



**HAL**  
open science

# Creation and application of future typical weather files in the evaluation of indoor overheating in free-floating buildings

Obaidullah Yaqubi, Auline Rodler, Sihem Guernouti, Marjorie Musy

## ► To cite this version:

Obaidullah Yaqubi, Auline Rodler, Sihem Guernouti, Marjorie Musy. Creation and application of future typical weather files in the evaluation of indoor overheating in free-floating buildings. *Building and Environment*, 2022, 216, pp.109059. 10.1016/j.buildenv.2022.109059 . hal-03686066

**HAL Id: hal-03686066**

**<https://hal.science/hal-03686066>**

Submitted on 28 May 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



## 1           **Abstract**

2   Expected Global warming and heatwaves coupled with the urban heat island effect (UHI) can  
3   overheat indoor environments of free-floating buildings in temperate climate regions.

4   Overheating assessment requires practitioners to use appropriate climate data and suitable  
5   measurement indices. The aim of this article is first, to propose a practical approach to  
6   generate yearly and typical ready-to-use future typical weather datasets (FTWY) using high-  
7   resolution Regional Climate Model (RCM) data from Coordinated Regional Climate  
8   Downscaling Experiment (CORDEX), and second, investigate the potential of FTWYs in the  
9   assessment of indoor overheating, considering UHI effect.

10   To achieve these objectives, three dynamically downscaled (DDS) FTWYs generated from  
11   RCMs (IPSL-SMHI, CNRM-ALADIN, MPI-REMO) were compared with one statistically  
12   downscaled (ESD) FTWY from Meteonorm, and observed heatwave weather data of 2003.  
13   Comparative analysis was performed in two stages: comparison of monthly statistical  
14   distribution of climate variables, and analysis of heatwave presence. Urban weather generator  
15   (UWG) was used to project UHI effect on two weather files for two buildings, and three  
16   overheating measurement indices were used to exploit results. Comparative analysis of  
17   weather files show that temperature in a FTWY in the medium future (2040 -2070) is likely  
18   not as intense as the heatwave of 2003 for Nantes. Results also confirm that it is better to use  
19   two weather files, and at least two overheating indices to obtain reliable outputs. This study  
20   also revealed that indoor overheating is not limited to densely built areas where impact of  
21   UHI is highest; buildings located in sparsely built neighbourhoods are also at risk.

22

# 1 **1 Introduction**

## 2 **1.1 Climate change & extreme weather events**

3           2011-2020 was the warmest decade on record and the global average temperature in  
4 2020 was approximately 14.9 ° C, which is 1.2°C higher than the pre-industrial (1850-1900)  
5 level (WMO 2020). The projections of IPCC in their latest reports warns that even with the  
6 best estimates, regardless of what emission scenario is considered, the warming will reach  
7 1.5°C before 2040 (IPCC 2021). National Climate Assessment report states that the number  
8 and strength of heatwaves, heavy downpours, and major hurricanes have increased over the  
9 last decades and will continue to do so in the future. This increase will disrupt and damage  
10 critical infrastructures and vitality of communities, putting vulnerable population  
11 disproportionately at risk of climate-related adverse consequences (Doherty et al. 2018).

12           Europe in particular is more likely to be affected by heatwaves and cold snaps  
13 compared to other extreme weather events such as hurricanes that form in tropical and  
14 subtropical latitudes.

15           An example is the exceptional heatwave in the summer of 2003 that resulted in at  
16 least 30,000 excess deaths in Europe, of which nearly 15,000 were in France, between August  
17 1 and 20, 2003 (Wagner 2018).

18           Heatwaves simulated using EURO-CORDEX regional multi-model demonstrate that  
19 under future climate conditions, the frequency, duration and intensity of heatwaves will  
20 increase across France and other parts of Europe. Heatwave events could occur during a  
21 larger span of summertime and the 2003 event would be a typical event by the end of the  
22 century (Ouzeau et al. 2016).

## 23 **1.2 Extreme weather events and cities**

24           Influences of changing frequencies and intensities of extreme weather events are  
25 amplified in the urban areas by a distinct urban microclimate feature known as *urban heat*

1 *island (UHI)* effect. This effect is characterized by higher temperatures within the build-up  
2 urban area as compared to rural surroundings (Pyrgou et al. 2017). UHI is the result of many  
3 factors that modify the climatic exchanges in the city: shape and density of urban fabric,  
4 thermo-physical specifications of artificial urban surfaces and heat generated from  
5 anthropogenic human activities. These factors change the urban energy balance by entrapping  
6 solar radiation, changing humidity and intensity of air circulation, increasing thermal storage  
7 capacity, and decreasing the latent heat transfer due to the reduced presence of vegetation and  
8 water bodies. As a result, urban air and surface temperatures cool down slowly in the  
9 evening, maintaining a hot environment for buildings and people. UHI has a significant  
10 impact on heat stress, thermal comfort and energy demand of the buildings and people in  
11 urban areas. Therefore, it is important to consider it in building design and simulations  
12 (Manoli et al. 2019).

13         This study uses Urban Weather Generator (UWG) method to project the influence of  
14 UHI effect on typical future weather data and observed weather data. UWG is a methodology  
15 and software tool that estimates hourly urban canopy air temperature and humidity ratio  
16 based on urban morphological parameters and urban land use (Bueno et al. 2013). It can be  
17 used alone or in conjunction with other existing programs to account for the impact of UHIs.

18         UWG model contains four interacting components: Rural Station Model (RSM)  
19 which estimates sensible heat fluxes; Vertical Diffusion Model (VDM) that calculates vertical  
20 air temperature profiles at a rural weather station; Urban Boundary Layer (UBL) that  
21 accounts for vertical histograms of the air temperature above the urban coverage; and Urban  
22 Canopy and Building Energy Model (UC-BEM) that allows taking into consideration  
23 temperature and humidity ratio of the air in the urban canyon (Bueno et al. 2013; Kamal et al.  
24 2021). UWG has previously been validated in several studies for Basel, Singapore, Toulouse,  
25 Rome, Barcelona, and Abu Dhabi (Bande et al. 2019).

### 1 **1.3 Future climate and buildings**

2 Comprehensive time-activity studies in Europe and US have shown that people on  
3 average spend 16 hours/day indoors. This number increases to approximately 20 hours/day  
4 for those above 64 years old (Brasche and Bischof 2005), asserting the importance of indoor  
5 air quality and indoor thermal conditions.

6 Projected variations in extreme weather events and global temperature increase will  
7 further add pressure on buildings, making them uncomfortable or even potentially dangerous  
8 to occupants' wellbeing (Green et al. 2016; Hamdy et al. 2017; Yang et al. 2019). Heatwaves  
9 in particular can cause severe overheating in buildings that are not equipped to cope with it. It  
10 could lead to several problems ranging from thermal discomfort and productivity reduction to  
11 illnesses and even death of occupants (Hamdy et al. 2017).

12 Furthermore, recent buildings have been designed to answer to past climate conditions  
13 and often with typical meteorological year (TMY) weather files that are obtained by means  
14 and thus do not include heatwaves (Lauzet et al. 2018) or heat island effect. Moreover, past  
15 construction regulations and most of the current ones in western and northern Europe are not  
16 focused on summer conditions and as a result, even recent buildings can already be highly  
17 uncomfortable during the heatwaves (Lomas and Porritt 2017; R. Mitchell and Natarajan  
18 2019; Petrou et al. 2019).

19 The magnitude of occupant vulnerability inside the building due to overheating  
20 depends on several parameters such as duration and intensity of exposure to heat, as well as,  
21 on personal adaptation capacity of the occupant. Installation of cooling systems in the already  
22 energy-intensive building sector could mitigate associated risks. However, the resulting  
23 increase in energy demand would affect global climate change. Moreover, if installed in every  
24 household, these systems would dramatically increase the electricity demand for cooling at  
25 peak time and at the same time discharge hot air that will further intensify urban warming.

1 Another factor that affects occupants' vulnerability to future climate conditions and  
2 heatwaves is energy precariousness (Battersby 2016). This is especially relevant for naturally  
3 ventilated buildings that have traditionally not relied on energy to keep occupants safe from  
4 overheating during summer.

5 For practitioners in the thermal evaluation of buildings, this means that typical  
6 weather files created from historical records collected from rural weather stations may no  
7 longer be suitable to assess buildings' resilience in the context of future climate and  
8 heatwaves.

#### 9 **1.4 Indoor overheating assessment indices**

10 Indoor overheating, similar to thermal comfort, is a dynamic phenomenon that varies  
11 both spatially and temporally. Researchers over the years have proposed numerous methods  
12 to describe indoor overheating, but still, there is no consensus on how to evaluate it through  
13 simulation or measurement (Lomas and Porritt 2017). Therefore, there is a need to specify  
14 what we mean by overheating or heat stress in buildings. A literature review on indoor  
15 overheating indices by Epstein et al. collected and analysed more than 40 different heat stress  
16 indices (Epstein and Moran 2006). Authors argue that too much emphasis has been placed on  
17 the academic accuracy of many of these indices at the expense of practicality. They  
18 recommend using simple and easy to use indices. Their literature review covered indices that  
19 were in use or proposed until 2005. Since then indoor overheating and comfort measurement  
20 indices have evolved and a number of new indices have been introduced. The most important  
21 change in that front is probably the adoption of adaptive comfort indices by ANSI/ASHRAE  
22 Standard 55 and ISSO 74 (Dutch Guidelines) in 2004 and 2005. European standard adopted it  
23 in 2007 in EN 15251-1. Adaptive indices were slightly modified and updated in  
24 ANSI/ASHRAE Standard 55 in 2017, and EN 16978-1 was introduced in 2019 to replace EN  
25 15251. A review of indices by (Carlucci and Pagliano 2012) proposes to classify

1 homogeneous indices into four families: (1) percentage indices that demonstrate comfort as a  
2 percentage [of time] inside a range such as PMV and CIBSE guidelines; (2) cumulative  
3 indices such as degree-hour criterion in EN 15251, and exceedance metrics illustrated by  
4 (Borgeson and Brager 2011); (3) risk indices such as Nicol et al.'s overheating risk (J. Fergus  
5 Nicol et al. 2009) that suggests thermal discomfort is related to the difference between  
6 operative temperature and EN adaptive thresholds, and Robinson and Hadi's overheating risk  
7 index (Robinson and Haldi 2008) which is based on the analogy that (the storage) of human  
8 tolerance to overheating stimuli may be equivalent to storage of charge in an electrical  
9 capacitor, and proposes a simple mathematical model to predict overheating risk given a set  
10 of measured environmental conditions; (4) averaging indices such as the average predicted  
11 percentage of dissatisfied (PPD), and the difference between peak temperature and annual  
12 average. A more recent review on time-integrated overheating evaluation methods for  
13 temperate climate regions by Rahif, Amaripadath, and Attia (Rahif, Amaripadath, and Attia  
14 2021) state that most standards recommend using adaptive comfort methods in the  
15 assessment of indoor thermal conditions for free-floating buildings, and static approaches for  
16 air-conditioned buildings. Their review analyzes 11 international standards, 5 national  
17 building codes, and a number of scientific literature that present overheating indices for  
18 temperate climate regions. The large number of indices in the literature and national  
19 standards indicate that researchers are trying to quantify the relation between human body  
20 and climatic stress in a single formula or by a single index. It is, however, obvious that there  
21 is a complex relation between the two and using a single index could mask or even  
22 exaggerate the indoor thermal conditions. Using multiple indices could probably better  
23 explain this relationship because some indices give complementary results and highlight  
24 certain aspect of occupants' sensation that are ignored or given less attention by other indices.



1 In this study, we used three easy to use indices to describe what constitutes indoor over-  
2 temperature in a naturally ventilated building.

### 3 **1.5 Weather data for Building Performance Simulations (BPS)**

4 Three methods of thermal simulations are commonly used nowadays for building  
5 performance evaluations: static, semi-dynamic, and dynamic. Of the three, the dynamic  
6 method is considered more appropriate in building thermal assessment. This method requires  
7 at least hourly weather data that contains temperature, humidity, radiation, wind, atmospheric  
8 pressure, etc. Depending on the objective of dynamic BPS, two distinctive weather data types  
9 are used: synthesized and observed data. The latter is often used in the performance  
10 monitoring phase and is collected from weather stations or by in-situ measurements. The  
11 former is more frequently used in the design phase and is synthetically generated from  
12 climate normals. WMO defines climate normals as a period that covers at least 30 years of  
13 data. For evaluation of buildings' climate resilience, future weather data are required. These  
14 data are based on future emission scenarios and projections produced using climate models.  
15 Emission scenarios are used as input for General Circulations Models also referred to as  
16 Global Climate Models (GCMs). GCMs cover the entire surface of the globe and their spatial  
17 resolution is coarse, typically between 150 to 600 km (P.Tootkaboni et al. 2021). Application  
18 of given GCMs for building thermal evaluation requires downscaling to a finer spatial and  
19 temporal resolution to consider regional and local scale estimates of climate variability and  
20 change. As can be seen in Figure 1, there are two main approaches to downscale GCMs:  
21 Dynamical downscaling (DDS) and empirical-statistical downscaling (ESD).

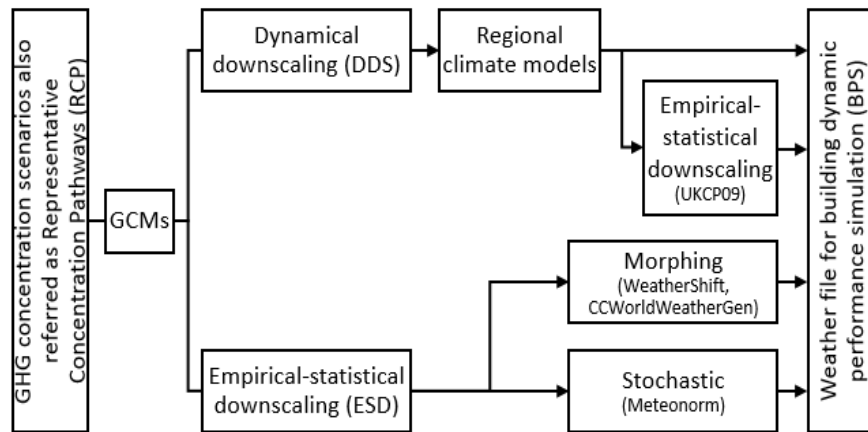


Figure 1: downscaling approaches

1        DDS and ESD stand on two distinctive philosophies: DDS relies on climate data that are  
 2        based on our knowledge of physical processes (solving equations for humidity, temperature,  
 3        local wind, etc.) and ESD makes use of information obtained from the statistical analysis (e.g.  
 4        regression relationships) of previously observed climate data.

5        Erlandsen et al. and Moazami et al. (Erlandsen et al. 2020; Moazami et al. 2019) in their  
 6        studies have also discussed a hybrid approach in which the results of dynamically  
 7        downscaled GCMs, also referred to as Regional climate model (RCM), stored at a coarse  
 8        resolution undergo further downscaling using statistical approach.

9        Several studies have been conducted on the relative difference of DDS and ESD on  
 10       climate impact assessments. P.Tootkabani et al. (P.Tootkabani et al. 2021) in their paper on  
 11       comparative analysis of different future weather data for building energy simulations,  
 12       compared weather files from three tools that are based on ESD (WeatherShift, Meteonorm,  
 13       and CCWorldWeatherGen) with one DDS future typical meteorological year. Their results  
 14       show that all ESD weather files have relatively similar operation in predicting thermal  
 15       comfort and energy consumption in buildings in comparison to DDS weather files. Their  
 16       paper also states that the ESD method, regardless of how it is used can provide sufficient  
 17       information to perform comparative analysis on long-term variations in energy consumption  
 18       of buildings, but existing inconsistency within the method can lead to significant prediction

1 error. Under such conditions, they found the DDS method more reliable when the objective of  
2 the study is to investigate and communicate the resilience of buildings to future climate  
3 conditions. Ramon et al. (Ramon et al. 2019) in their paper state that ESD method is more  
4 suited to investigate average energy performance in future climate realization but less suited  
5 to assess extreme conditions. DDS, on the other hand, can be used for both average and  
6 extreme assessment purposes. Moazami et al. (Moazami et al. 2019) in their study on the  
7 impact of future weather data types on building energy performance concluded that weather  
8 files generated using DDS that take into account both typical and extreme climatic conditions  
9 are most reliable to evaluate energy robustness in the context of future climate uncertainties.  
10 In the present study, availability of open-source RCMs (dynamically downscaled GCM) data  
11 from EURO-CORDEX presented an opportunity to systematically compare three future DDS  
12 climate models and one future ESD model, assuming the high-emission scenario  
13 [representative concentration pathway (RCP) 8.5], with observed weather data of 2003. The  
14 latter was accessed from MeteoFrance archives and transformed into EnergyPlus (.epw) file  
15 format that can be used in BPS.

16 The aim of this study is, first, to provide insights for practitioners in BPS on how to generate  
17 future and present ready-to-use weather files using open-source RCMs, and second, through a  
18 comparative analysis with heatwave weather data of 2003 show their potential in indoor  
19 overheating assessment of buildings' considering urban heat island effect. The method  
20 described here does not illustrate in detail the uncertainties associated with emission  
21 scenarios, climate projections, climate models, and bias adjustment of climate models as they  
22 were addressed previously by (Hosseini, Bigtashi, and Lee 2021; Machard et al. 2020;  
23 Maraun 2016).

24 The method/workflow to generate typical weather files is of particular interest for  
25 practitioners in building simulations that use current or future weather data in thermal

1 performance evaluation of buildings. Implementation of the approach we used to compare  
2 and evaluate indoor overheating of two free-floating buildings with two weather files and  
3 three indices contribute to the existing body of knowledge in the assessment and study of  
4 climate-change-proof buildings.

5 The next section of this document, materials and methods, is structured as follows: first sub-  
6 section describes the workflow to extract yearly weather data for any location; second sub-  
7 section demonstrates the methodology to assemble typical weather file from downloaded  
8 yearly data; third sub-section presents the method used in comparative analysis of weather  
9 files; fourth sub-section depicts the application of weather files on two buildings case study.  
10 The final section summarizes and discusses the results, limitations and prospects.

11

## 12 **2 Materials and Methods**

### 13 **2.1 Extracting yearly weather data**

14 Coordinated Regional climate Downscaling Experiment CORDEX ([www.cordex.org](http://www.cordex.org))  
15 is an international coordinated effort supported by World Climate Research Programme's  
16 Working Group on Regional Climate. As a part of CORDEX, EURO-CORDEX is today the  
17 main reference framework for regional downscaling research of climate data. The main goals  
18 of this experiment are: (1) to evaluate and improve different RCMs, (2) to better understand  
19 regional and local climate phenomena through downscaling, (3) to generate coordinated  
20 RCM projections at the global scale, (4) and enable users of regional climate data to  
21 exchange knowledge (Daniela et al. 2020).

22 EURO-CORDEX maintains a consistent database of multi-year historical and  
23 projected data that can be used for climate adaptation studies in various sectors. The data for  
24 Europe is available on a horizontal grid resolution of  $0.11^\circ \times 0.11^\circ$ , equivalent of 12.5 km  
25 (Jacob et al. 2014). All necessary components to generate weather files for building

1 simulations can be downloaded at 3h, 6h, daily, monthly and seasonal temporal resolution.  
2 For this study, we downloaded 3h time-step data.

3 In this study, EURO-CORDEX regional climate projection data were accessed via the  
4 Climate Data Store (CDS) portal supported by the Copernicus Climate Change Service (C3S)  
5 initiative that provides information about past, present, and future climate in Europe and the  
6 rest of the world<sup>1</sup>. CDS portal allows accessing climate variables of GCMs and RCMs in  
7 various combinations and different horizontal and temporal resolutions. Raw data is available  
8 in NetCDF (Network Common Data Form) file format that is commonly used within the  
9 climate modelling community to share array-oriented scientific data. Climate data in this  
10 format are stored in multi-dimensions and users can view/access geographical coordinates  
11 (latitude, longitude), time, level, climate variable (temperature, relative humidity, etc.).  
12 Practitioners are cautioned to check for bias-adjustment of climate data before using them in  
13 BPS. In this study, raw data were downloaded from the CDS portal and they are not bias  
14 adjusted.

15 Figure 2 depicts the near-surface air temperature of an RCM in EURO-CORDEX region as  
16 well as the position of our case study city (Nantes) in a NetCDF file.

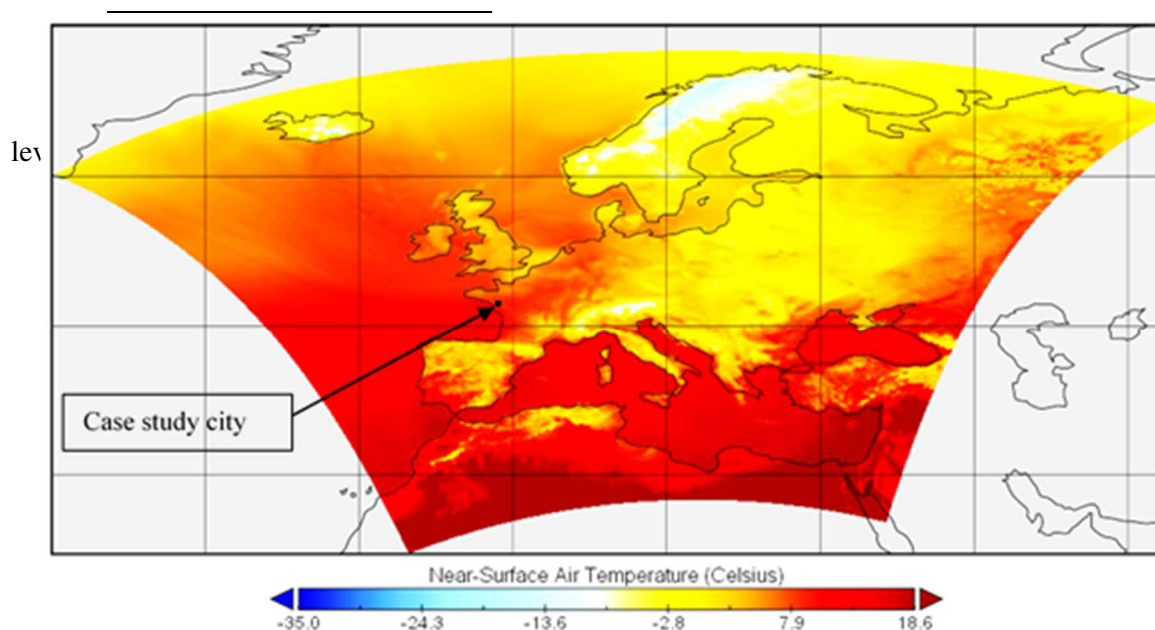


Figure 2: Near surface air temperature NetCDF data file visualized in Panoply

1

2 Data of Nantes were extracted using a python script that identified the closest point of the  
3 data grid in the NetCDF file to the assigned latitude and longitude coordinates.

4 Six climate variables (dry-bulb temperature [K], relative humidity [%], global solar  
5 irradiance [ $W/m^2$ ], cloud cover [%], atmospheric pressure [Pa], and wind speed [m/s]) as  
6 suggested by (Machard et al. 2020) were downloaded for thirty years (2040 to 2070) of the  
7 following global-regional climate models:

8 *Table 1: dynamically downscaled climate models*

|          | <b>Institution</b> | <b>Global climate model (GCM)</b> | <b>Regional climate model (RCM)</b> | <b>GCM_RCM names used</b> |
|----------|--------------------|-----------------------------------|-------------------------------------|---------------------------|
| <b>1</b> | CNRM               | CNRM-CERFACS-CM5 (France)         | CNRM-ALADIN63 (France)              | CNRM_ALADIN               |
| <b>2</b> | SMHI               | IPSL-CM5A-MR (France)             | SMHI-RCA4 (Sweden)                  | ISPL_SMHI                 |
| <b>3</b> | GERICS             | MPI-M-MPI-ESM-LR (Germany)        | GERICS-REMO2015 (Germany)           | MPI_REMO                  |

9 The climate models in Table 1 were chosen based on the availability of completed  
10 simulations with all six climate variables for RCP8.5 scenario experiments at 3h time-step  
11 interval. More combinations of GCM and RCM are possible in the CDS portal but, here, we  
12 only used each GCM and RCM once.

13 Dry-bulb temperature was first converted from Kelvin to degrees Celsius. Polynomial  
14 interpolation ( $n=7$ ) was used to convert 3h time-step data to 1h time-step for dry-bulb  
15 temperature and global solar irradiance and linear interpolation for the rest of the variables.

16 Dew point temperature ( $T_d$ ) was estimated from dry bulb temperature and relative  
17 humidity using August–Roche–Magnus formula for dew point temperature approximation  
18 (Thiis et al. 2017).

$$T_d = \frac{b[\ln\left(\frac{RH}{100}\right) + \frac{a \cdot T}{b + T}]}{a - \ln\left(\frac{RH}{100}\right) - \frac{a \cdot T}{b + T}}$$

Where: RH Relative humidity [%]

T Dry bulb temperature [ $^{\circ}\text{C}$ ]

$a = 17.27$ ,  $b = 237.7$   $^{\circ}\text{C}$ , for  $T \leq 60$   $^{\circ}\text{C}$  and an error of  $\pm 0.4$   $^{\circ}\text{C}$ .

1

2 Sunrise and sunset time for the given location was calculated using Python Astral  
3 package, which is based on equations from Astronomical Algorithms, by Jean Meeus.  
4 Interpolated global solar irradiance data that were before sunrise and after sunset were set to  
5 zero. Solar zenith angle, direct normal irradiance, and diffuse horizontal irradiance were  
6 calculated following the methodology described by (Machard et al. 2020). Following the  
7 steps described above, for each year of each climate model, a yearly weather file was  
8 generated. In the next step, 30 years of weather data for each climate model were assembled  
9 to generate future typical weather files.

10

11

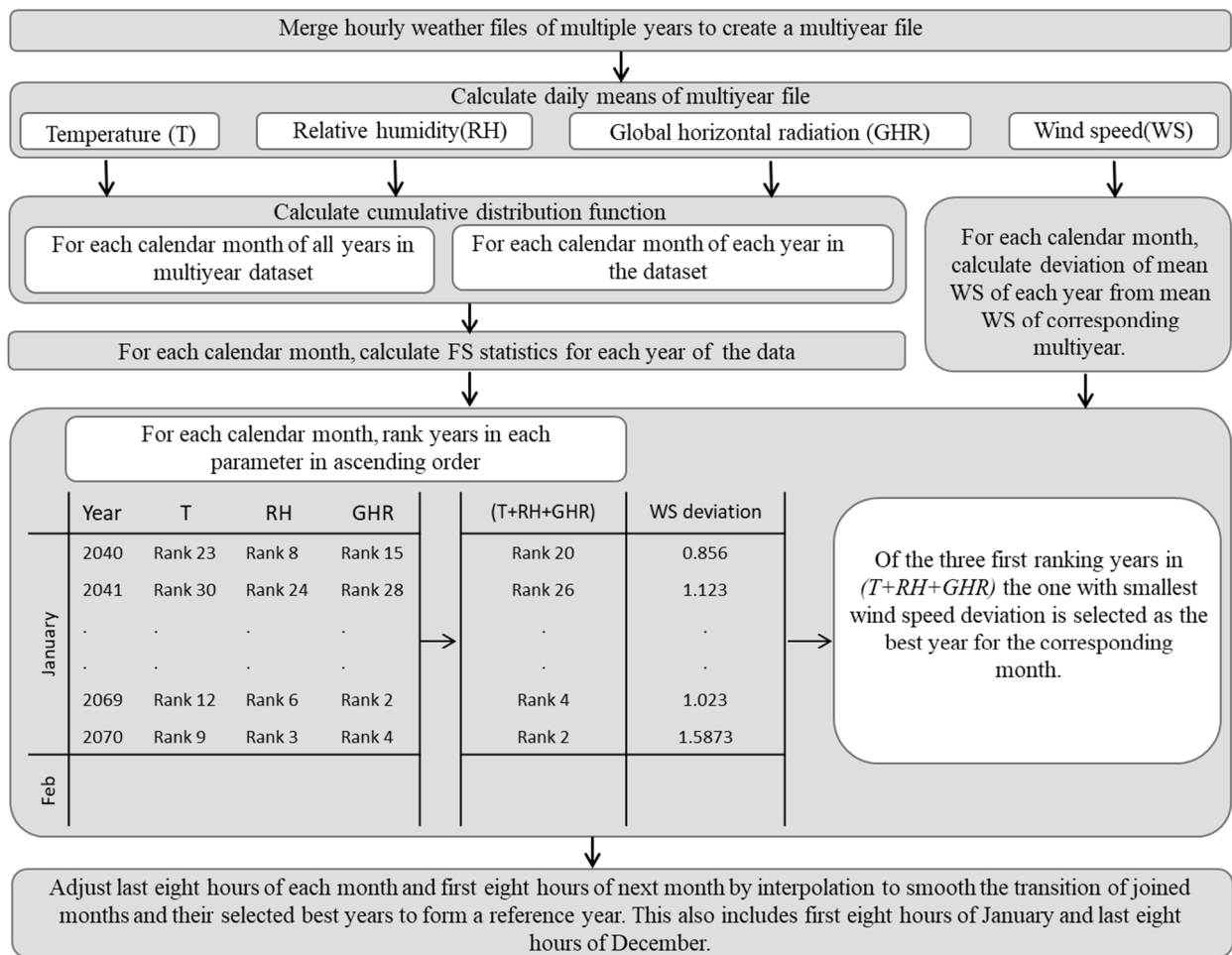
## 12 **2.2 Assembling typical weather files**

13 We used EN ISO 15927-4 2005 standard created by the European Committee for  
14 Standardization, proposing a method for constructing reference year of hourly weather data to  
15 generate typical future weather file. In this method, dry-bulb temperature, relative humidity,  
16 and global horizontal irradiance climate variables are the key parameters in the selection of  
17 “best” months to form reference year, with wind speed as a secondary (ISO 15927-4 2005).

18 Following the ISO 15927-4 method for each climate model, we first merged 30 years  
19 of hourly weather data and calculated daily means. Then for each calendar month, cumulative  
20 distribution function (CDF) of daily means of every year and of multiple-year were  
21 calculated.

22 For each calendar month, Finkelstein-Schafer statistic (FS) was calculated and  
23 individual months from the multiple-year dataset were ranked in ascending order.

1 For each calendar month and each year, separate ranks were added for each of the  
 2 three key parameters. ISO 15927-4 gives equal weighting to three key climate parameters.  
 3 Therefore, ranks of key parameters were only added to one another and ranked in ascending  
 4 order. Of the three months with lowest total ranking for three key parameters, the one with  
 5 the smallest wind speed deviation was selected as the “best” month to be included in the  
 6 reference year. After identification of “best” month for each month from multiyear data, they  
 7 were joined together to form a reference year. In order to smooth the transition from one  
 8 month to another, eight hours at the end and beginning of subsequent months were  
 9 interpolated, including last eight hours of December and first eight hours of January. The  
 10 procedure is also presented in Figure 3.



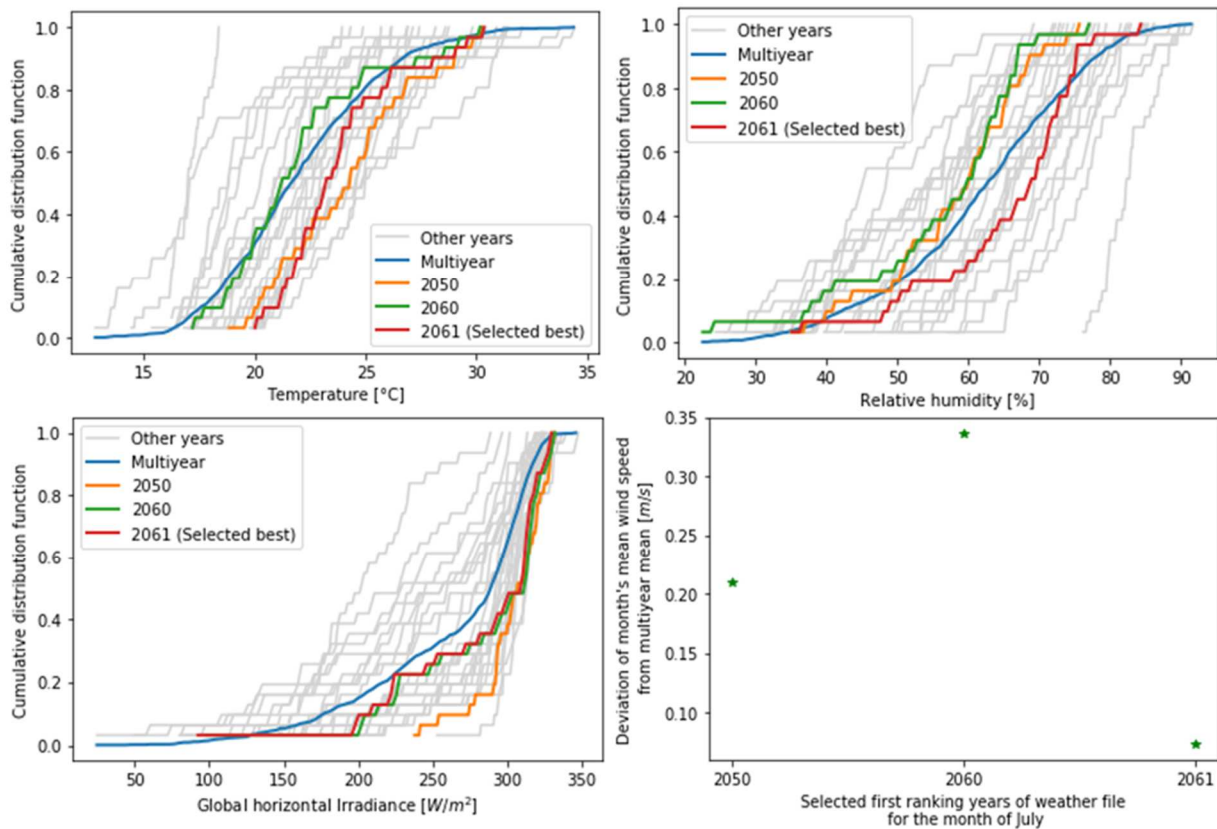
11

12

Figure 3: Workflow to assemble typical weather file



1 As an example, Figure 4 shows cumulative distribution function plots of dry-bulb  
 2 temperature, relative humidity, global horizontal irradiance and mean wind speed deviation  
 3 plot for the calendar month of July in the IPSL-SMHI model. In this example, from the three  
 4 key parameters, July of 2050, July of 2060 and July of 2061 were candidates of the best  
 5 month for reference year. Among them, July of 2061 had the smallest wind speed deviation  
 6 from July in the multiyear dataset. Therefore, it was selected as the “best” month for the



7 reference year.

8 *Figure 4: CDF plots of three key parameters and plot of wind speed deviation for July calendar*  
 9 *month in IPSL-SMHI climate model*

10 Using the method described, three future typical weather files (2040 to 2070) for the  
 11 case study city from dynamically downscaled climate models were assembled.

12 For comparative analysis, observed weather data of 2003, and one ESD future weather  
 13 scenario (Meteonorm RCP 8.5 2050) was also downloaded from MeteoFrance archives and  
 14 Meteonorm v.8 software respectively, for our case study city, Nantes.

### 1 2.3 Comparative analysis of weather files

2 Statistical distribution of monthly dry bulb temperature, relative humidity, and global  
3 horizontal irradiance of each DDS climate model, as well as Meteonorm RCP 8.5 2050, and  
4 measured weather data of 2003 were compared. Additionally, heating degree-days (HDD)  
5 and cooling degree-days (CDD) indices in each weather file were calculated using the  
6 methodology and base temperatures recommended by EUROSTAT to form a common and  
7 comparable basis in comparison. These two indicators are commonly used to give a rough  
8 estimation of heating and cooling energy demand. Calculation of HDD and CDD both rely on  
9 base temperature, which depends in principle on various factors related to building and  
10 surrounding. In this study, base temperature in HDD calculation was set to constant value of  
11 15°C and in CDD calculation to 24°C. In HDD calculation, if  $T_m \leq 15^\circ\text{C}$  then  $\text{HDD} =$   
12  $\sum_i(18^\circ\text{C} - T_m^i)$ , else  $\text{HDD} = 0$ , where  $T_m^i$  is the mean air temperature of day  $i$ .

13 Similarly in calculation of CDD, if  $T_m \geq 24^\circ\text{C}$  then  $\text{CDD} = \sum_i(T_m^i - 21^\circ\text{C})$ , else  $\text{CDD}$   
14  $= 0$  (Bhatnagar, Mathur, and Garg 2018).

15 Weather files were also investigated with a temperature-based index to check the  
16 frequency and intensity of heatwaves in them. This temperature-based heatwave index was  
17 developed for France after the exceptional heatwave in the summer of 2003. This index  
18 relies on the heatwave and health alert system (Sacs) piloted by Public Health France. The  
19 objective of it is to anticipate heat waves that are likely to have a major health impact. Every  
20 day, in each metropolitan department, the level of risk is assessed by MeteoFrance comparing  
21 forecasts of meteorological indicators with departmental alert thresholds. Thresholds are  
22 shown in Figure 5, below.

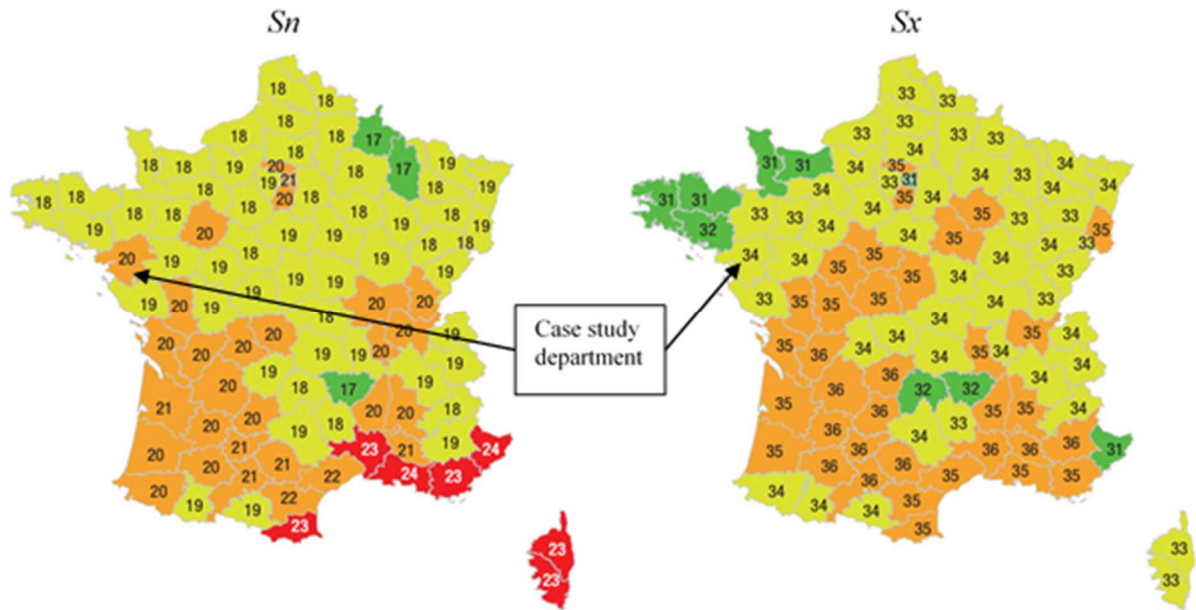


Figure 3: Heatwave meteorological indicator thresholds,  $S_n$ : threshold for the three-day average of minimum temperatures in  $[^{\circ}\text{C}]$ .  $S_x$ : threshold for the three-day average of maximum temperatures in  $[^{\circ}\text{C}]$ .

1            These thresholds are defined on the basis of a historical analysis and with an aim to  
2            anticipate heat waves that are likely to be associated with excess mortality of at least 50% in  
3            4 major cities and 100% in smaller cities. In this method, “A heatwave is defined as a period  
4            when the minimum and maximum temperatures, averaged over three days, simultaneously  
5            reach or exceed departmental alert thresholds”. The onset of a heatwave corresponds to the  
6            first day on which the meteorological indicators of Sacs (average over three consecutive days  
7            of minimum and maximum temperatures) reaches or exceeds alert thresholds (Figure 5). The  
8            end of a heatwave is the last day of meeting or exceeding these thresholds (Wagner, 2006).  
9            The Sacs thresholds have seen certain evolutions over the years and the threshold presented  
10           in Figure 5 are those of 2016. Selected weather files for the case study city were measured  
11           against the heatwave meteorological thresholds of the case study city department. To do so,  
12           maximum daily temperatures (IBM\_max) and minimum daily temperature (IBM\_min) of  
13           weather files were extracted from hourly data. A python script was written to detect and  
14           measure the heatwaves parameters such as start date, duration, peak temperature, intensity of  
15           maximum temperatures, and intensity of minimum temperatures.

## 2.4 Application of weather data on two residential buildings

One single-family house (SFH) and one multifamily house (MFH), located in Nantes city, were used to carry out comparative analysis of weather data by assessing hourly indoor thermal conditions of five summer months (May, June, July, August, September). The two buildings were selected after a typological analysis of residential building stock and these two were identified as representative of two types of residential buildings in Nantes city. MFH was located in a densely built part of the city, where building footprint density is 53%, and SFH was located in a more sparsely built neighbourhood, where buildings covered 18% of the land surface in a 200-meter radius (Figure 6).

10

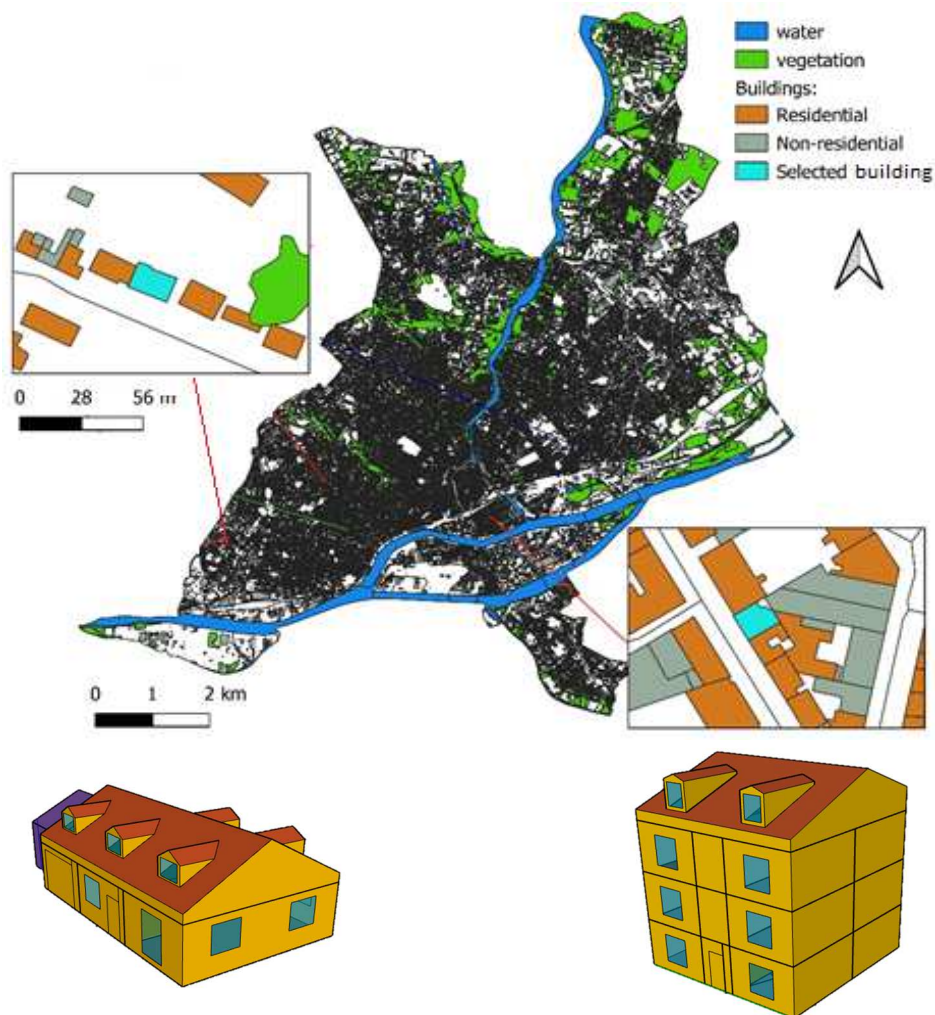


Figure 4: The two studied buildings (down), and their location in the city (up)

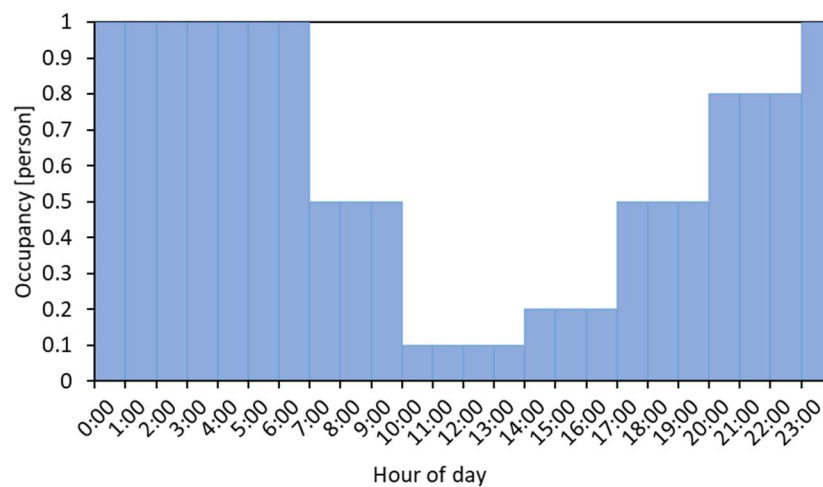
1 SFH built in 1981 has insulated envelop components as it was constructed after the  
 2 first French law on energy saving. MFH has uninsulated envelope elements because it was  
 3 constructed before the introduction of the first French law on energy saving. Both buildings  
 4 are connected to a central heating system for winter heating but they do not have mechanical  
 5 cooling mechanism. Table 2 contains estimated thermo-physical properties of envelop  
 6 elements for the selected buildings. Thermo-physical parameters of the buildings were  
 7 estimated as a function of their year of construction from the article of Civel and Elbeze  
 8 (Civel and Elbeze, 2016).

9 *Table 2: Thermo-physical properties of envelop elements*

| # | Envelope element            | U value [W/m <sup>2</sup> K] |           |
|---|-----------------------------|------------------------------|-----------|
|   |                             | SFH                          | MFH       |
| 1 | Exterior wall               | 0.8                          | 2.42      |
| 2 | Exterior roof               | 0.5                          | 2.3       |
| 3 | Window                      | 2.8                          | 2.9       |
| 4 | Adjacent walls              | 2                            | 2         |
| 5 | Adjacent roof/ceiling       | 3                            | 3         |
| 6 | Orientation of main facades | North-South                  | East-west |

10

11 Heat gains from lighting load both in SFH and MFH was estimated to be 10 W/m<sup>2</sup>. Density  
 12 of occupants was set according to EN 16798-1 to 42.5 m<sup>2</sup>/person and 28.3 m<sup>2</sup>/person in SFH



13 and MFH respectively. Occupancy schedule for both SFH and MFH is presented in Figure 7.

14

*Figure 7: Occupancy schedule according to EN 16798 -1*

1 Occupants of both buildings are assumed to be highly conscious of their environment  
 2 and would adjust natural air inflow and shading for better comfort. During five summer  
 3 months, occupants would open the windows every day 2 hours in the morning and 5 hours in  
 4 the evening, which is approximately 29% of the day. Air inflow rate to each zone was  
 5 assumed 0.7 ACH when openings/windows were closed or there was no window in the zone.  
 6 It was assumed 1.3 ACH if there is one opening in a thermal zone and its status is open. For  
 7 two or more openings in a thermal zone, air inflow rate was assumed 1.9 ACH when its status

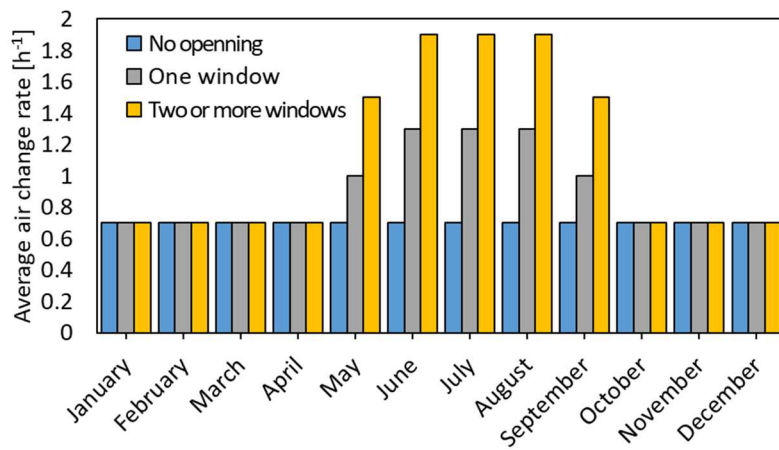
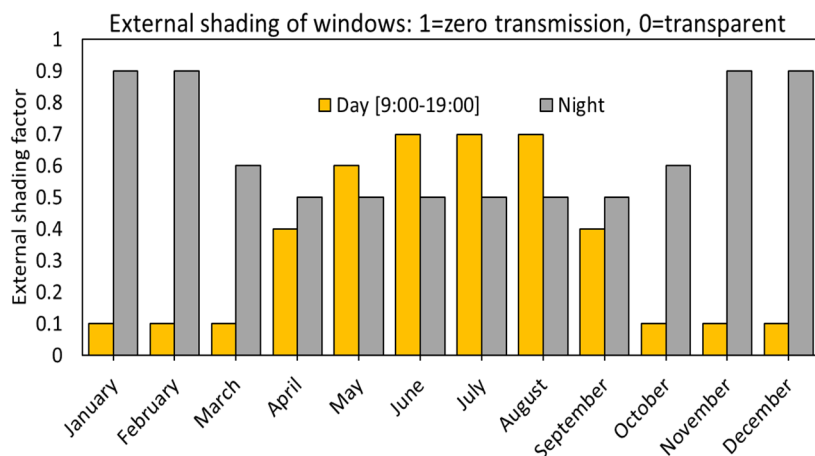


Figure 5 : Modelled infiltration rate into different thermal zones

8 is open. (Figure 8).

9 Windows in SFH and MFH, both were equipped with manual roller blinders/shutters  
 10 allowing occupants to control direct solar radiation intake into the zones. In the summer  
 11 months, during the day, occupants were assumed to use external shadings to cover 60% of the  
 12 area of window and during the night 50% of the area (Figure 9).



## 1   **2.5   Considering urban heat island effect**

2           UWG Python package was used to project the influence of UHI effect on the weather  
3 files. Main input of UWG is the rural weather file, also referred to as baseline weather file, in  
4 EnergyPlus (.epw) file format. Other input parameters are climate zone/location of the city,  
5 building typology distribution, urban parameters, and building parameters. UWG model  
6 allows practitioners to add detailed information about buildings and its surrounding, but  
7 (Salvati, Palme, and Inostroza 2017) in their paper on key parameters for urban heat island  
8 assessment in a Mediterranean context, suggest that urban morphological parameters have the  
9 highest effect on UHI intensity and therefore can be used as descriptors of urban climatic  
10 performance in various urban areas.

11           In this study, urban morphological input parameters for UWG model were calculated  
12 within the 200-meter radius of each building. Both SFH and MFH were located in the same  
13 city, therefore had the same climate zone, 4A. Approximately 60% of buildings within the  
14 200-meters radius of MFH were multifamily residential buildings and the rest were non-  
15 residential buildings. Almost 80% of buildings located within the 200-meter buffer radius of  
16 SFH were residential buildings, both single family and multiple family houses. Within the  
17 200-meters radius, building footprint density, average height, tree coverage ratio, green  
18 coverage rate, ratio of vertical surfaces to horizontal surfaces, and year of construction were  
19 estimated for SFH and MFH separately. These parameters were used as input for the UWG  
20 model to modify weather files for the urban heat island effect.

21 Urban morphological parameters listed above for each building, within the assigned radius,  
22 were accessed and calculated from BDTOPO database. BDTOPO is a 2D and 3D vector  
23 spatial database containing the description of landscape elements including but not limited to  
24 building footprint, building height, building year of construction, vegetation coverage, water  
25 coverage ratio, presence of trees, transportation routes, etcetera throughout France.

1 Two baseline weather files (2003 observed weather data & IPSL-SMHI 2040-2070)  
2 were modified using UWG model for SFH and MFH separately. Monthly average  
3 temperatures differences between baseline and modified weather files were calculated for  
4 both buildings. The differences calculated show the average monthly intensity of UHI effect  
5 projected on the baseline weather file by UWG model.

## 6 **2.6 Indoor overheating assessment indices**

7 In this study, we employed three widely used indoor overheating indices to measure  
8 summer performance of buildings: EN 16798-1 adaptive comfort index, Givoni bioclimatic  
9 index, and constant temperature of 27 °C. These three indices were selected to check if the  
10 impact of the weather file employed also depends on the way results are exploited.

11 Adaptive comfort index is based on the idea that control over the immediate  
12 environment allows occupants to adapt to a wider range of thermal conditions. With reference  
13 to this principle, EN 16798-1 norm for adaptive comfort is related to exponentially decaying  
14 weighted mean outdoor temperature ( $T_{RM}$ ).

$$T_{RM} = (1-\alpha) [T_{N-1} + \alpha T_{N-2} + \alpha^2 T_{N-3} + \alpha^3 T_{N-4} + \alpha^4 T_{N-5} + \dots] (\text{°C})$$

Where:  $\alpha$  Constant between 0 and 1

$T_{N-n}$  Mean outdoor daily temperature for  $n$  days prior to target day

15  
16 In the calculation of weighted mean outdoor temperature,  $\alpha$  constant controls the speed of  
17 changes in running mean outdoor temperature. Based on Smart Controls and Thermal  
18 Comfort (SCATs) project recommended value for it is 0.8 (McCartney and Fergus Nicol  
19 2002). Standard also recommends that prevailing mean outdoor temperature shall be based on  
20 no fewer than seven sequential days prior to target day. EN 16798-1 norm for adaptive  
21 thermal comfort index illustrates indoor thermal comfort from operative temperatures in three  
22 categories: category I, II, III (EN 16798-1 2019).



1 Category I is considered more suitable for high demanding comfort levels, category II for  
 2 typical situations and category III for low demanding levels.  
 3 Following equations calculate maximum and minimum allowable indoor operative  
 4 temperature limits ( $T_{MAX}$  &  $T_{MIN}$ ) when  $10\text{ }^{\circ}\text{C} < T_{RM} < 30\text{ }^{\circ}\text{C}$ .

|              |              |   |
|--------------|--------------|---|
| Category I   | Upper limit: | $T_{MAX} (^{\circ}\text{C}) = 0.31 * T_{RM} + 18.8 + 2$ |
|              | Lower limit: | $T_{MIN} (^{\circ}\text{C}) = 0.31 * T_{RM} + 18.8 - 3$ |
| Category II  | Upper limit: | $T_{MAX} (^{\circ}\text{C}) = 0.31 * T_{RM} + 18.8 + 3$ |
|              | Lower limit: | $T_{MIN} (^{\circ}\text{C}) = 0.31 * T_{RM} + 18.8 - 4$ |
| Category III | Upper limit: | $T_{MAX} (^{\circ}\text{C}) = 0.31 * T_{RM} + 18.8 + 4$ |
|              | Lower limit: | $T_{MIN} (^{\circ}\text{C}) = 0.31 * T_{RM} + 18.8 - 5$ |

5  
 6 Optimal operative temperature in EN 16798-1 equals to:

$$T_{COMFORT} (^{\circ}\text{C}) = 0.31 * T_{RM} + 18.8$$

8 In this study, *degree-hours* and *percentage-of-hours* indoor operative temperature inside  
 9 each thermal zone of building exceeding the upper boundary limits in category I, II, and III of  
 10 EN 16798-1 were calculated.

11 In Givoni bioclimatic index, as depicted in Figure 10, thermal comfort polygons are

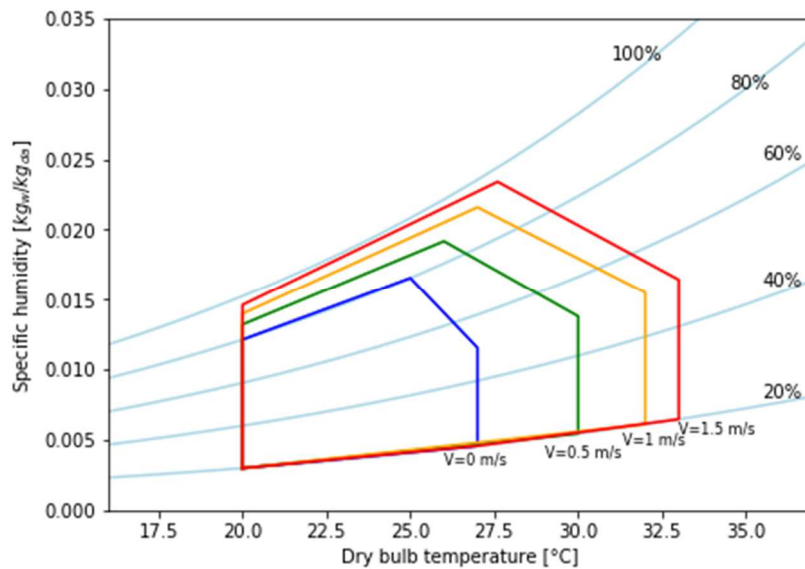


Figure 7: Psychrometric chart and Givoni bioclimatic design polygons

12 presented on a psychrometric chart (Malet-Damour 2012).

1 The lines of polygons, shown above, determine the limits of effectiveness of design strategies  
2 for indoor thermal conditions in relation to indoor wind speed for an occupant engaged in  
3 sedentary activity and wearing summer clothing (0.5 clo). Psychometric chart lines, on which  
4 thermal comfort polygons are drawn, are related to the air pressure. The latter is estimated  
5 using barometric formula as a function of height above sea level. Average height of our case  
6 study city from sea level is around 30 meters.

$$7 \quad p = 101325 (1 - 2.25577 * 10^{-5} h)^{5.25588}$$

8 Where:

9 h – Average height above sea level

10 Ideal comfort region with this index is the polygon (v=0 m/s), where air temperature is  
11 between 20 to 27°C, relative humidity is between 20 to 80%, and indoor air velocity is 0 m/s.  
12 Second polygon is called natural ventilation comfort zone, where indoor air temperature is  
13 between 20 to 30°C, relative humidity is between 20 to 90%, and air velocity is up to 0.5 m/s.  
14 Air velocity in the third polygon is 1m/s and it is induced both by natural ventilation and  
15 ceiling fans. Indoor air temperature in the third polygon is between 20 to 32°C and relative  
16 humidity is between 20 to 94%. We added the fourth polygon, where air speed is 1.5 m/s, for  
17 extreme cases, because it has been used and considered acceptable in some hot and warm  
18 countries (J.F. Nicol 1974). Marginal temperature gain of air velocity increase from 1 m/s to  
19 1.5m/s is less than 1 degree Celsius (Kumar et al. 2019), therefore, the maximum temperature  
20 of polygon four (v=1.5 m/s) is 1 degree Celsius higher than polygon three (v=1 m/s).

21 In comparative analysis, **number of hours** that indoor air temperature and relative humidity  
22 were within and outside the depicted polygons were calculated for all zones and buildings.

23 Constant temperature of 27 °C as an index of thermal comfort, in this study, was  
24 selected with reference to the night-time temperature threshold of 26 °C proposed by  
25 Chartered Institution of Building Services Engineers (CIBSE). According to CIBSE, night-

1 time indoor temperature should not exceed 26 °C more than 1% of annual hours for  
2 occupants to sleep well. Considering the adaptive capacity of occupants, difference between  
3 the climate of UK and France, mild relative humidity of our case study city, and the fact that  
4 we use this index both during day and night, it was decided to use 27 °C instead of 26°C as  
5 the threshold value to measure comfort along with other indices. In comparative analysis,  
6 peak indoor temperature and maximum number of consecutive hours that indoor temperature  
7 exceeded 27 °C were calculated.

## 8 **3 Results and Discussions**

### 9 **3.1 Comparative analysis of weather files**

1 The objective of this sub-section is to analyse the differences in various climate models at  
 2 monthly scale with different climate variables. Monthly statistical distribution of dry bulb  
 3 temperature, global horizontal irradiance, and relative humidity of three DDS models, one

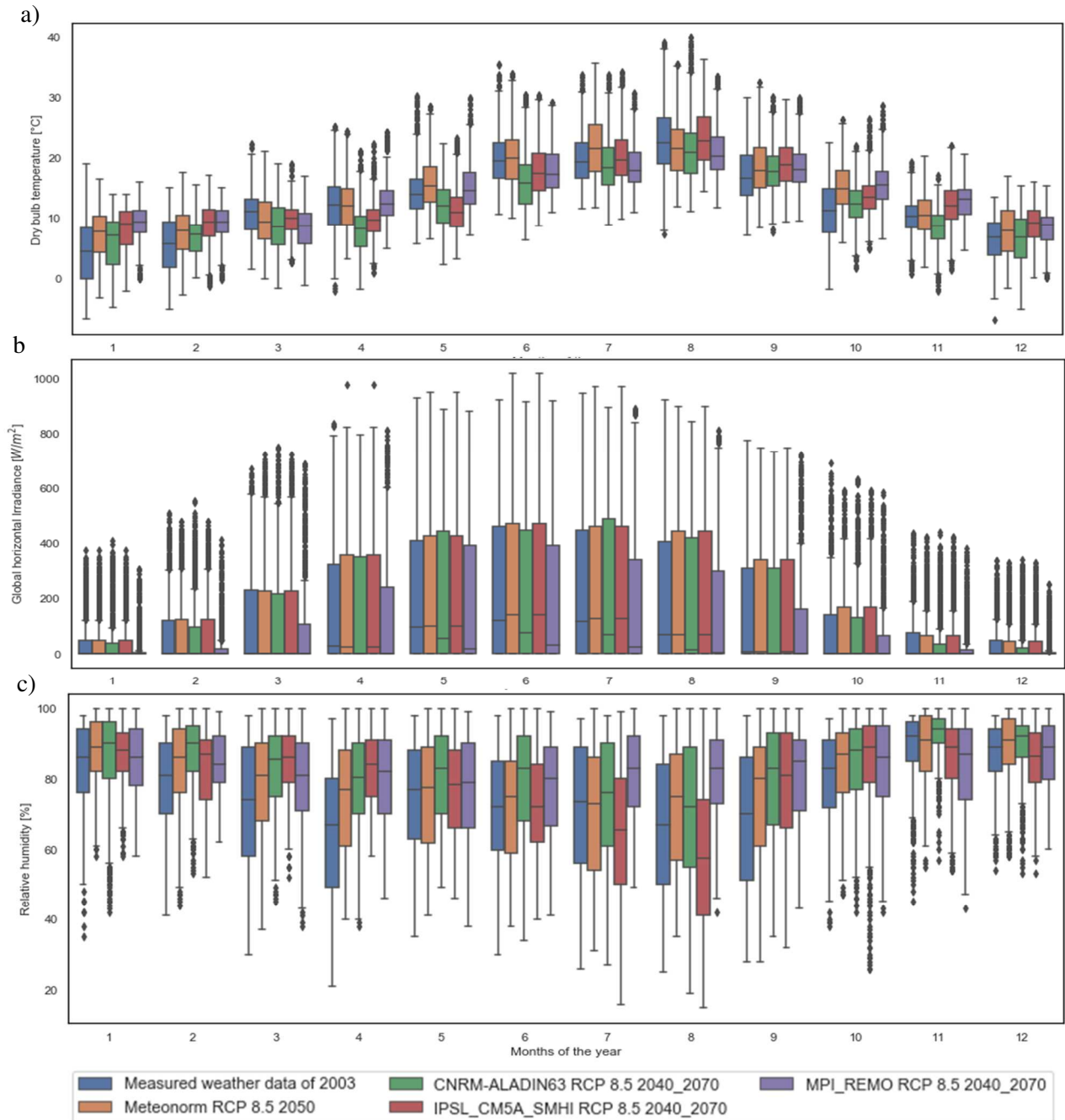


Figure 8: Monthly statistical distribution of: a) dry bulb temperature, b) global horizontal irradiance, c) relative humidity

4 ESD (meteonorm 2050), and 2003 observed weather data are shown in Figure 11.

1 Observed weather of 2003 was selected for comparison because it was the severest  
2 heatwave recorded in France up until June 28, 2019, when a temperature of 45.9°C was  
3 recorded during another heatwave in a weather station in France, exceeding previous record  
4 temperature of 2003 by almost 2°C. In contrast to the 2003 heatwave, number of excessive  
5 mortality was considerably lower mainly because the duration of 2019 heatwave was shorter  
6 and there were better heat-response plans in place (D. Mitchell et al. 2019).

7 Moving back to comparative analysis, boxplots in Figure 11 show significant  
8 variations in monthly mean values among the selected weather data files. This indicates a  
9 great difference in predictions from one climate model to another. All three dynamically  
10 downscaled weather files and Meteonorm weather file for 2050 show a consistent higher  
11 mean monthly value of dry bulb temperature and relative humidity compared to observed  
12 weather data of 2003 in winter months. However, the differences in global horizontal  
13 irradiance seem insignificant and do not provide enough evidence to notice an upward or  
14 downward trend.

15 Zooming in into summer months, we notice that mean monthly dry bulb temperature in July,  
16 August, and September of IPSL-SMHI climate model is closest to mean monthly temperature  
17 of 2003 measured weather data. For the same summer months, mean relative humidity of  
18 Meteonorm 2050 is closest to 2003 measured weather file.

19 Among dynamically downscaled weather files, CNRM-ALADIN and MPI-REMO  
20 predict higher relative humidity but lower global horizontal irradiance and dry bulb  
21 temperature during summer months. IPSL-SMHI, on the other hand, predicts higher  
22 temperature and global horizontal irradiance but lower relative humidity for the same summer  
23 months. Comparing the length of whiskers and size of interquartile ranges in boxplots for dry  
24 bulb temperature and relative humidity variables show that Meteonorm 2050, MPI-REMO,  
25 and IPSL-SMHI weather files have relatively smaller dispersion compared to measured

1 weather data of 2003 and CNRM-ALADIN weather files, in most months of the year. The  
 2 dispersion is better visible in the month of August when the heatwave of 2003 occurred. This  
 3 could indicate that measured weather of 2003 and CNRM-ALADIN contain more severe  
 4 temperature anomalies compared to other climate models investigated here. Variations in  
 5 weather files are also reflected in the number of HDD and CDD, presented in Table 3.

6 *Table 3: Number of Heating Degree Days (HDD) and Cooling Degree Days (CDD) in different*  
 7 *climate models for case study city*

| #   | Base temperature for HDD and CDD calculation [°C] | Observed data                 | Statistically downscaled | Dynamically downscaled FTWY   |                             |                            |
|-----|---|-------------------------------|--------------------------|-------------------------------|-----------------------------|----------------------------|
|     |   | Measured weather data of 2003 | Meteonorm RCP 8.5 2050   | CNRM-ALADIN RCP 8.5 2040-2070 | IPSL_SMHI RCP 8.5 2040-2070 | MPI_REMO RCP 8.5 2040-2070 |
| HDD | 15  | 2106                          | 1741                     | 2365                          | 1873                        | 1595                       |
| CDD | 24  | 103                           | 86                       | 62                            | 67                          | 26                         |

8  
 9 Main purpose of HDD and CDD is to demonstrate heating or cooling energy demand  
 10 of buildings. The spike in CDD for observed weather data of 2003 is most likely due to  
 11 heatwave data for the month of August in the weather file. Spike in HDD in CNRM-  
 12 ALADIN, on the other hand, is probably due to a cold snap in March and April, shown in  
 13 (Figure 11, a). Application of heatwave presence assessment index, described in section 2.3,  
 14 also detects heatwave that is likely to have major health impact only in CNRM-ALADIN  
 15 typical future weather data and measured weather file of 2003 (Figure 12).

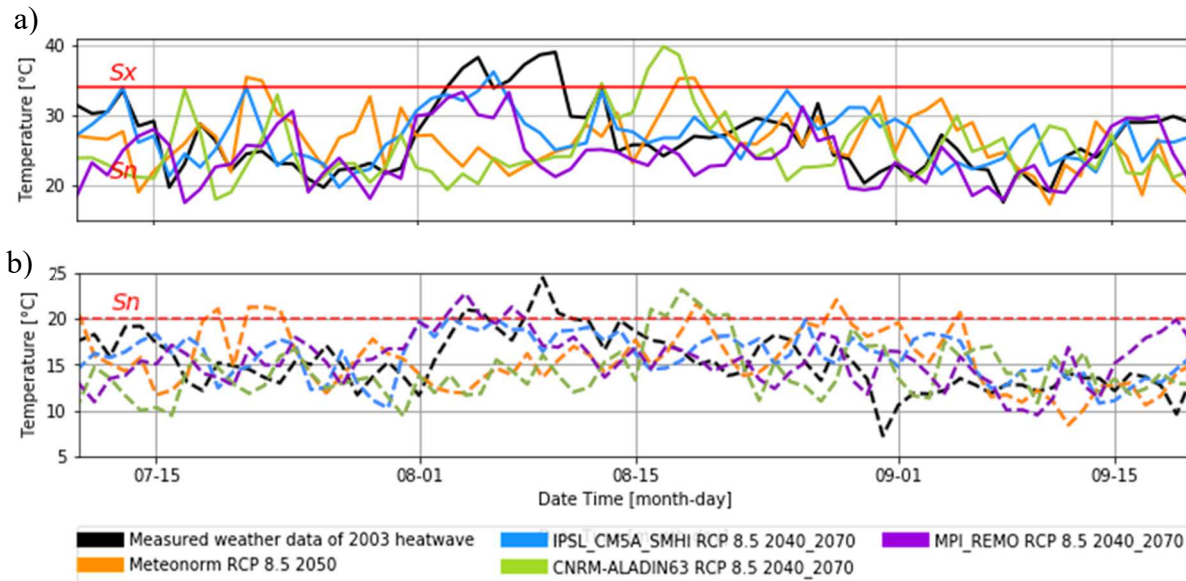


Figure 9: a) Maximum and, b) minimum daily temperatures of weather files plotted alongside heatwave meteorological indicator thresholds

1 In Figure 12, red straight lines show the position of heatwave thresholds, colours represent  
 2 weather files, solid lines demonstrate maximum daily temperatures, and dashed lines indicate  
 3 minimum daily temperatures.

4 Duration of heatwave detected in CNRM-ALADIN weather file is 3 days and peak  
 5 temperature is 39.9 degrees. In 2003 measured weather data, the duration of heatwave is 9  
 6 days and peak temperature reaches up to 39.1 degrees.

7 The absence of major heatwave in IPSL-SMHI, Meteonorm, and MPI-REMO could  
 8 be due to two reasons: first, future weather files generated with this methodology selected the  
 9 most typical months of the medium future scenario that do not contain extreme weather  
 10 scenarios and second, the thresholds specified by the definition of heatwave for this  
 11 administrative department are too high. For instance, maximum consecutive peak daily  
 12 temperature threshold for Paris is 33°C but for our case study city, it is 34 °C. The definition  
 13 of heatwaves used here only quantifies the health and mortality impact of the most serious  
 14 historical events, but not the total impact of heat. Since a moderate temperature increase also  
 15 has an impact if it persists for an extended period, we think in the future studies of heatwaves  
 16 in this administrative department, when the focus is more than just health implications, then a

1 different heatwave definition could be used, such as upper tail percentile approach described  
2 by Raei et al. (Raei et al. 2018).

3 In this study, weather data of heatwave in 2003 and CNRM-ALADIN future weather  
4 file both meet the heatwave thresholds that could lead to excess mortality for our case study  
5 city. Therefore, for our case study city, measured weather data of 2003 and CNRM-ALADIN  
6 are both suitable to study heatwave impact on indoor overheating during summer months for  
7 medium future. However, if the study period also includes winter months, the 2003 measured  
8 weather file alone may not be suitable because it underestimates temperature increase due to  
9 climate change for winter months. Therefore, 2003 weather file has to be accompanied with a  
10 FTWY to obtain results that are more reliable. Due to the absence of a concrete reference for  
11 future weather conditions, it is difficult to declare one climate model is better than others;  
12 nonetheless, considering monthly statistical dispersion and presence of anomalies we selected  
13 measured weather data of 2003 for indoor overheating evaluation of our studied buildings  
14 during heatwave and IPSL-SMHI weather file for future climate scenario.

### 15 **3.2 Urban heat island effect on weather data**

16 Weather files selected in previous section were then modified for urban heat island  
17 effect, individually for each studied building, using UWG model before being used in Trnsys  
18 v.17 for multi-zone dynamic building simulations. Inputs of UWG model were urban  
19 morphological parameters and two baseline weather files (2003 observed weather data and  
20 IPSL-SMHI typical future weather file). Outputs of UWG model were new weather files  
21 containing urban microclimate data in terms of temperature and relative humidity. The output  
22 files were then compared to baseline weather files to evaluate the efficacy of UWG  
23 methodology on different weather files. In this comparison, mean monthly temperature of  
24 baseline weather file was subtracted from mean monthly temperature of modified weather  
25 file. Results of this comparison are presented in Table 4. Differences between baseline and



1 modified weather files show the intensity of UHI effect projected by UWG model for each  
 2 studied building as a function of their urban morphological characteristics.

3 *Table 4: Monthly mean UHI effect projected by UWG model for SFH and MFH (°C)*

|           | 2003 observed weather data |      | IPSL SMHI 2040_2070 |      |
|-----------|----------------------------|------|---------------------|------|
|           | MFH                        | SFH  | MFH                 | SFH  |
| January   | 0.67                       | 0.48 | 0.32                | 0.19 |
| February  | 0.78                       | 0.60 | 0.26                | 0.17 |
| March     | 0.84                       | 0.74 | 0.32                | 0.22 |
| April     | 0.94                       | 0.84 | 0.65                | 0.52 |
| May       | 1.01                       | 0.88 | 0.82                | 0.68 |
| June      | 0.97                       | 0.84 | 0.91                | 0.81 |
| July      | 1.04                       | 0.91 | 0.88                | 0.77 |
| August    | 1.88                       | 1.68 | 0.90                | 0.76 |
| September | 1.64                       | 1.54 | 1.06                | 0.94 |
| October   | 0.79                       | 0.66 | 0.97                | 0.87 |
| November  | 0.44                       | 0.33 | 0.33                | 0.24 |
| December  | 0.48                       | 0.33 | 0.36                | 0.26 |

4  
 5 As can be seen in Table 4, temperature difference between modified and baseline weather  
 6 files for both buildings is consistently higher in summer compared to winter months. UHI  
 7 effect projected on MFH is higher than on SFH throughout the year, most likely because it is  
 8 located in a more densely built area and has a lower ratio of vegetation and greenery.  
 9 Additionally, UHI effect projected on two weather files by UWG for the same urban  
 10 morphological parameters varies considerably. To investigate this variation, we compared  
 11 climate variables of the two weather files and the difference in the magnitude of UHI effect  
 12 between the two but did not notice any clear correlation between model performance and  
 13 climate variables. However, temperature, relative humidity, wind speed, global horizontal  
 14 irradiance, etc. in the two weather files were not identical and the difference between UHI  
 15 effect projected on two weather files for the same urban morphological parameters indicates  
 16 that the magnitude of UHI effect projected also depends on the choice of weather station.  
 17 This is in line with findings reported by (Bueno, Nakano, and Norford 2015).

1 **3.3 Comparing indoor thermal comfort**

2 Hourly indoor thermal conditions for five summer months (May, June, July, August,  
3 September) were evaluated using two weather files for each studied building. Main facades  
4 of SFH were oriented north-south and main facades of MFH were oriented east-west (Figure  
5 13). In SFH, attic, thermal zone in the middle of the building and one thermal zone in the east  
6 side of the building were selected in thermal comfort evaluation, because they were more  
7 exposed to external environmental conditions. In MFH, attic, one thermal zone oriented east,  
8 one thermal zone oriented west of the first and middle floor were selected for evaluation.  
9 Hourly indoor overheating indicators for each thermal zone were calculated after running  
10 building performance simulations using the weather files selected and modified in previous  
11 sections.

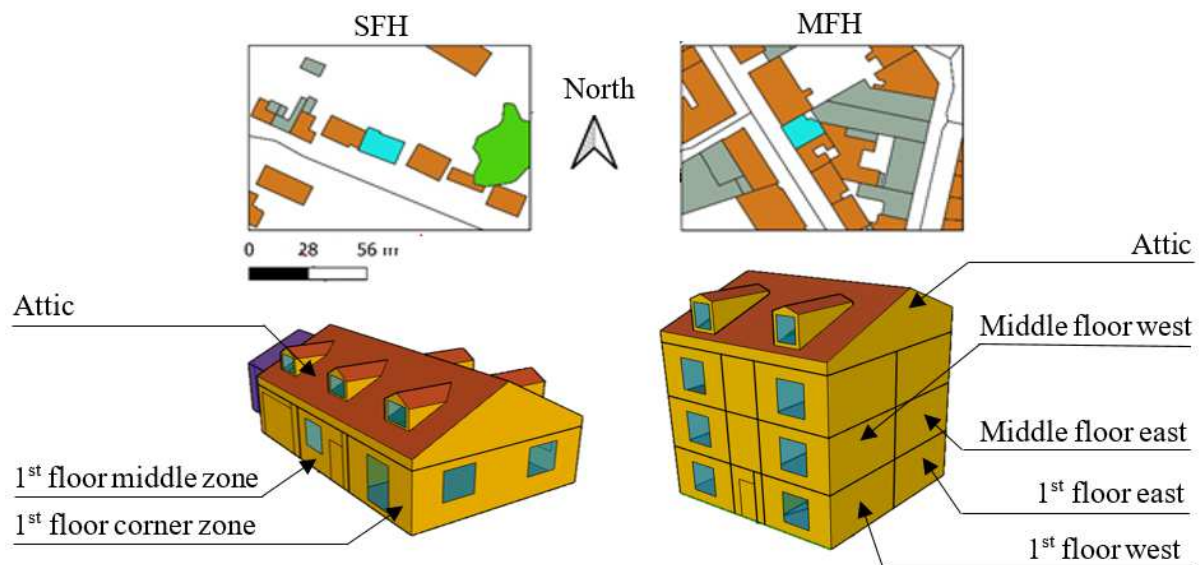


Figure 10: SFH and MFH buildings and their urban context

12  
13  
14

1 Figure 14, demonstrates the percentage of hours when indoor air temperature and humidity  
 2 ratio were within each polygon of Givoni bioclimatic index for five summer months in MFH  
 3 and SFH with two different weather files.

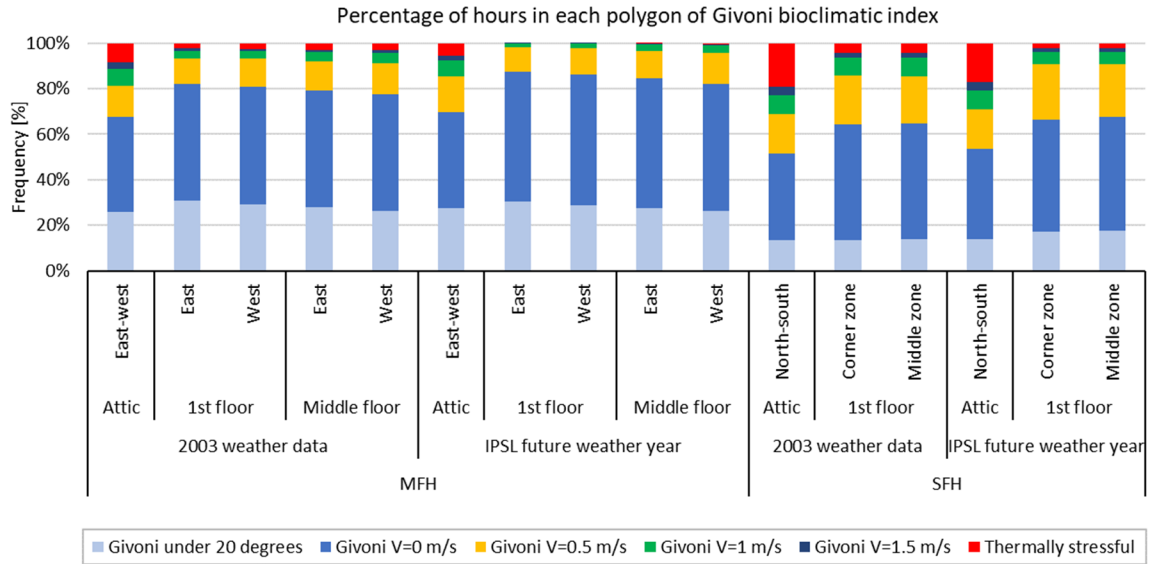


Figure 11: Percentage of hours indoor air temperature and relative humidity were within each polygon of Givoni bioclimatic index

4 Givoni diagram presented in Figure 10, assess summer thermal comfort of occupants  
 5 subjected to various indoor air velocities. This index was selected primarily because  
 6 installation of a ceiling or a portable fan is the first response of occupants to extreme  
 7 temperature in naturally ventilated houses when passive strategies fail to provide expected  
 8 comfort. Temperature, humidity ratio and indoor air velocity are the main parameters  
 9 involved in comfort evaluation with this index. With weather data of 2003, approximately  
 10 20% and 10% of hourly data points in attics of SFH and MFH were outside polygon four  
 11 ( $v=1.5$  m/s), respectively. With IPSL-SMHI weather file, 17% of hourly data points in the  
 12 attic of SFH and 4% in the attic of MFH were outside of polygon four ( $v=1.5$  m/s).

- 1 Below, Figure 15 depicts degree-hours and percentage of hours indoor operative temperature
- 2 in selected zones that exceeded maximum allowable operative temperatures in EN 16798-1.

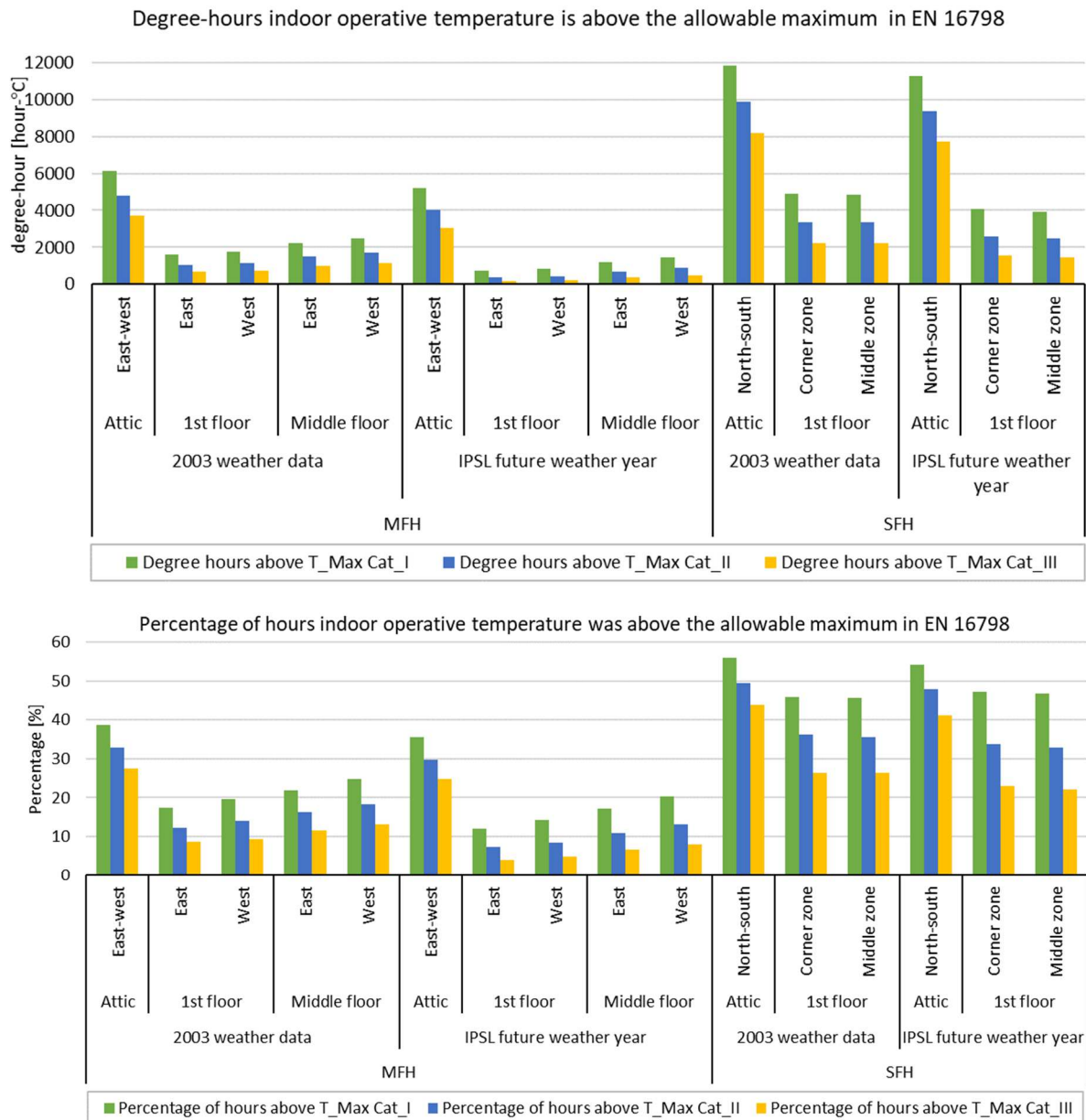


Figure 12: Degree hours and percentage of hours indoor operative temperature exceeded maximum adaptive thresholds of EN 16798-1

- 3 Degree-hours, although is an excellent unit of measurement that shows both the frequency
- 4 and intensity of exceeding operative temperature, but it fails to create a picture on the scale of
- 5 discomfort for practitioners due to the absence of a degree-hour threshold. Hence, percentage
- 6 of exceeding hours is proposed. For instance, with 2003 weather file, indoor operative
- 7 temperature in the attic of MFH exceeded maximum allowable threshold of EN 16798-1

1 category II by 4700 degree-hours during five summer months. This statement although  
 2 accurate does not give a meaningful picture of discomfort level to practitioners or users.  
 3 However, practitioners may find it easier to imagine the level of discomfort if they hear that  
 4 indoor operative temperature in the attic of MFH exceeded maximum allowable threshold of  
 5 EN 16798-1 category II, 31% of summertime. Presenting discomfort with percentage and  
 6 degree-hours for five summer months are good indicators to represent the overall comfort  
 7 performance of a thermal zone or building to overheating but they also fail to depict the  
 8 intensity and severity of heatwave or its consequences on indoor thermal conditions.

9 Therefore, we decided to illustrate indoor thermal conditions with the constant  
 10 temperature of 27 °C degrees as well. In this index, peak indoor air temperature and  
 11 maximum number of consecutive hours when indoor air temperature exceeds 27 °C are  
 12 calculated. Figure 16, presented below, shows peak indoor air temperature and maximum  
 13 consecutive hours when temperature is above 27°C with both weather files and in both  
 14 buildings.

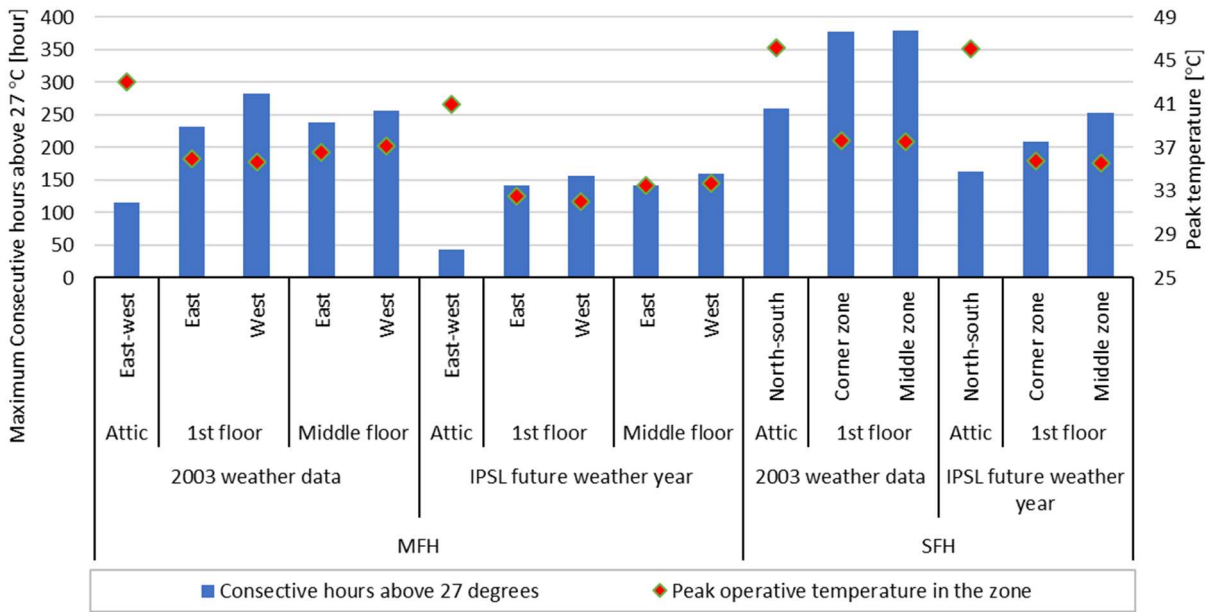


Figure 13: Peak indoor temperature and maximum consecutive hours above 27°C.

1 Similar to indices presented earlier, peak indoor temperatures are higher in the attics  
2 compared to other zones. Inversely, number of maximum consecutive hours above the  
3 selected threshold is considerably lower in the attics compared to other zones.

4 As can be seen in Figure 14 to Figure 16, attic of SFH oriented north-south  
5 experiences the worst indoor temperature conditions compared to other zones in the first floor  
6 of SFH. Indoor peak temperature in the attic of SFH reaches up to 46 °C during the heatwave  
7 with 2003 weather file. However, the duration of consecutive hours that temperature is above  
8 27 °C is significantly lower in the attic of SFH in comparison to thermal zones in the first  
9 floor of SFH. This could be due to large direct exposure surface of attic to external  
10 environments. Large contact surface allows attic of SFH to experience rapid rise and drop in  
11 indoor temperature. Some may argue that it is because of smaller thermal capacity, but in  
12 simulation tool, thermal capacity of attic in SFH is twice as much as the thermal capacity of  
13 corner zone in the first floor of SFH. Attic of MFH, which is oriented east-west, also showed  
14 similar behaviour but the intensity of over-temperature is comparatively less than attic of  
15 SFH.

16 In contrast to SFH, roof and exterior walls of MFH have considerably larger U-  
17 values. MFH is also located in a more densely built urban area, which means it is more likely  
18 to be influenced by the UHI effect. MFH has two joint neighbours in the south and north  
19 orientations. West and east orientations are open and exposed to external environment. SFH,  
20 on the other hand, is almost entirely in contact with the external environment and main  
21 orientations are toward south and north. SFH also has a larger window to wall ratio than  
22 MFH, 13% versus 10%. Overall, MFH performs comparatively better than SFH in all zones  
23 under future climate scenario (IPSL-SMHI weather file) and during the heatwave (2003  
24 weather file). This could mean that when it comes to summer overheating risks in naturally  
25 ventilated houses, solar heat gains through the window; contact surface of a thermal zone to

1 the external environment; and orientation play a more significant role than thermo-physical  
2 properties such as U-value or location of building within the city. This is in coherence with  
3 the findings of (Baba and Ge 2020; Fosas et al. 2018). In both buildings, air inflow rate,  
4 shading rate and percentage, occupancy and plug load were assumed the same.

5 Comparing thermal comfort indices shows that Givoni bioclimatic index, due to initial  
6 assumptions on indoor air velocity may underestimate indoor overheating intensity compared  
7 to EN16798-1 and 27 °C degrees fixed temperature. For instance, in the attic of SFH, with  
8 weather data of 2003, using Givoni bioclimatic index, the frequency of times that indoor air  
9 temperature and relative humidity are outside polygon two ( $v=0.5$  m/s) is about 31 % of  
10 summertime. Whereas, EN 16798-1 for the same thermal zone shows that indoor operative  
11 temperature exceeding category-II is nearly 10000-degree-hours or 49% of the summer  
12 period. This reaches 56% in category-I and 43% in category-III. Under both climate  
13 conditions, this percentage considerably exceeds the 3% threshold recommended by CIBSE  
14 for free-running buildings (Chartered Institution of Building Services Engineers 2013).

15 Considering uncertainties in the input data for different indices, it can be concluded that  
16 adaptive thermal comfort index better represents general thermal comfort performance in  
17 free-running buildings during summer months. However, when it comes to intensity  
18 assessment of indoor over-temperature conditions, maximum consecutive hours above a  
19 specific threshold and peak indoor temperature create a better picture.

20 High intensity of heatwave in the summer period and higher number of HDD in 2003  
21 weather data indicate that observed weather data of 2003 contains a higher discrepancy  
22 compared to IPSL-SMHI and therefore is more suitable for the evaluation of buildings to  
23 heatwaves but it might be overestimating energy demand for heating under future climate  
24 scenario.

#### 1   **4   Limitations and prospects**

2   In this study, the raw data of all necessary climate variables used to construct typical weather  
3   data for the future are not bias-adjusted, therefore only a comparative assessment can be done  
4   with them. In addition, the thresholds used in heatwave detection, are fixed absolute  
5   thresholds for maximum and minimum daily temperatures and are based on the worst  
6   historical heatwave event. In future studies, for France or any other locations around the  
7   world, other methods of heatwaves measurement could also be used.

8   Furthermore, comparative analysis of weather files in this study was focused on medium  
9   future and on typical weather files. Further study is suitable to perform a comparative  
10   analysis of observed heatwave weather data of 2003 with near, and far future weather files,  
11   and with artificially generated extreme hot years. It is also worthwhile to note that the 2003  
12   heatwave data may be suitable for overheating assessment in France but the application of  
13   historical heatwave data in other locations deserves further research.

14   Further research is suggested in the creation of Extreme Hot Year weather files from EURO-  
15   CORDEX to be compared with historical extreme weather years, and performing sensitivity  
16   analysis to determine if passive strategies help to reduce overheating risk in free-floating  
17   buildings that are located in temperate climate regions, such as our case study city.

18

#### 19   **5   Conclusions**

20   In the first part of this paper, a methodology/workflow was described to generate yearly and  
21   typical ready-to-use weather files for BPS using EURO-CORDEX database of dynamically  
22   downscaled climate data of the past, present, and future.

23   We generated three FTWYs using this methodology, then compared them with future weather  
24   file of Meteonorm 2050, and measured weather data of 2003. Comparative analysis of future  
25   weather files showed a difference not only between the weather files that were generated by



1 DDS or ESD approaches but also between different DDS files themselves. This difference  
2 was demonstrated by statistical distribution plots of monthly air temperature, relative  
3 humidity and global horizontal irradiance in each weather file.

4 This comparative analysis also showed that the intensity of heatwave observed in  
5 2003 is higher than typical hot days in the medium future for our case study city. However,  
6 the application of this conclusion in other regions requires further study.

7 The second part of the study investigated indoor overheating in two buildings that  
8 have distinct morphological and thermo-physical characteristics in Nantes, France, with 2003  
9 heatwave weather data and with a typical medium future weather data, measuring indoor  
10 overheating in five summer months. Buildings were modelled in Trnsys v.17 and the two  
11 weather files used in simulations were modified for each building individually by UWG to  
12 take into account the effect of UHI.

13 Results revealed that solar heat gains through the window, contact surface of a  
14 thermal zone to the external environment, and orientation play a significant role in summer  
15 over-temperature vulnerability compared to U-value. It was also noted that buildings located  
16 in sparsely built areas could be even more vulnerable to extreme summer temperatures in  
17 comparison to those located in densely built urban areas, which receive less direct solar  
18 irradiance.

19 Three indicators (Givoni bioclimatic index, EN 16798-1, and constant temperature of  
20 27 °C) were used to measure indoor overheating rate. Results of comparison between comfort  
21 indices showed that adaptive index better represents general thermal comfort performance in  
22 free-running buildings during summer months. However, when it comes to intensity  
23 assessment of indoor over-temperature conditions, maximum consecutive hours above a  
24 specific threshold and peak indoor temperature should also be included.

1 Overall, this study provided a deeper understanding into the analysis of climate  
2 change effect and heatwaves on indoor overheating in naturally ventilated residential  
3 buildings considering urban heat island effect, different weather data, different climate  
4 models and, different measurement indices.

5 **Python Script Availability:** Following Python scripts are available from the  
6 corresponding author, for academic purposes, upon request: Python script to plot  
7 psychometric chart and calculate points inside each polygon of Givoni bioclimatic index;  
8 Python script to download historical weather data of French weather stations and write them  
9 on an epw. file; Python script to extract yearly weather data from EURO-CORDEX NetCDF  
10 files; Python script to assemble typical weather file from yearly weather data.

11

## 12 **References**

- 13 Baba, Fuad Mutasim, and Hua Ge. 2020. 'Overheating Risk of a Single-Family Detached  
14 House Built at Different Ages under Current and Future Climate in Canada' eds. J.  
15 Kurnitski and T. Kalamees. *E3S Web of Conferences* 172: 02004.
- 16 Bande, Lindita et al. 2019. 'Validation of UWG and ENVI-Met Models in an Abu Dhabi  
17 District, Based on Site Measurements'. *Sustainability* 11(16): 4378.
- 18 Battersby, Stephen. 2016. *Clay's Handbook of Environmental Health*. New York: Taylor and  
19 Francis.  
20 <http://public.ebookcentral.proquest.com/choice/publicfullrecord.aspx?p=4578981>  
21 (November 3, 2021).
- 22 Bhatnagar, Mayank, Jyotirmay Mathur, and Vishal Garg. 2018. 'Determining Base  
23 Temperature for Heating and Cooling Degree-Days for India'. *Journal of Building*  
24 *Engineering* 18: 270–80.
- 25 Borgeson, Sam, and Gail Brager. 2011. 'Comfort Standards and Variations in Exceedance for  
26 Mixed-Mode Buildings'. *Building Research & Information* 39(2): 118–33.
- 27 Brasche, Sabine, and Wolfgang Bischof. 2005. 'Daily Time Spent Indoors in German Homes  
28 – Baseline Data for the Assessment of Indoor Exposure of German Occupants'.  
29 *International Journal of Hygiene and Environmental Health* 208(4): 247–53.
- 30 Bueno, Bruno, Aiko Nakano, and Leslie Norford. 2015. 'Urban Weather Generator: A  
31 Method to Predict Neighborhood-Specific Urban Temperatures for Use in Building  
32 Energy Simulations'. In *12th Symposium on the Urban Environment*, , 6.  
33 [http://www.meteo.fr/icuc9/LongAbstracts/udc5-4-6531531\\_a.pdf](http://www.meteo.fr/icuc9/LongAbstracts/udc5-4-6531531_a.pdf).

- 1 Bueno, Bruno, Leslie Norford, Julia Hidalgo, and Grégoire Pigeon. 2013. 'The Urban  
2 Weather Generator'. *Journal of Building Performance Simulation* 6(4): 269–81.
- 3 Carlucci, Salvatore, and Lorenzo Pagliano. 2012. 'A Review of Indices for the Long-Term  
4 Evaluation of the General Thermal Comfort Conditions in Buildings'. *Energy and  
5 Buildings* 53: 194–205.
- 6 Chartered Institution of Building Services Engineers. 2013. *The Limits of Thermal Comfort  
7 Avoiding Overheating in European Buildings ; CIBSE TM52: 2013*. London: CIBSE.
- 8 Civel, Edouard, and Jeremy Elbeze. 2016. 'Energy Efficiency in French Homes : How Much  
9 Does It Cost ?' *Climate Economics Chair of Paris-Dauphine University*: 30.
- 10 Daniela, Jacob et al. 2020. 'Regional Climate Downscaling over Europe: Perspectives from  
11 the EURO-CORDEX Community'. *Regional Environmental Change* 20(2): 51–66.
- 12 Doherty, Sarah et al. 2018. *National Climate Assessment Report. Chapter 2: Our Changing  
13 Climate*. <https://nca2018.globalchange.gov/chapter/2/> (August 4, 2021).
- 14 EN 16798-1. 2019. 'Energy Performance of Buildings - Ventilation for Buildings - Part 1:  
15 Indoor Environmental Input Parameters for Design and Assessment of Energy  
16 Performance of Buildings Addressing Indoor Air Quality, Thermal Environment,  
17 Lighting and Acoustics'.
- 18 Epstein, Yoram, and Daniel S. Moran. 2006. 'Thermal Comfort and the Heat Stress Indices'.  
19 *Industrial Health* 44(3): 388–98.
- 20 Erlandsen, Helene Birkelund et al. 2020. 'A Hybrid Downscaling Approach for Future  
21 Temperature and Precipitation Change'. *Journal of Applied Meteorology and  
22 Climatology* 59(11): 1793–1807.
- 23 Fosas, Daniel et al. 2018. 'Mitigation versus Adaptation: Does Insulating Dwellings Increase  
24 Overheating Risk?' *Building and Environment* 143: 740–59.
- 25 Green, Helen K. et al. 2016. 'Mortality during the 2013 Heatwave in England – How Did It  
26 Compare to Previous Heatwaves? A Retrospective Observational Study'.  
27 *Environmental Research* 147: 343–49.
- 28 Hamdy, Mohamed, Salvatore Carlucci, Pieter-Jan Hoes, and Jan L.M. Hensen. 2017. 'The  
29 Impact of Climate Change on the Overheating Risk in Dwellings—A Dutch Case  
30 Study'. *Building and Environment* 122: 307–23.
- 31 Hosseini, Mirata, Anahita Bigtashi, and Bruno Lee. 2021. 'Generating Future Weather Files  
32 under Climate Change Scenarios to Support Building Energy Simulation – A Machine  
33 Learning Approach'. *Energy and Buildings* 230: 110543.
- 34 IPCC. 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working  
35 Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate  
36 Change*. [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger,  
37 N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R.  
38 Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)].  
39 Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg1/#SPM>.

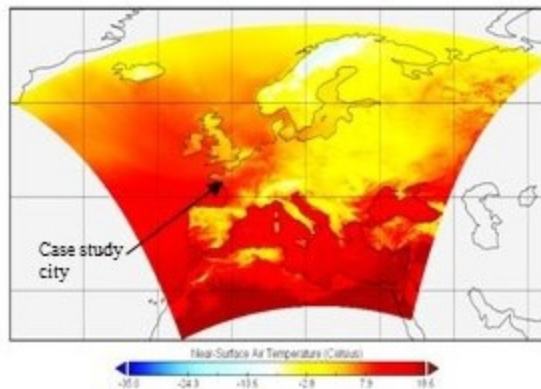
- 1 ISO 15927-4. 2005. '[EN ISO 15927-4\_2005] -- Hygrothermal Performance of Buildings.  
2 Calculation and Presentation of Climatic Data. Hourly Data for Assessing the Annual  
3 Energy Use for Heating and .Pdf'.
- 4 Jacob, Daniela et al. 2014. 'EURO-CORDEX: New High-Resolution Climate Change  
5 Projections for European Impact Research'. *Regional Environmental Change* 14(2):  
6 563–78.
- 7 Kamal, Athar et al. 2021. 'Impact of Urban Morphology on Urban Microclimate and Building  
8 Energy Loads'. *Energy and Buildings*: 111499.
- 9 Kumar, Sanjay et al. 2019. 'Comparative Study of Thermal Comfort and Adaptive Actions for  
10 Modern and Traditional Multi-Storey Naturally Ventilated Hostel Buildings during  
11 Monsoon Season in India'. *Journal of Building Engineering* 23: 90–106.
- 12 Lauzet, Nicolas, Dasaraden Mauree, Thibaut Colinart, and Marjorie Musy. 2018.  
13 'Construction of reusable urban microclimate weather files for BPS/Construction d'un  
14 fichier microclimatique urbain utilisable en STD. (in French)'. : 8.
- 15 Lomas, Kevin J., and Stephen M. Porritt. 2017. 'Overheating in Buildings: Lessons from  
16 Research'. *Building Research & Information* 45(1–2): 1–18.
- 17 Machard, Anaïs et al. 2020. 'A Methodology for Assembling Future Weather Files Including  
18 Heatwaves for Building Thermal Simulations from the European Coordinated  
19 Regional Downscaling Experiment (EURO-CORDEX) Climate Data'. *Energies*  
20 13(13): 3424.
- 21 Malet-Damour, Bruno. 2012. 'Impact of the Climate on the Design of Low-Energy Buildings  
22 for Australia and Reunion Island'. In *12th Conference of International Building  
23 Performance Simulation Association, Sydney, 2867–73*. hal-00768497.
- 24 Manoli, Gabriele et al. 2019. 'Magnitude of Urban Heat Islands Largely Explained by  
25 Climate and Population'. *Nature* 573(7772): 55–60.
- 26 Maraun, Douglas. 2016. 'Bias Correcting Climate Change Simulations - a Critical Review'.  
27 *Current Climate Change Reports* 2(4): 211–20.
- 28 McCartney, Kathryn J, and J Fergus Nicol. 2002. 'Developing an Adaptive Control Algorithm  
29 for Europe'. *Energy and Buildings* 34(6): 623–35.
- 30 Mitchell, Dann, Kai Kornhuber, Chris Huntingford, and Peter Uhe. 2019. 'The Day the 2003  
31 European Heatwave Record Was Broken'. *The Lancet Planetary Health* 3(7): e290–  
32 92.
- 33 Mitchell, Rachel, and Sukumar Natarajan. 2019. 'Overheating Risk in Passivhaus Dwellings'.  
34 *Building Services Engineering Research and Technology* 40(4): 446–69.
- 35 Moazami, Amin, Vahid M. Nik, Salvatore Carlucci, and Stig Geving. 2019. 'Impacts of  
36 Future Weather Data Typology on Building Energy Performance – Investigating  
37 Long-Term Patterns of Climate Change and Extreme Weather Conditions'. *Applied  
38 Energy* 238: 696–720.

- 1 Nicol, J. Fergus, Jake Hacker, Brian Spires, and Hywel Davies. 2009. 'Suggestion for New  
2 Approach to Overheating Diagnostics'. *Building Research & Information* 37(4): 348–  
3 57.
- 4 Nicol, J.F. 1974. 'An Analysis of Some Observations of Thermal Comfort in Roorkee, India  
5 and Baghdad, Iraq'. *Annals of Human Biology* 1(4): 411–26.
- 6 Ouzeau, G. et al. 2016. 'Heat Waves Analysis over France in Present and Future Climate:  
7 Application of a New Method on the EURO-CORDEX Ensemble'. *Climate Services*  
8 4: 1–12.
- 9 Petrou, Giorgos et al. 2019. 'The Summer Indoor Temperatures of the English Housing  
10 Stock: Exploring the Influence of Dwelling and Household Characteristics'. *Building*  
11 *Services Engineering Research and Technology* 40(4): 492–511.
- 12 P.Tootkaboni, Mamak, Ilaria Ballarini, Michele Zinzi, and Vincenzo Corrado. 2021. 'A  
13 Comparative Analysis of Different Future Weather Data for Building Energy  
14 Performance Simulation'. *Climate* 9(2): 37.
- 15 Pyrgou, Andri et al. 2017. 'On the Effect of Summer Heatwaves and Urban Overheating on  
16 Building Thermal-Energy Performance in Central Italy'. *Sustainable Cities and*  
17 *Society* 28: 187–200.
- 18 Raei, Ehsan et al. 2018. 'GHWR, a Multi-Method Global Heatwave and Warm-Spell Record  
19 and Toolbox'. *Scientific Data* 5(1): 180206.
- 20 Rahif, R., D. Amaripadath, and S. Attia. 2021. 'Review on Time-Integrated Overheating  
21 Evaluation Methods for Residential Buildings in Temperate Climates of Europe'.  
22 *Energy and Buildings* 252: 111463.
- 23 Ramon, Delphine et al. 2019. 'Future Weather Data for Dynamic Building Energy  
24 Simulations: Overview of Available Data and Presentation of Newly Derived Data for  
25 Belgium'. In *Energy Sustainability in Built and Urban Environments*, Energy,  
26 Environment, and Sustainability, eds. Emilia Motoasca, Avinash Kumar Agarwal, and  
27 Hilde Breesch. Singapore: Springer Singapore, 111–38.  
28 [http://link.springer.com/10.1007/978-981-13-3284-5\\_6](http://link.springer.com/10.1007/978-981-13-3284-5_6) (May 20, 2021).
- 29 Robinson, Darren, and Frédéric Haldi. 2008. 'Model to Predict Overheating Risk Based on an  
30 Electrical Capacitor Analogy'. *Energy and Buildings* 40(7): 1240–45.
- 31 Salvati, Agnese, Massimo Palme, and Luis Inostroza. 2017. 'Key Parameters for Urban Heat  
32 Island Assessment in A Mediterranean Context: A Sensitivity Analysis Using the  
33 Urban Weather Generator Model'. *IOP Conference Series: Materials Science and*  
34 *Engineering* 245: 082055.
- 35 Thiis, Thomas K. et al. 2017. 'Monitoring and Simulation of Diurnal Surface Conditions of a  
36 Wooden Façade'. *Procedia Environmental Sciences* 38: 331–39.
- 37 Wagner, Véréne. 2018. 'Evolution of heatwaves and associated mortality in France, 2004-  
38 2014/Évolution des vagues de chaleur et de la mortalité associée en France, 2004-  
39 2014 (in French)'. : 6.

- 1 WMO. 2020. *State of the Global Climate 2020*. World Meteorological Organization, 2021.  
2 [https://library.wmo.int/doc\\_num.php?explnum\\_id=10618](https://library.wmo.int/doc_num.php?explnum_id=10618).
- 3 Yang, Jun et al. 2019. 'Heatwave and Mortality in 31 Major Chinese Cities: Definition,  
4 Vulnerability and Implications'. *Science of The Total Environment* 649: 695–702.
- 5

## Future climate & heatwave weather data

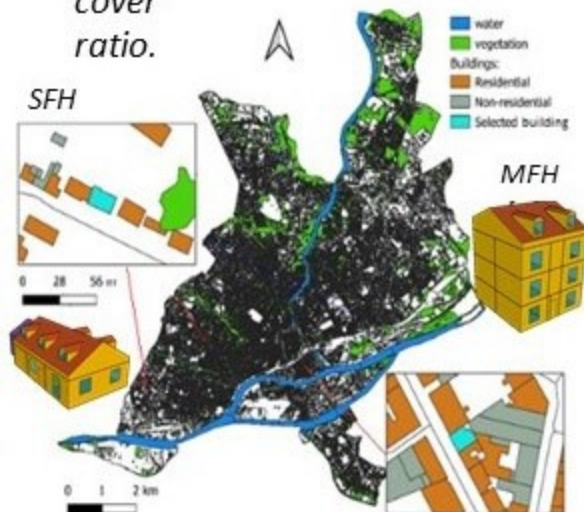
- 3 dynamically downscaled future typical weather files of median future (2040-2070) from RCP 8.5 emission scenario.
- Measured weather data of 2003 exceptional heatwave.
- Future weather file from meteonorm for 2050, RCP 8.5 emission scenario.



## Urban heat island effect on two types of buildings

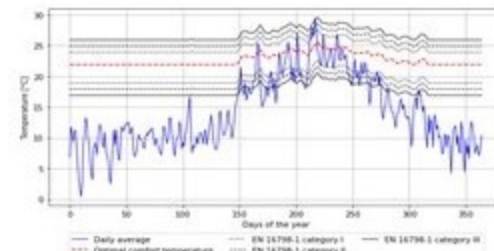
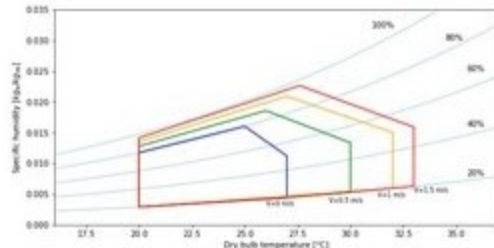
Urban morphology parameters in 200 meter radius for UWG:

- Average building height.
- Build density.
- Tree Cover ratio.
- Grass cover ratio.
- Vertical to horizontal area ratio.
- Year of construction.
- Climate zone: zone 4A for both buildings



## Building performance evaluation indices

- Givoni bioclimatic index.
- EN 16798-1 adaptive index.
- Maximum consecutive hours above 27 °C & Peak indoor temperature.



## Key findings

- Temperature in a typical summer in medium future (2040 -2070) is likely not as intense as the heatwave of 2003 for Nantes, France.
- Buildings located in sparsely built locations that are less affected by UHI are also at risk of overheating
- Results confirm it is better to use two weather files and at least two indoor overheating indices to evaluate a building's summer performance.