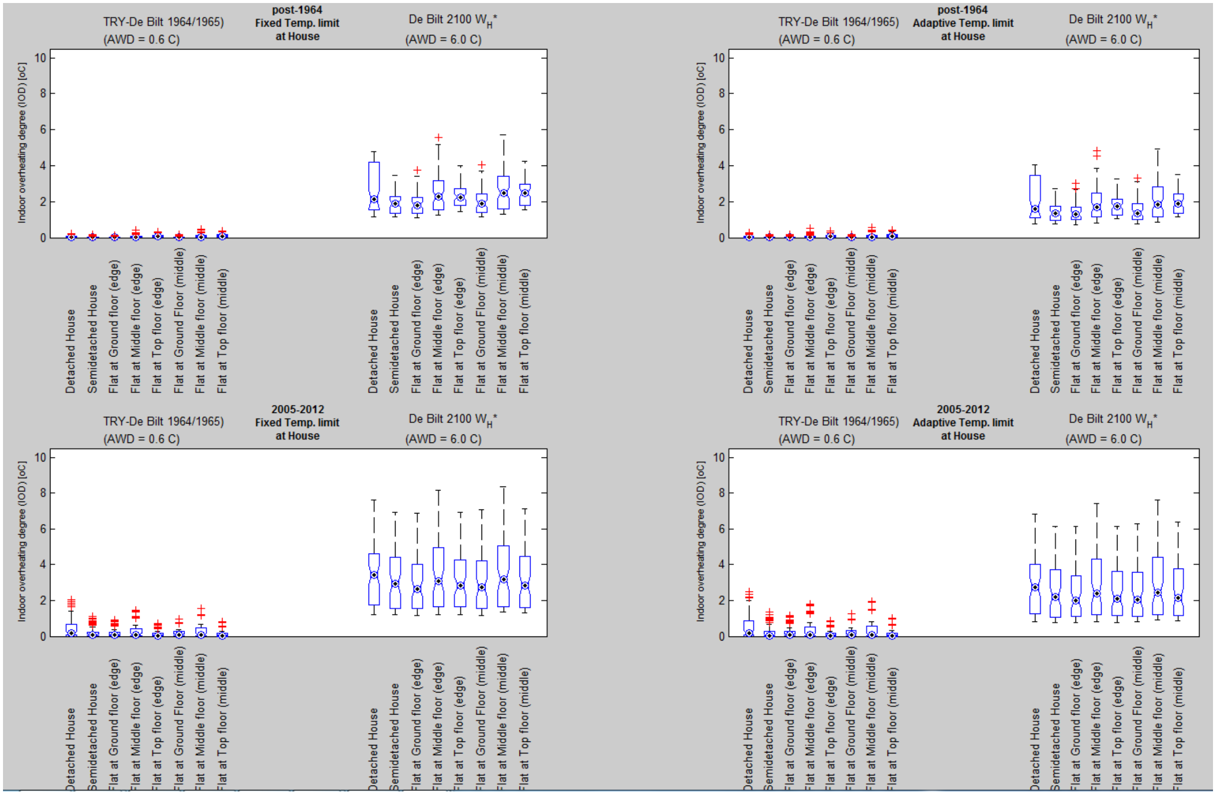

Figure 5 The boxplots show ranges of indoor overheating (IOD) classified in according to 8 dwelling archetypes, 2 ages (post-1961 and 2005-2012), and 2 comfort criteria (Fixed and adaptive comfort temperature limit) at two given climate scenario with 0.6 ^{o}C and 6 ^{o}C ambient warmness degrees (AWD).(The red points''+'' present the outlier more/less than 3/2 times of upper/lower quartile).

CONCLUSIONS

The impact of climate change on the overheating risk in dwellings is investigated comprehensively in the current study. The overheating risk in 9,216 of dwelling cases, consistent with the characteristics of the Dutch dwelling stock from 1964 to 2012, is quantified for four climates based on historical and future-scenario data sets obtained from the Dutch metrological institute (KNMI). The results show that the Dutch dwellings with minimum ventilation rate (0.9 l/sm^2) are already vulnerable to overheating and they are likely to get worse as global warming continues. For a given climate scenario, there is a significant difference in overheating risk in dwellings. The new defined performance indicator (indoor overheating degree, IOD) shows that the difference will increase in the future as global warming continues mainly because of the reduction in natural ventilative cooling potential. Dwellings with high solar heat gains (e.g., detached houses with inefficient shading) and/or with low heat transmission (e.g., flats with a small well-insulated façade area) are at higher risk of overheating than others. Adaptation interventions should be taken quickly for protecting those more sensitive dwelling to climate change.

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