606: Projection of the rural and urban human thermal comfort in the Netherlands for 2050

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Abstract

Warm summer days may reduce thermal discomfort, labour productivity, and may raise morbidity and mortality for vulnerable groups. The projected climate change may raise this thermal discomfort. Implementing measures to prevent adverse health conditions, robust estimates of the future human thermal comfort are required. This study analyses the future human thermal comfort for the Netherlands based on four KNMI-06 climate scenarios. Weather data from 1976-2005 are transformed to future weather design data representative for 2050. Subsequently, the Physiological Equivalent Temperature (PET) is estimated for these future scenarios. All scenarios foresee substantially increased heat stress abundance for both urban and rural areas, particularly under the most intense warming scenario. Then, the frequency of hours with heat stress will more than double, and the increase will develop faster in an urban canyon than in rural areas. For the urban areas, PET appears to have a maximum which is a function of sky-view factor due to a competition between wind speed reduction that increases the PET, and shading that reduces the PET for a reducing sky-view factor.

Keywords: thermal comfort, physiological equivalent temperature, Netherlands, climate scenarios.

1. Introduction

On warm summer days, the adverse environmental temperatures affect human health (Luber and McGeehin, 2008), labour productivity (Dunne et al., 2013), and energy demand. Here, we quantify the current and future human thermal comfort (HTC) in the Netherlands. It is a densely populated country in northwest Europe, which has prevailing south-westerly winds, and a maritime climate due to the proximity of the North Sea (Fig. 1). The population amounts to 16.10^6, i.e. a population density of 488 inhabitants/km2 (CBS, 2014). More than 40% of the population lives in the agglomeration of the cities of Amsterdam, Rotterdam, Den Haag and Utrecht.

Climate scenarios project that the mean 2-m temperature will increase and that heat waves will become more frequent (Van den Hurk et al., 2006), which will affect both the rural and urban HTC, but quantitative HTC projections and public awareness are limited. Adequate measures to prevent adverse health for vulnerable groups the future HTC requires quantification.

We quantify the Dutch HTC development, by transforming current day meteorological time series to the year 2050 for four KNMI climate scenarios. Subsequently, the trends in HTC are evaluated for six WMO weather stations (Fig 1). We quantify the human comfort trends within the urban environment.

2. Physics of urban heat and thermal comfort

Heat balance models of the human body are powerful tools to analyse the HTC (Mayer and Höppe, 1986; Budd, 2001; Heusinkveld et al., 2014). Here we employ the Physiologically Equivalent Temperature (PET), because of its solid physical basis (Deb and Ramachandraiah, 2010). PET estimates are performed by the RayMan model (Höppe, 1999; Matzarakis et al., 2000), and classified on the HTC experience. The classes indicate slight heat stress (PET: 23-29°C), moderate heat stress (PET: 29-35°C), strong heat stress (PET: 35-41°C) and extreme heat stress (PET: 41°C or higher). To quantify HTC in various urban areas, it is important to study different street configurations, i.e. for different sky-view factor (SVF; Oke 1981).

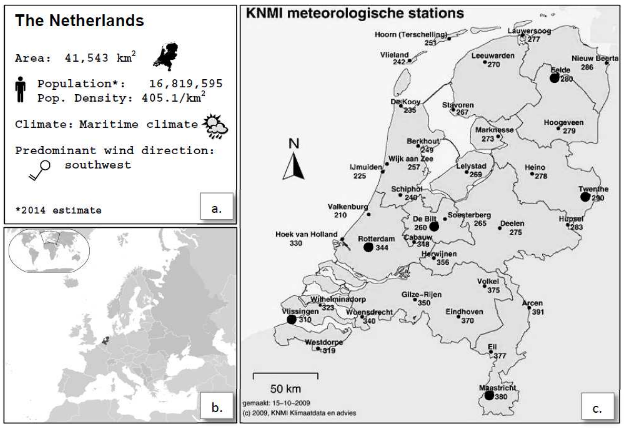

Fig 1: Topographic maps indicating the Netherlands including KNMI weather stations (panel c).

3. Methodology

3.1 KNMI-06 climate scenarios

To transform existing climate records to obtain weather data representing the year 2050, we use four scenarios as published by Van den Hurk et al. (2006). These scenarios have been formulated based on output for western Europe from 5 global climate models and from 8 regional climate models (RCM). The RCM results have been grouped concerning their projected warming, circulation changes over Western Europe, and climate change in the Netherlands.

The climate scenarios contain either a moderate warming of 1ºC ("G"), or a strong warming, of 2ºC ("W") in 2050. In general, a modified atmospheric circulation pattern in Western Europe significantly affects temperature (Van Ulden and Van Oldenborgh, 2006). Thus, both scenarios are employed by subscenarios accounting for circulation changes ("+"). Overall, the four scenarios are G, G+, W and W+ (Fig. 2).

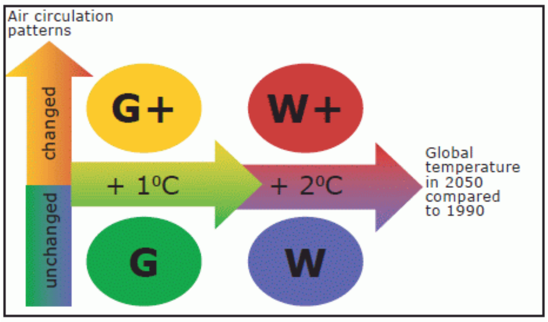

Fig 2: Overview of the KNMI climate scenarios.

The KNMI scenarios provide monthly change coefficients for selected meteorological variables. The produced time series preserve realistic weather sequences. Hence, the transformed series provides information about averages, variation between days, and the probability of extremes for a plausible future climate (Bakker & Bessembinder, 2012). First daily mean values of temperature and RH are transformed, resulting in daily change factors, that are subsequently applied to the hourly data of each day. Wind speed and cloud cover remain unchanged, since insufficient signal was obtained from RCM simulations (Bakker, pers. comm., 2013).

3.2 Weather stations

We have selected six weather stations across The Netherlands to perform the analysis on, i.e. De Bilt, Eelde, Rotterdam, Maastricht, Twente and Vlissingen (Fig 1). De Bilt is the country's main station for the general public. Note that the wind speed is relatively low, since the site is affected by nearby roughness elements as trees, parks and urban areas upwind of the prevailing wind direction.

The other stations are located at remote rural sites. Eelde, is located in the northernmost station though relatively inland. The landscape is relatively open and flat with a sandy soil. Twente is located on an army base weather station in the east side of the country. The landscape is gently rolling with a mixture of forest and grassland on a sandy soil. Maastricht is the most southerly located site of the Netherlands. This airport is located in gently rolling terrain with neighboring grass and cropland. Several forested slopes are present in the surroundings. Rotterdam is a more coastal station, and is situated in a polder with grassland on a clay soil. Vlissingen is a coastal station in the southwest.

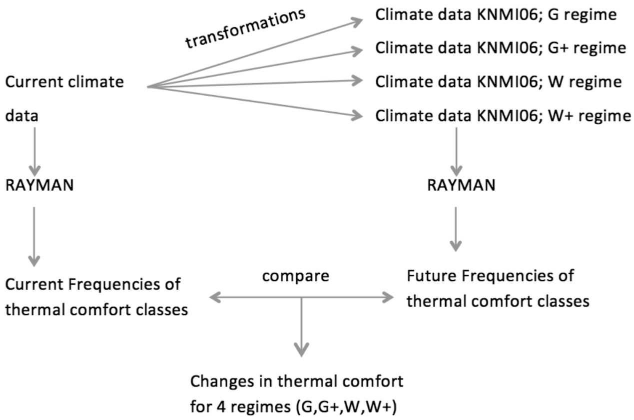

Fig 3: Workflow to estimate future PET frequencies.

3.3 RayMan, sky-view, wind speed reduction

We use the RayMan (v1.2, Matzarakis et al., 2000) model to estimate the HTC. RayMan uses time series of temperature, RH, wind speed, sky-view photographs and cloud cover as input. Rayman uses the skyview photographs to calculate solar radiation penetration into the urban canyon. Three urban areas were selected for this analysis, we estimate the SVF from fish-eye photos, i.e. with SVF = 0.841, SVF = 0.41, and SVF= 0.262.

Wind speed is the second most important factor affecting HTC. We reduce the rural 10-m wind to the street canyon (height H, weight W) using traverse observations by Heusinkveld et al. (2014), and derived an empirical wind adjustment factor (WAF) for z=1.2 m (PET reference level):

$$WAF = e^{-(\mathrm{H/W})/(20\ \mathrm{z/H})}$$

Fig 3 summarizes the overall workflow followed in this research.

4. Results

4.1 Thermal comfort rural environment

This subsection presents the projected HTC for the countryside, i.e. for a SVF=1.0 and WAF=1, expressed as the yearly hours with heat stress (PET>23ºC). Table 1 presents the PET distribution for a rural environment around Rotterdam. Most of the heat stress is found in the slight heat stress class of 23<PET<29ºC, i.e. ~178 h/y. Compared to the current climate, heat stress hours will increase by about 31 h in the G scenario, by 96 h in the G+ scenario, by 68 h in the W scenario and by 116 h in the W+ scenario. Also, the other heat stress classes show strong increases of adverse HTC abundance.

Table 1: Overview of current and future hours of heat stress in Rotterdam.

PET (ºC)	Current	G	G+	W	W+
< 4	4215	3832	3662	3417	3121
4 – 8	1488	1504	1359	1559	1553
8 – 13	1577	1680	1577	1747	1729
13 – 18	863	1001	1167	1146	1265
18 – 23	362	425	543	499	588
23 – 29	178	209	274	246	294
29 – 35	70	91	131	114	144
35 – 41	14	24	47	34	58
> 41	0	2	8	4	14
Sum PET >23	**262**	**325**	**459**	**398**	**510**

The class of PET>41ºC, this range is hardly reached in the current climate for a 30 y period. In the future climate projections this class will be populated with 2, 8, 4, and 14 h/y in the G, G+, W, and W+ scenarios respectively (Table 1).

The bottom row in Table 1 aggregates the frequencies for PET > 23°C. Currently, these amount to 262, and 325 for the G, 459 for G+, 398 for W, and 510 h for the W+ scenario respectively. All scenarios foresee a substantial heat stress increase, and even a doubling in the W+ scenario.

Fig 4 depicts the results per weather station. Inland stations, i.e. Maastricht, Twente and De Bilt have the highest amount of heat stress. The lowest heat stress abundance is found in Eelde, Rotterdam and Vlissingen. Regarding the moderate heat stress class (PET: 29-35ºC), an analogous pattern is found, i.e. the coastal stations (Vlissingen, Eelde and Rotterdam) experience the lowest heat stress load. Vlissingen counts for the current climate 45 hours in this class, though this is projected to increase to 104 h in the G+ scenario and 112 h in the W+ scenario, which is more than a doubling. In general, results for other cities confirm this finding in this class.

The highest frequency is found again in the G+ and W+ scenario as Table 1. Remarkably De Bilt, Rotterdam and

Vlissingen contain more heat stress hours under the G+ compared to the W scenario.

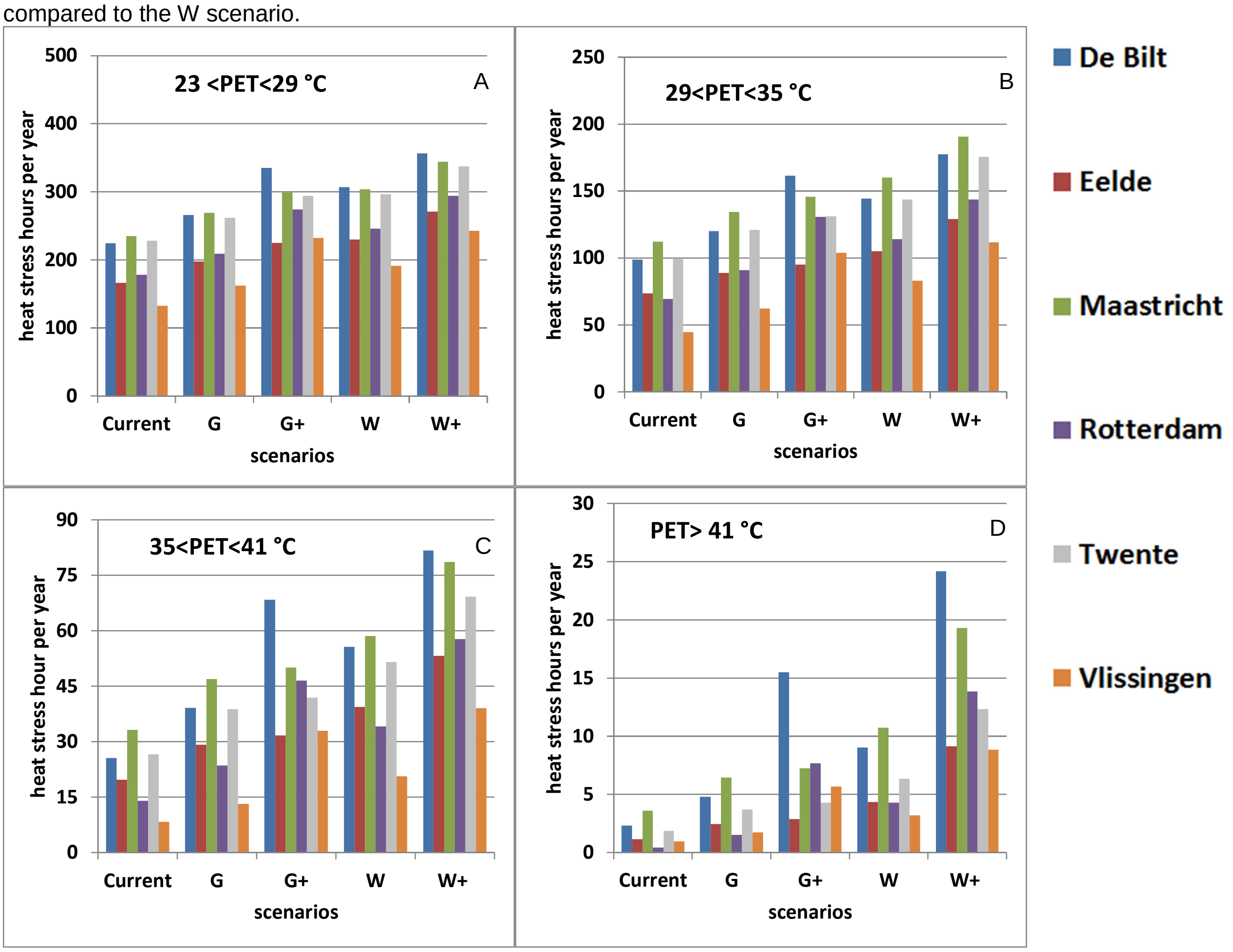

Fig 4: Current and future hours with heat stress per class (A-D) and per rural weather station.

The change of the 90 percentile of the temperature distribution for both classes is approx. equal for the months July, August and September. However, the G+ climate scenario has a somewhat larger increase in reference crop evapotranspiration and thus RH than the W scenario. The higher PET frequency in this class for the G+ scenario is thus due to the humidity contribution to the HTC. Eelde, Maastricht and Twente do not show this effect, probably because of the contrasting RH regime in these inland stations. Also in PET class of 35-41ºC, the G+ and W+ scenarios contain the most heat stress. Remarkably, De Bilt shows high peaks for these scenarios. The same behaviour for De Bilt is found for the HTC in the class PET>41ºC. Currently, PET>41ºC hardly exists. The lowest frequency is found in Rotterdam with 1 h/y and the highest in Maastricht with 4 h/y. In the G scenario this raises to 2 h/y in Rotterdam and 6 h/y in Maastricht. For the W+ scenario, this amounts to 14 h/y for Rotterdam and 19 h/y for Maastricht.

4.2 Thermal comfort urban environment

Fig 5 shows the yearly number of hours with heat stress for the various KNMI-06 scenarios averaged over the six weather stations various SVFs and PET classes. The results for the relatively open area represented by Fig. 4 and 6 are analogous as discussed for the rural area in the previous section. In the current climate about 220 h/y of heat stress, which increases to ~290 h/y in the G scenario, 380 h/y in the G+ scenario, 355 in the W scenario, and 455 h/y in the W+ scenario.

In (PET>23ºC) the amount of heat stress equals to 296 h/y for the current climate (sum over all bars), 361 h for G, 451 h for G+, 432 h for W, and 535 h/y for the W+ scenario. Compared to the current climate this results in an increase of 22% for G, 52% for G+, 46% for W and 80% for W+. An analogous development is projected for a street with SVF = 0.41, with again the highest amount of heat stress occurs under the G+ and W+ scenarios (Fig. 5b). Moreover in the current climate, PET>41ºC occurs only 2 h/y if we take the average for all the six stations. However, in the G; G+; W and W+ scenarios this will be respectively 3, 7, 6, and 14 h/y.

Fig. 5c presents results for a representative example of an E-W oriented urban canyon. This configuration shows also the highest amount of heat stress. The yearly amount of heat stress is 347 hours in the current climate. In the climate projections these values will raise to 417 for G, 522 for G+, 494 for W and 615 for the W+ scenario. Compared to the current climate this is an increase of respectively 70, 175, 147 and 268 h/y. This is approximately the same relative increase compared to the previously discussed configurations and for some scenarios even more. Compared to rural conditions this increase is significantly higher. E.g. if we take the sum of the total amount of heat stress in the rural climate, this will lead to 300 hours in the current climate. In the KNMI-06 climate projections this will be 366 for G, 458 for G+, 437 for W, and 541 for W+. Compared to the current climate this is an increase of 66, 158, 137 and 241 h extra per year. These values of the rural climate projections are lower than those that are found for the urban climate.

Hence we conclude that the total amount of heat stress would develop fastest in urban areas.

Overall, the total amount is slightly lower in a street with trees. However if we zoom in on the more extreme heat stress classes the effect of the vegetation is more evident. E.g. for PET>41ºC for the W+ scenario 10 heat stress hours per year in an urban E-W street without trees are expected. In a street with trees, this is only 8 h/y. Hence, including trees in a street will lead to 20% less extreme heat stress hours in this climate projection. Considering the class of 35<PET<41ºC, the case without trees results in 61 heat stress hours, while this amounts to 53 h/y with trees, i.e. a decrease of 13%.

In general, Fig. 5 shows that the wind speed reduction due to SVF results in an increase of the overall number of heat stress hours. However for the most extreme conditions (PET>41ºC) a different development is found. E.g. in the W+ scenario, the number of hours with heat stress in class PET>41ºC amounts to 14 h/y with SVF=0.84 (Fig. 5), increases for SVF=0.411, and then decreases for the SVF= 0.26 cases (Fig. 5c,d). This can be explained by the mechanism as explained in Theeuwes et al. (2014). The street canyon radiation balance, and thereby also PET, is the net effect of trapping of longwave radiation and by shadow effects to the shortwave radiation. For relatively large SVF the longwave radiative trapping effects dominates for a reduction of the SVF, i.e. shortwave radiation is still able to enter the canyon, though longwave radiation is less efficiently able to leave the canyon, resulting in an increased temperature and PET. For very narrow canyons, also the solar radiation can limitedly enter the canyon, resulting is a cooling effect and hence less stress. In addition, narrow canyons result in a substantial wind speed reduction which increases the PET for low SVF. Apparently the last mechanism dominates for small SVFs in our analysis too.

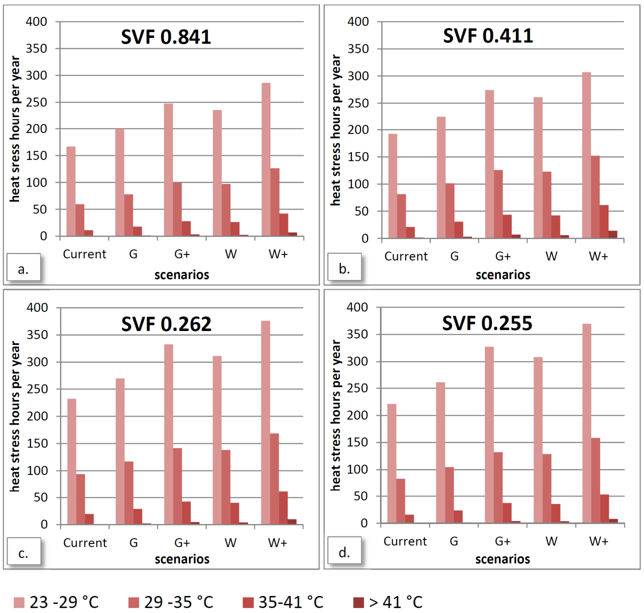

Fig 5: Current and future hours with heat stress scenario (A-D) and SVF class, averaged over the 5 weather stations.

5. Conclusion

We project the future thermal comfort for the Netherlands, based on four climate scenarios as formulated by the Royal Netherlands Meteorological Institute. Observed weather data from 1976-2005 are transformed to future weather design data representative for the climate of 2050, and the Physiological Equivalent Temperature (PET) is estimated, for both coastal and inland rural weather stations, for four contrasting urban street configurations, and for four climate scenarios.

The amount of hours with heat stress will approximately double of the hours with heat stress (PET>23ºC). The heat stress abundance will increase by 66, 158, 137 and 241 h/y for the G, G+, W and W+ scenarios respectively. In a typically Dutch urban environment, these intensifications amounts to 70, 175, 147 and 268 h/y. Moreover, while the class of the most intense heat stress (PET>41ºC) is currently absent, it will appear for 14 h/y in the W+ scenario.

Street configurations largely affect the projected thermal comfort via reduced wind speed and shadowing. E-W oriented streets experience less shadow during daytime than N-S oriented streets, and thus a higher PET magnitude. On the contrary, streets with relatively high vegetation cover experiences a reduction in the high PET classes. The abundance of the extreme PET-classes can be reduced by 20% by including trees in a street with the same sky view.

6. Acknowledgements

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7. References

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