Africa-Europe Bioclimatic Collaboration 21

Africa-Europe BioClimatic buildings for XXI century

REPORT ON AVAILABILITY OF WEATHER FILES & INDICATORS FOR TODAY AND FUTURE WEATHER IN AFRICA AND EU

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ABC 21 Project

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Executive summary

In the current context of significant climate change there is an increased need to consider future weather data in the building design phase. Ideally this data must be available in two forms: simplified weather indicators and detailed hourly weather files. Both forms are crucial inputs for the early and late stages of modern building design processes. This report presents a review of available weather files and discusses methodologies for simplified weather indicators, weather datasets, and production of future weather files for Africa and EU.

Weather files can provide a comprehensive characterization of the local climate by including meteorological and solar radiation data elements (such as, dry-bulb outdoor air temperature, relative humidity, global horizontal irradiation, and wind speed and its direction). Building thermal simulation is a widely used support tool for the design of building energy systems and building energy labelling/certification. This tool requires, at least, one year weather data with one hour time resolution that describes the climate of the building location. Weather data can be found in different formats, and all contain several climate data elements that are essential to perform a reliable building thermal simulation. This report lists the usual weather data elements and typical resolution used in each format of weather files.

Weather file providers usually have large databases with data that is directly collected from weather stations or interpolated data from satellite-derived data, climate reanalysis models and weather stations. The latter databases have a larger uncertainty since its data is derived from spatial interpolation models. From the nine weather databases identified, four were based on weather stations data only, and four were free services. Climate One Building is the only free service that has current weather datasets for all the locations in Africa and Europe considered in this project.

The freely available databases of weather files do not include weather files of future climate. Currently, the simplest form of production of future weather files is the CCWorldWeatherGen tool, which relies on the morphing methodology. As an input, this tool needs a weather file of current climate and expected climate change outputted by a climate model (climate change factors). These climate change factors need to be referenced to an historical base climate (time period) similar to the one that was used to produce the historical weather file, otherwise climate change projections will not be correct. The climate change factors used in the CCWorldWeatherGen tool are based on the climate change projections of the Intergovernmental Panel on Climate Change (IPCC) for three different periods: 2020, 2050 and 2080, considering a baseline climate between 1961-1990.

Weather indicators can be useful to predict the impact of climate change in building design, especially in passive buildings where the natural ventilation and the building envelope plays the main role. This report reviews the definitions of heating and cooling degree-days as weather indicators (that are usually used for estimation of building energy needs and weather classification), discusses the diversity of base temperature definitions used in the degree-days calculations, and presents the bioclimatic indicators that assess the natural ventilation (NV) cooling potential and the availability of weather indicators data.

In the building energy analysis area, degree-days (DD) are a metric used for estimating the energy consumption of a given building that is required for heating (heating degree-days, HDD) or cooling (cooling degree-days, CDD). The degree-days are defined as the cumulated difference between a base temperature and the outdoor air temperature. To assess the heating required, the difference between the base temperature and the outdoor air temperature is

calculated and, if the value is positive, then that number represents the HDD. To assess the cooling needs, is the reverse process, as in this case it is calculated the difference between the outdoor air temperature and the base temperature, and if the resulting value is positive, it is considered as CDD. There are several methods to calculate the HDD and CDD, such as the mean daily degree-day, the mean daily outdoor air temperature, and the residual cooling degree-days. We have also reviewed the different proposed base temperatures present in literature. In most cases, the base temperature is dependent on the degree-days method used (i.e., the base temperature used to calculate HDD differs from the one used to calculate the CDD). Even for the same DD method, several base temperatures were already proposed (with huge differences between them), indicating that there is no consensus in the scientific community for a universal base temperature for each method. This finding implies that HDD or CDD values should not be directly compared, and attention must be given to ensure that comparisons are only made with equal base temperatures.

The combination of higher air temperatures and continuously increasing building occupant comfort expectations and standards will lead to higher cooling energy demand in both commercial and residential buildings. To contain this increase, building designers are encouraged to use passive design strategies and low energy cooling systems such as natural ventilation (NV), night cooling (NC), shading and exposed thermal mass. These strategies have in common their use of the outdoor climate as a source of free or low energy cooling. To assess the cooling capacity of different strategies in buildings, passive cooling indicators were proposed, such as the climate cooling potential (CCP), the natural ventilation hour (NV hour), the climate potential for natural ventilation (CPNV), and the suitability of air temperature for natural ventilation (SNV). The CCP indicator consists of the average accumulated hourly indoor and outdoor temperature differences for the night period when this difference is above 3ºC. This indicator is based on the concept of degree-days and considers that the base temperature corresponds to the comfort building temperature and has a sinusoidal oscillation during the year. Although the comparison of the CCP for the current and future climates allows for the assessment of the impact of climate change on the passive cooling systems, the CCP have known drawbacks, such as: the neglecting of the wind effect on the NV (assuming that NV only occurs through stack effect); not considering that NV can occur during the day or used as a night cooling system; and not accounting for the humidity as comfort criterion (especially relevant for hot and humid climates). The concept of natural ventilation hour can be defined as the number of hours in a typical year when the outdoor weather condition is suitable to use passive cooling strategies. The NV hour assesses only if the outdoor weather is suitable for natural ventilation using an upper and a lower threshold for the dry-bulb temperature and the expected indoor air velocity. Some limitations of the NV hour indicator are related to the humidity control criteria that do not prevent the possibility of providing saturated air, or to the neglecting of the vertical gradient that exists in the speed of atmospheric wind, or to the fact that it does not distinguish the suitability of passive cooling strategies for day and night period. The climatic potential for NV (CPNV) follows a similar approach to the NV hour, where is established when the climate has favourable conditions for natural ventilation, but the difference between them relies on the definition of comfort. The CPNV does not account for how wind velocity affects the indoor air velocity during NV time and considers that NV can occur if the outdoor air temperature and the humidity ratio are between the thresholds set. The CPNV indicator accounts for both daytime NV (during occupied hours) and night cooling (unoccupied hours), allowing different lower thresholds for each NV strategy. It also accounts for the indoor humidity ratio with values ranging from 30% to 70%, which ensures that the indoor environment is in humidity comfort range. The suitability of air temperature for NV indicator defines that when the outdoor temperature is between 10ºC and 26ºC, NV can be used to increase both the indoor air quality and thermal conditions. This large temperature interval is then divided into two small intervals: between 10ºC and 16ºC is considered that outdoor air is suitable to improve indoor air quality through fresh air supply; while between 16ºC and 26ºC is considered that ventilated cooling can be performed to remove heat gains and improve or maintain thermal comfort. This indicator has a simplified approach compared with the previous indicators but has the advantage of easy application. Nevertheless, it does not account for the possibility of night cooling strategies, or the relevance of humidity control for some climates, and it does not account for the effect of wind during the NV period.

The currently available weather indicators were produced using different methods, weather sources, assumptions, and spatial resolution levels. Whenever possible weather indicators should be calculated using the best available current and morphed future TMY files.

Abbreviations

Term	Name
CCP	Climate cooling potential
CDD	Cooling degree-days
CPNV	Climatic Potential for Natural Ventilation
DD	Degree-day
ECMWF	European Centre for Medium-Range Weather Forecasts
GDD	Growing degree-days
GHG	Greenhouse gas
HDD	Heating degree-days
IPCC	Intergovernmental Panel on Climate Change
IWEC	International Weather Year for Energy Calculations
NC	Night cooling
NV	Natural ventilation
RCP	Representative Concentration Pathways
TMY	Typical Meteorological Year
UKMO	UK Meteorological Office
CCP	Climate cooling potential
CDD	Cooling degree-days
CPNV	Climatic Potential for Natural Ventilation
DD	Degree-day
ECMWF	European Centre for Medium-Range Weather Forecasts
GDD	Growing degree-days
GHG	Greenhouse gas

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1. Introduction

In the current context of significant climate change there is an increased need to consider future weather data in the building design phase. Ideally this data must be available in two forms: simplified weather indicators and detailed hourly weather files. Both forms are crucial inputs for the early and late stages modern building design processes. This report presents a review of available weather files and simplified weather indicators for current and future weather in Africa and EU.

In the context of the ABC 21 project this report reviews and discusses methodologies for weather indicators, weather datasets, and production of future weather files that are useful for deliverables 3.5 and 3.6 of Task 3.2, and for Task 3.5. D3.5 will present the available methods and tools for the generation of future weather files, and the D3.6 will discuss the effect of future weather on the performance of one or more case studies. In Task 3.5 this report will assist the definition of technical guidelines and tools for future-proof passive design in warm climates.

2. Review of available weather file sources for Africa and EU

2.1. Weather data elements

Building thermal simulation is a widely used support tool for the design of building energy systems and building energy labelling/certification. This tool requires, at least, one year weather data with one hour time resolution that describes the climate of the building location. Weather data can be found in different formats(1) that all contain several climate data elements that are essential to perform a building thermal simulation. Table 2.1 lists the usual weather data elements and typical resolution used in these files. The resolution can vary according to the quality of available data or the accuracy of the building thermal simulation that will be performed.

Table 2.1 – Data elements usually present in weather files for building thermal simulation [1,2]

Element	Symbol	Unit	Resolution	Comment
Date	-	YYYY/MM/DD	-	Date of data record
Time	-	HH:MM	-	Time of data record (local standard time)
Dry-bulb Temperature	T_{db}	Degree Celsius	0.1 ºC	-
Dew-point Temperature	T_{dp}	Degree Celsius	0.1 ºC	-
Relative Humidity	ϕ	Percentage	1%	-
Atmospheric Pressure	p	Pascal	0.1 Pa	-
Global Horizontal Irradiance	G_h	Watt-hour per square meter	1 Wh/m^2	Total amount of direct and diffuse solar radiation received on a horizontal surface
Direct Normal Irradiance	$G_{D,\perp}$	Watt-hour per square meter	1 Wh/m^2	Amount of solar radiation received in a collimated beam on a surface normal to the sun
Diffuse Horizontal Irradiance	$G_{h,\mathrm{df}}$	Watt-hour per square meter	1 Wh/m^2	Amount of solar radiation received from the sky (excluding the solar disk) on a horizontal surface
Wind Direction	θ_{w}	Degree	1 º	Degrees from north]0º , 360º]
Wind Speed	u_{w}	Meter per second	0.1 m/s	-

Table 2.2 presents the most common climate variables used in building thermal simulation that can be calculated from weather files that include the variables shown in Table 2.1. Data from weather files can be used to calculate heating degree-days (HDD), cooling degree-days (CDD), and natural ventilation potential, for example.

Table 2.2 – Example of data elements that can be calculated from weather files [2,3].

Elements	Symbol	Unit	Function of	Comment
Humidity Ratio	W	$\mathrm{kg_{vapor}/kg_{air}}$	T_{db}, ϕ, p	-

(1) Some examples of data types: .epw – EnergyPlus Weather; TM2 – Typical Meteorological Year 2; .fmt – DOE-2 formatted file; .wea – Ecotect WEA file.

Elements	Symbol	Unit	Function of	Comment
Saturated Water Vapour Pressure	p_{ws}	Pa	T_{db}	-
Water Vapour Pressure	p_{w}	Pa	ϕ , p_{ws}	-
Air Density	ρ_{air}	kg/m^3	T_{db} , ϕ , p	-
Wet-bulb temperature	T_{wb}	ºC	T_{db} , W	-
Air Enthalpy	h	kJ/kg$_{\mathrm{air}}$	T_{db} , W	-
Solar Altitude	α	º	G_h , $G_{h,\mathrm{df}}$, $G_{\mathrm{D},\perp}$	-

In some cases the weather files can provide a more comprehensive characterization of the local climate by including additional data elements such as sky cover, visibility, aerosol optical depth or liquid precipitation depth [1,2]. Typically, data elements used to assess the outdoor air quality are not included in the weather datasets produced according to weather files standards [1].

2.2. Sources of current weather files

The most commonly available weather datasets are produced using the Typical Meteorological Year method [4]. TMY files are assembled by compiling the individual months which best correspond to the long-term monthly means of different climate variables [5]. The first version of TMY methodology was introduced by I. J. Hall et al. [4] and consists on the selection of twelve typical months from 30 years of hourly data to assemble one year of representative weather data for a given location. The twelve typical months are selected by statistical analysis of 9 different variables using different weighting factors used to rank the 30 months that are available for each month (see Table 2.3). Although discrepancies in the transition between months can occur in TMY files, several studies show that typical building operation is adequately simulated by a single TMY file [5,6,7,8].

In 1994, the TMY weighting factors were adjusted (TMY2 [9]). In 1997, the initiative called International Weather Year for Energy Calculations (IWEC) created climate files using the TMY methodology with updated weighting factors [10]. The last update of this dataset occurred in 2008, using 15 years of data to assemble TMY files [1].

Table 2.3 - Weather Variables and Weighting factors in different TMY methods [11].

Weather Variable	TMY [4]	TMY2 [9]	IWEC [10]
Maximum dry bulb temperature	1/24	1/20	5/100
Minimum dry bulb temperature	1/24	1/20	5/100
Mean dry bulb temperature	2/24	2/20	30/100
Maximum dew point temperature	1/24	1/20	2.5/100
Minimum dew point temperature	1/24	1/20	2.5/100
Mean dew point temperature	2/24	2/20	5/100
Maximum wind speed	2/24	1/20	5/100
Mean wind speed	2/24	1/20	5/100
Total horizontal solar radiation	12/24	5/20	40/100
Direct normal solar radiation	-	5/20	-

Table 2.4 presents a shortlist of providers for weather data. The first four databases provide only collected data from weather stations while the remain databases use interpolation models based on satellite-derived data, climate reanalysis models and weather station data. Using data from spatial interpolation models increases uncertainty, especially when subjective considerations are used to adjust the observed data to any location [12]. Therefore, this uncertainty is extended to the TMY files, compromising their accuracy. The Climate One Building has the most accurate and recent weather data in comparison to the remaining freely available database.

Table 2.4 – Shortlist of weather databases.

Database	Type	Available for		Comment
		Europe	Africa	
EnergyPus WeatherData	free	188 locations	153 locations	Most TMY files produced with a date before the year 2001. [LINK]
Climate One Building	free	3454 locations	896 locations	TMY files available for the whole period of record and the most recent 15 years (2004-2018). [LINK]
Meteonorm	paid	1640 locations	600 locations	Historical hourly data available from 2010 to present in TMY format. Includes three IPCC scenarios and allows projections to the year 2100. [LINK]
White Box Technologies	paid	+3400 locations	+800 locations	Weather data available from 2001 to the present. TMY files are not available for all the European or African locations. [LINK]
Weather Source	paid	any location	any location	Weather data available from the year 2000 to the present. Data available in TMY format. [LINK]
PVGIS	free	any location	any location	TMY produced using the ECMWF ERA-interim reanalysis and solar satellite data with a resolution of ~80km. Data available for three periods: 2005-2014, 2006-2015 and 2007-2016. [LINK]
Solcast	paid	any location	any location	Satellite-derived data from 2007 to present with a resolution of 1-2km available on TMY format. [LINK]
SOLARGIS	paid	any location	any location	Satellite-derived data from 2000 to present with a resolution of 0.25-35km available on TMY format. [LINK]
SIREN	paid	any location	any location	Program to produce synthetic weather data for a specific year from 1979 to present based on data from NASA MERRA-2. [LINK]

Current weather datasets for the locations used in ABC 21 can be found in the repository of Climate One Building [13] (Table 2.5). The TMY files were created using the ISO 15927-4:2005 [14] with two different baseline periods: the first considering the whole period of record, and a second considering the most recent and complete 15 years. As a result, climate change effects, which were present during these years, are considered in these TMY files. The repository provides for each location a TMY in the .epw format along with an ESP-r weather format, a DAYsim weather format, ASHRAE Design Conditions, hourly precipitation (if available) and expanded EnergyPlus weather statistics [13].

Table 2.5 – Current Typical Meteorological Year for partner's locations [13].

City	Weather Station Location	Period of Record	Download Link
Milan (Italy)	Milan-Linate Airport	2004-2018	Milano-Linate
Rabat (Morocco)	Rabat-Sale Airport	2004-2018	Rabat-Sale
Midelt (Morocco)	Midelt (urban area)	2004-2018	Draa-Tafilalet-Midelt
Wien (Austria)	Wien (urban area)	2004-2018	Wien Innere

City	Weather Station Location	Period of Record	Download Link
Lisbon (Portugal)	Lisbon (urban area)	2002-2019	Lisbon Inst. Geofísico
Nairobi (Kenya)	Nairobi-Kenyatta Airport	2004-2018	Nairobi-Kenyatta
Dakar (Senegal)	Dakar-Senghor Airport	2004-2018	Dakar-Senghor
Saint-Denis (La Reunion, France)	Roland Garros Airport	2004-2017	La Reunion-Saint Marie
Lomé (Togo)	Lome-Tokoin-Eyadema Airport	2004-2018	Lome-Tokoin-Eyadema

2.3. Sources of future weather files

The last decade was the warmest decade on record for the globe [15], a side effect of climate change and having carbon-based economy [16]. In spite of these increasingly felt effects, the freely available databases of weather files do not include weather files of future climate.

Currently the simplest form of production of future weather files is the CCWorldWeatherGen tool, that relies on the morphing methodology [5]. As inputs, this tool needs a weather file of current climate (from one of the databases listed in Table 2.4) and expected climate change outputted by a climate model (climate change factors). These climate change factors need to be referenced to an historical base climate (time period) similar to the one that was used to produce the historical weather file [17], otherwise climate change projections will not be correct [18].

The climate change factors used in the CCWorldWeatherGen tool are based on the climate change projections of IPCC fourth assessment report [19] for three different periods: 2020, 2050 and 2080, considering a baseline climate between 1961-1990. More recently, a new set of climate projections were simulated from 1850 to 2100 and, in some cases, until 2300 [20]. Four different climate scenarios (named Representative Concentration Pathways, RCPs) were simulated based on socio-economic, technological, energy, land use and cover, emissions of GHG and air pollutant assumptions [20]. For each RCPs scenario a radiative forcing, or increase from background radiation, is defined for the year 2100 (8.5 W/m^2, 6 W/m^2, 4.5 W/m^2 and 2.6 W/m^2) relative to pre-industrial levels. Considering the difficulties to mitigate and reduce the impacts of GHG emission, RCP 8.5 is often used in long-term climate change impact studies [21,22].

In Europe, the CORDEX project provides the highest resolution climate model simulations that are used to produce climate change factors. These are available at 11º (~12.5km) spatial resolution and there are more than 20 models available for three RCPs scenarios (RCP2.6, RCP4.5 and RCP8.5) [23]. For Africa, the CORDEX highest resolution of climate models available is 22º (~12.5km) and there are only 9 models for RCP2.6 and RCP8.5. J. Dias Bravo et al. [5] showed that using a proper morphing methodology, and considering the correct baseline climate for the climate delta changes, morphed future weather files allows similar performances compared to more accurate methods that rely on future TMY files produced using several years of future weather data.

The alternative to the tools previously referred, are paid software tools: WeatherShift and Meteonorm, which use the morphing method and have same a resolution limitations as CORDEX.

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3. Review of available weather indicators for Africa and EU

Weather indicators can be useful to predict the impact of climate change in building design, especially in passive buildings where the natural ventilation and the building envelope plays the main role.

The review of the availability of weather indicators is divided into three sections. The first section explores the definitions of heating and cooling degree-days that are usually used for estimation of building energy needs and weather classification. In addition, this section also discusses the diversity of base temperature definitions used in degree-days calculations. The second section presents bioclimatic indicators that assess the natural ventilation (NV) cooling potential. The third section presents and discusses the availability of data for weather indicators.

3.1. Degree-days

The degree-days concept was originally introduced for the assessment of weather and crop growing conditions [25], more specifically in the prediction of plant and pest growing stages and the date that a crop reaches maturity [24]. In this case, the degree-days are defined as growing degree-days (GDD) and only account for the cumulated heat below a base temperature value that varies among species and the growth stage being considered [24].

In the building energy analysis area degree-days correspond to the cumulated temperature difference, below (for HDD) or above (for CDD), to a given a base temperature and the outdoor air temperature [25]. This is defined as the temperature at which an active climate control system (for heating or cooling) does not need to run to maintain indoor comfort conditions (more details about the base temperature in section 3.1.4.).

The concept of degree-days is not unique to building energy analysis. Using databases of degree-days requires special attention because GDD and HDD or CDD have specific calculation methods and assumptions [25]. Also, some definitions of HDD and CDD are only used in weather classification [57,58,64].

Mean daily degree-day

The most rigorous and accurate method for calculation of degree-days is to sum, on an hourly basis, the temperature differences, that are then divided by 24 (Eq. (3.1) and (3.2)). Only the positive difference values are summed, and for the case of negative differences, the value is set to zero for that hour [25]. The mean daily degree-days can be calculated for the desired period (N): a month, the heating or the cooling season, a year, etc. The HDD and CDD are given by the equations (3.1) and (3.2), respectively, where $T_{\mathrm{out},j}$ is the outdoor temperature in hour j and T_{b} is the base temperature. The subscript h and c denotes for heating and cooling season, respectively.

$$\mathrm{HDD} = \sum_{d=1}^{N} \left(\frac{1}{24} \sum_{j=1}^{24} \left[T_{\mathrm{b},h} - T_{\mathrm{out},j} \right]^{+} \right)_{d} \tag{3.1}$$

$$\mathrm{CDD} = \sum_{d=1}^{N} \left(\frac{1}{24} \sum_{j=1}^{24} \left[T_{\mathrm{out},j} - T_{\mathrm{b},c} \right]^{+} \right)_{d} \tag{3.2}$$

The main limitation of this method is the requirement for hourly temperature profiles, which are not readily available for most locations. Also, calculating degree-days with a high resolution, 1 minute, for example, is possible, but there is no gain in the accuracy of the final value [25]. Still, using hourly temperature to calculate degree-days does not mean necessarily that the estimation of hourly building energy needs can be produced accurately [25].

Mean daily temperature

According to the ASHRAE handbook [3], the degree-days can be calculated using the mean daily temperature, defined as the arithmetic mean of maximum and minimum temperatures of a given day as shown in Eq. (3.3). Therefore, HDD and CDD are calculated according to equations (3.4) and (3.5).

$$\bar{T}_{\mathrm{out},d} = (T_{\max,d} + T_{\min,d})/2 \tag{3.3}$$

$$\mathrm{HDD} = \sum_{d=1}^{N} (T_{\mathrm{b},h} - \bar{T}_{\mathrm{out},d})_d^+ \tag{3.4}$$

$$\mathrm{CDD} = \sum_{d=1}^{N} (\bar{T}_{\mathrm{out},j} - T_{\mathrm{b},c})_d^+ \tag{3.5}$$

This definition makes the calculation of degree-days simpler allowing for a significant reduction of data, requiring only the daily maximum and minimum temperature. However, the ASHRAE definition has a limitation when it sets to zero the degree-day value also when the maximum and minimum daily temperature exceeds, below or above, the base temperature threshold, but the mean daily temperature does not [47]. This may occur, for example, in the cases in which the maximum daily temperature is above the base temperature, but the daily mean temperature is equal or lower to the base temperature the CDD is set to zero, while a heat flow through the building envelope can occur during a certain period of the day.

Using the UK Meteorological Office equations (UKMO) it is possible to calculate the degree-days without neglecting the variation of diurnal temperature [25], overcoming the limitation of ASHRAE method. Assuming a quasi-sinusoidal pattern in the temperature the HDD and the CDD are given by the equations (3.6) and (3.7), respectively, where $\Delta T_{\max,d} = T_{\max,d} - T_{\mathrm{b}}$, $\Delta T_{\min,d} = T_{\mathrm{b}} - T_{\min,d}$ and $\bar{T}_{\mathrm{out},d}$ is given by equation (3.3).

$$\mathrm{HDD}_d = \begin{cases} T_{\mathrm{b},h} - \bar{T}_{\mathrm{out},d} & T_{\max,d} \le T_{\mathrm{b},h} \\ 0.5 \cdot \Delta T_{\min,d} - 0.25 \Delta T_{\max,d} & T_{\min,d} < T_{\mathrm{b},h} \ \wedge \Delta T_{\max,d} < \Delta T_{\min,d} \\ 0.25 \cdot \Delta T_{\min,d} & T_{\max,d} > T_{\mathrm{b},h} \ \wedge \ \Delta T_{\max,d} > \Delta T_{\min,d} \\ 0 & T_{\min,d} \ge T_{\mathrm{b},h} \end{cases} \tag{3.6}$$

$$\mathrm{CDD}_d = \begin{cases} \bar{T}_{\mathrm{out},d} - T_{\mathrm{b},c} & T_{\min,d} \ge T_{\mathrm{b},c} \\ 0.5 \cdot \Delta T_{\max,d} - 0.25 \Delta T_{\min,d} & T_{\max,d} > T_{\mathrm{b},c} \ \wedge \Delta T_{\max,d} > \Delta T_{\min,d} \\ 0.25 \cdot \Delta T_{\max,d} & T_{\min,d} < T_{\mathrm{b},c} \ \wedge \ \Delta T_{\max,d} < \Delta T_{\min,d} \\ 0 & T_{\max,d} \le T_{\mathrm{b},c} \end{cases} \tag{3.7}$$

Nevertheless, comparing the ASHRAE method and the UKMO equations with the mean daily degree-day method the deviation is less than 3% [47]. The ASHRAE method has a lower deviation for the calculation of CDD (-0.8%) and the UKMO equations a lower deviation for the calculation of HDD (-0.5%) [47]. According to the results of [47], probably a good approach for the degree-days calculation, when only the daily maximum and minimum temperature are available, is combining the definition of the HDD of UKMO with ASHRAE method for CDD.

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Residual Cooling degree-days

The previous methods for the calculation of the degree-days, more specifically for CDD, do not account for the possible effect of natural ventilation (NV). To overcome this limitation, G. Chiesa and M. Grosso [26,27] introduced the concept of "residual" CDD considering the NV due wind-driven ($\mathrm{CDD_{res\text{-}WD}}$) and the NV night cooling due buoyancy-driven ($\mathrm{CDD_{res\text{-}NC}}$)(2). The $\mathrm{CDD_{res\text{-}WD}}$ accounts for the cooling skin effect due to the increase of indoor air velocity caused by the airflow driven by wind (Eq. (3.8)).

$$\mathrm{CDD_{res\text{-}WD}} = \sum_{d=1}^{N}\left(\frac{1}{24}\sum_{j=1}^{24}\left[\left(T_{\mathrm{out},j} - \Delta T_{\mathrm{v,air}}\right) - T_{\mathrm{b},c}\right]^{+}\right)_{d} \quad (3.8)$$

The impact of the air velocity on the reduction of temperature on the skin perceived by the occupants ($\Delta T_{\mathrm{v,air}}$) is given by equation (3.9) and the indoor air velocity ($\mathrm{v_{air}}$) by equation (3.10). This approach corrects the wind velocity with a reduction factor ($\mathrm{f_{rw}}$), that corresponds to the discharge coefficient of a conventional window ($c_d = 0.6$) [27], where for wind velocities higher than 1.5 m/s the $\mathrm{v_{wind}}$ equals 1 m/s considering the comfort upper limit for indoor air velocity [27]. Also, the effect of $\mathrm{v_{air}}$ for values lower than 0.25 m/s are not perceived by the occupants being neglected.

$$\Delta T_{\mathrm{v,air}} = \begin{cases} 2.139\mathrm{v_{air}} + 0.4816 & 0.25 < \mathrm{v_{air}} \le 1.5 \\ 0 & \mathrm{v_{air}} \le 0.25 \end{cases} \quad (3.9)$$

$$\mathrm{v_{air}} = \begin{cases} \mathrm{v_{wind}} \times \mathrm{f_{rw}} & \mathrm{v_{wind}} \le 1.5 \\ 1 \times \mathrm{f_{rw}} & \mathrm{v_{wind}} > 1.5 \end{cases} \quad (3.10)$$

The $\mathrm{CDD_{res\text{-}NC}}$ considers the building can be cooled during the night period with buoyancy-driven ventilation when the outdoor temperatures are lower than the base temperature (Eq. (3.11)) [27]. The building thermal mass exposed cooled along the night, absorbs the heat generated by the solar and internal gains, allowing a start "fresh" in the morning, and maintaining the indoor temperature in the comfort band for a longer period without the help of active cooling systems.

$$\mathrm{CDD_{res\text{-}NC}} = \sum_{d=1}^{N}\frac{1}{24}\left[\sum_{j=1}^{24}\left(T_{\mathrm{out},j} - T_{\mathrm{b},c}\right) + \left[\sum_{j=1}^{24}\left(T_{\mathrm{out},j} - T_{\mathrm{b},c}\right)\right]^{-} \times 0.7\right]_{d}^{+} \quad (3.11)$$

This approach is applicable in offices buildings where are unoccupied, usually, during night-time and have a significant internal gains load. In a domestic scenario, the night cooling probably should be limited to lower threshold temperature value to avoid considering overcooling moments.

Base temperature

The base temperature is a central variable to have a comprehensive understanding and use of degree-days. This is defined as the outdoor temperature at which the indoor temperature is in a comfort band without the use of any active system for heating or cooling [25,28]. The base temperature can be defined as [25]:

$$T_{\mathrm{b}} = T_{\mathrm{setpoint}} - \frac{G_{\mathrm{i}} + G_{\mathrm{solar}}}{U_{\mathrm{global}}} \quad (3.12)$$

(2) The original concept of residual CDD presented by G. Chiesa and M. Grosso [26,27] is expressed in degree-hour. All the equations related with this concept were adapted to a degree-day basis.

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where the T_{setpoint} is temperature threshold (upper or lower limit of the comfort band) [ºC], G_{i} and G_{solar} are, respectively, the internal heat and solar rate gains [W], and the U_{global} the heat transfer coefficient of the building envelope [W/K]. The equation above represents the outdoor balance-point temperature approach. This approach is only feasible when all the variables of the building heat transfer process are known or available.

Another way to define a base temperature, in a balance-point perspective, is using the energy signature method or the performance line method [25]. The energy signature method consists in a plot of the building energy consumption against the mean daily outdoor temperature, and the base temperature is given by the interception of the weather-independent and weather-dependent energy consumption [25,29,36,39,41]. The second method corresponds to the best-fit straight lines through data of monthly energy consumption against the average monthly HHD or CDD, where the base temperature is obtained when a best-fit second-order polynomial of HDD or CDD versus energy consumption best approaches to linearity [25,30,36].

Defining a base temperature for more than one building and location is always a complex problem. This temperature is highly dependent on the building's thermal characteristics (heat transfers coefficient, thermal inertia, infiltration rate, occupancy, etc.) and the local weather. For example, the work of M. Bhatnagar et al. [36] shows the dependence of the base temperature on the building type (hotel or office) and local weather. Due to the difficulty of defining a base temperature for each case, some authors consider that this temperature corresponds to an indoor comfort temperature [44-52]. Unfortunately, the value for "base comfort temperature" does not have a full agreement between the various authors (Table 3.1).

One innovative way for the definition of the base temperature is introduced by G. Chiesa et al. [26], for the determination of CDD in Italy, that suggests this can be defined according to the adaptative comfort models (EN 15251:2007 [49] or ASHRAE Standard 55-2013 [50]). However, assuming a setpoint temperature value for the base temperature can lead to incorrect value DD. This assumption for HDD can result in an overestimation of energy use for heating if the heat gains, more specifically the solar gains, are not accounted properly. Also, if assumed that the total internal heat gains and solar gains have their maximum value and are constant can lead to underestimation of the heating needs [30,31]. For the case of CDD, besides the issues of accuracy of accounting the internal heat gains effect identified for the HDD, usually, the cooling needs estimated do not account the latent part leading to an underestimation [29], especially for wet climates [32].

Nevertheless, some authors [57-64] do not present a clear justification or criterion for the chosen value for the base temperature, that can be sometimes an arbitrary process. Also, the base temperature can be defined for weather monitoring [57-64], with application in the agricultural research area for the assessment of crop growing conditions [25,54].

Table 3.1 – Examples of base temperatures used for the calculation of HDD and CDD, and the criterion of definition.

Base Temp. (ºC) HDD	CDD	Location	Defined as	Weather Classification	Building Energy needs calculation	Comment	Reference
18	18	Global	balance	not stated	yes		M. Sivak [33]
10-20	20-27.5	Greece	balance	no	yes		K. Papakostas et al. [34]
14	-	Greece	balance	no	yes		A. Matzarakis and C. Balafoutis [35]
13.8-21.4 [(a)] 10.4-18.7 [(b)]	6.8-28.6 [(a)] 8.7-28.1 [(b)]	India	balance	no	yes	Depends on the local weather and type of building [(a)] hotel, [(b)] office. Calculated using the energy signature method and the performance line method.	M. Bhatnagar et al. [36]
18	25	Portugal	balance	yes	yes	Base temperatures defined in the Portuguese Energy Performance Building Regulation.	DGEG [37]
18-21	23.0-25.5[(c)] 25.5-27.8[(d)]	Saudi Arabia	balance	not stated	yes	[(c)] range of T_{base} for buildings without insulation [(d)] range of T_{base} for well-insulated buildings	S.A.M. Said [38]
14.7-19.4	14.7-19.4	South Korea	balance	not stated	yes	Varies with the mean outdoor air temperature. Defined using the energy signature method.	K. Lee [39]
18, 20	18, 24	Turkey	balance	yes	yes		I. Yildiz and B. Sosaoglu [40]
16.7	-	United Kingdom	balance	no	yes	Mean base temperature. Depends on the type of building. Calculated using the energy signature method.	Q. Meng and M. Mourshed [41]
20	26	Italy	balance	yes	yes	Definition according to ISO 15927-6	G. Chiesa and M. Grosso [42]
-	10	Switzerland	balance	not stated	yes	Only days with a daily mean outside temperature higher than a threshold temperature (18.3, 20 or 22 ºC) are counted.	M. Christenson et al. [43]
20	-	Switzerland	comfort	not stated	yes	Only days with a daily mean outside temperature less than a threshold temperature (8, 10 or 12 ºC) are counted.	M. Christenson et al. [43]
18.3	26.7	Europe	comfort	no	yes		M. de Rosa et al. [44]
18	22	Europe	comfort	no	yes		G.S Eskeland et al. [45]
20-23.5	21.5-27.5	Iran	comfort	no	yes	Depends on the local weather. Defined using Olgyay's diagram.	Gh.R. Roshan et al. [46]
18, 20, 22	22, 24, 26	Italy	comfort	yes	yes		M. de Rosa et al. [47]

Base Temp. (ºC) HDD	CDD	Location	Defined as	Weather Classification	Building Energy needs calculation	Comment	Reference
20	-	Italy	comfort	no	yes	Lower value of indoor temperature for the heating season	A. D'Amico et al. [48]
-	$0.31\bar{T}_{\text{out}} + 20.3$	Italy	comfort	no	yes	The outdoor mean prevalent temperature ($\bar{T}_{\text{out}}$) is calculated according to EN 15251:2008 [49].	G. Chiesa and M. Grosso [26]
-	$0.33\bar{T}_{\text{out}} + 20.8$	Italy	comfort	no	yes	The outdoor mean prevalent temperature ($\bar{T}_{\text{out}}$) is calculated according to ASHRAE 55-2013 [50].	G. Chiesa and M. Grosso [26]
18	18	Spain	comfort	no	yes		X. Labandeira et al. [51]
14-22	18-28	Turkey	comfort	not stated	yes	The range of T_{base} varies with 2 ºC increment	O. Büyükalaca et al. [52]
18	24	China	not stated	not stated	not stated	The base temperature defined probably as comfort temperature	F. Jiang et al. [53]
18	21	Europe	not stated	not stated	yes	Only days with a daily mean outside temperature less than 15 ºC for HDD or greater than 24 ºC for CDD are counted.	Joint Research Centre [54]
17	22	Italy (Florence)	not stated	not stated	not stated		M. Petralli et al. [55]
18, 20	18, 24	Saudi Arabia	not stated	not stated	not stated		S. Rehman et al. [56]
18	18	Belgium	not stated	yes	not stated		D. Ramon et al. [57]
18	18	China	not stated	yes	no		Y. Shi et al. [58]
15.5	22	Europe	not stated	yes	yes		J. Spinoni et al. [59,60]
10, 18.3	10, 18.3, 23.3, 26.7	Global	not stated	yes	yes	For energy estimating methods will be more reasonable to consider a $T_{\text{base}} > 10$.	ASHRAE Standard 169-2020 [61]
-	18	Global	not stated	yes	yes	The CDD are correct using the Heat Index defined by Lans P. Rothfusz [62,63] to account the effect of humidity and the perceived temperature by the occupants.	IEA [62]
18	18	South Africa	-	yes	no	Dual base temperature method used for the weather classification. This method is not recommended for estimating building energy needs.	D. Conradie et al. [64]

A possible definition of a base comfort temperature for HDD can be set as 18.6 ºC and for CDD set as 26 ºC. The value of 18.6 ºC corresponds to the minimum mean temperature value acceptable for buildings without active heating and cooling systems set by EN 15251:2007 Standard [49] and ASHRAE Standard 55-2013 [50], while the value of 26 ºC is the maximum outdoor air temperature suitable to provide ventilative cooling [65]. This definition for the base temperature is a suggestion for a static comfort temperature approach in an attempt to have a uniform definition of DD with reasonable assumptions. Nevertheless, the problems and limitations, identified previously, for assuming a setpoint temperature value for the base temperature remain.

3.2. Passive cooling indicators

The combination of higher air temperatures and continuously increasing building occupant comfort expectations and standards will lead to higher cooling energy demand in both commercial and residential buildings. To contain this increase, building designers are encouraged to use passive design strategies and low energy cooling systems such as natural ventilation (NV), night cooling (NC), shading and exposed thermal mass. These strategies use the outdoor climate as a source of free or low energy cooling. However, they are highly dependent on weather and, also, on the pollution of the outdoor environment (noise, fine particles, and heat) [66]. Therefore, for the designers, it is a difficult task to assess, at a general level, if the outdoor environment fulfils the requirements of air quality to promote the natural ventilation because it varies with time and the existing air quality data have low spatial density and is hardly available [67]. Neglecting the air quality, the suitability of outdoor air to promote natural ventilation relies exclusively on occupant's comfort criterion [67-71].

The methodologies for the assessment of passive cooling potential do not focus on a specific technology or uses simplifies building models. These methodologies are a theoretical analysis where the main goal is to give information to designers of the cooling climatic potential that is achievable in a given climate. Specifically, these methodologies assess the climate capacity to supply fresh air to the occupants without discomfort or the capacity for ventilative cooling along the unoccupied periods. The added value of these type of indicators is also the capability to evaluate the impact of climate change on the suitability of a given climate for passive cooling strategies. Nevertheless, the actual effectiveness of a natural ventilation system in a building will depend on the surroundings, the envelope characteristics, the internal and solar heat gains, the control strategy, and the occupant's behaviour, being necessary to check the expected performance with accurate models.

Climate cooling potential

The climate cooling potential (CCP) indicator has two possible, and distinct definitions. The concept of CCP was introduced by N. Artmann et al. [68] (Eq. (3.13)) and consists of the average accumulated hourly indoor and outdoor temperature differences for the night period when this difference is above 3 ºC (ΔT_{crit}).

$$\mathrm{CCP} = \frac{1}{N}\sum_{d=1}^{N}\left(\sum_{j=t_i}^{t_f}\left[m_j \cdot \left(T_{\mathrm{i},j} - T_{\mathrm{out},j}\right)\right] \quad \begin{cases} m_j = 1\mathrm{h} & T_{\mathrm{i},j} - T_{\mathrm{out},j} \geq \Delta T_{\mathrm{crit}} \\ m_j = 0 & T_{\mathrm{i},j} - T_{\mathrm{out},j} < \Delta T_{\mathrm{crit}} \end{cases}\right)_d \qquad (3.13)$$

It is assumed that the night period starts at 19h (t_i) and ends at 7h (t_f). This definition is based on the concept of degree-days and considers that the base temperature corresponds to the comfort building temperature ($T_{\mathrm{i},j}$) and oscillates harmonically (Eq. (3.14)).

$$T_{\mathrm{i},j} = 24.5 + 2.5\cos\left(2\pi\frac{j - t_{\mathrm{i}}}{24}\right) \quad (3.14)$$

The CCP in degree-hour can be used to predict the cooling capacity but not the energy savings of using NV. To overcome that limitation H. Campaniço et al. [69,70] proposed a new definition for the CCP that express the hourly difference between the amount of removed thermal energy from a building due to a natural ventilation system and the amount of thermal energy that is being removed or flowing into the same building at a reference flow rate (air renovation):

$$\mathrm{CCP} = \sum_{d=1}^{N}\left(\sum_{j=t_i}^{t_f}\left[c_s\cdot\rho\cdot\left(\dot{V}_j\cdot\left(T_{\mathrm{i}} - T_{\mathrm{NV},j}\right) - \dot{V}_{\mathrm{ref}}\cdot\left(T_{\mathrm{i}} - T_{\mathrm{out},j}\right)\right)\right] \begin{cases}\dot{V}_j = \dot{V}_{\mathrm{NV}} & T_{\mathrm{NV},j} < T_{\mathrm{i}}\\ \dot{V}_j = \dot{V}_{\mathrm{ref}} & T_{\mathrm{NV},j} \geq T_{\mathrm{i}}\end{cases}\right)_d \quad (3.15)$$

$$T_{\mathrm{NV}} = \begin{cases}T_{\mathrm{out}} & \text{sensible cooling}\\ T_{\mathrm{out}} + \eta\left(T_{\mathrm{wb}} - T_{\mathrm{out}}\right) & \text{evaporative cooling}\end{cases} \quad (3.16)$$

The CCP, in Eq. (3.16), is expressed in kWh/m³ where c_s is the specific heat capacity of air (kWh/K·kg), ρ is the air density (kg/m³), $\dot{V}$ is the air flow rate in air changes per hour (ACH), and T_{NV} is ventilation temperature (ºC) given by Eq. (3.16) according to the type of cooling strategy (sensible or evaporative). Evaporative cooling temperature can be estimated considering an efficiency (η) of 50% relatively to wet bulb temperature (T_{wb}) [70]. The building indoor temperature (T_{i}) is defined also as comfort temperature setpoint due the fact of CCP do not depend on buildings characteristics. The value assumed is 26 ºC. Unlike the first definition, CCP is calculated only for the working period, between 7h and 19h, being the NV system unavailable during the night period. The authors assume a fixed airflow rate of 1.5 ACH as a reference and explore two scenarios where the NV air flow rate has a fixed value of 1.5 and 6 ACH [70].

Although the comparison of the CCP for the current and future climates, for both definitions, allows the assessment of the impact of climate change on the passive cooling systems, the CCP have commons limitations. The first consists of neglecting the wind effect and assuming NV occurs only through stack effect. The second is not considering that the NV can occur during the day [68] or used as a night cooling system [70]. The third is not account for the humidity as comfort criterion, that can have high relevance in hot and humid climates or indoor environments with very low humidity [67]. The fourth, and last, is both definitions are not truly independent from building characteristics as assuming that the comfort temperature varies harmonically [68] or the necessity to define previously an airflow rate for the NV system that depends on the buildings characteristics and the weather conditions [69].

Natural Ventilation hour

The concept of Natural Ventilation hour, according to Y. Chen et al. [71], is defined as the number of hours in a typical year when the outdoor weather condition is suitable to use passive cooling strategies and is given by the Eq. (3.17). The NV hour assesses only if the outdoor weather is favourable for natural ventilation using an upper and a lower threshold for the dry-bulb temperature and the expected indoor air velocity.

$$\tau_{\mathrm{NV}} = \sum_{j=1}^{t_{\mathrm{year}}} t_{\mathrm{NV},j} \quad \begin{cases}t_{\mathrm{NV},j} = 1 & T_{\mathrm{out},j} \in \left]12.8\,, T_{\mathrm{in\,max},j}\right[\cap T_{\mathrm{dp}}\left(T_{\mathrm{out},j}, \phi_{\mathrm{out},j}\right) < 17 \cap u_{\mathrm{in\,max},j} \in [0\,, 0.8]\\ t_{\mathrm{NV},j} = 0 & T_{\mathrm{out},j} \notin \left]12.8\,, T_{\mathrm{in\,max},j}\right[\cup T_{\mathrm{dp}}\left(T_{\mathrm{out},j}, \phi_{\mathrm{out},j}\right) \geq 17 \cup u_{\mathrm{in\,max},j} \notin [0\,, 0.8]\end{cases} \quad (3.17)$$

The upper-temperature threshold ($T_{\mathrm{in\,max}}$) is defined according to the ASHRAE adaptive comfort model [50] and given by the eq. (3.18) where $\bar{T}_{\mathrm{out}}$ is the monthly mean prevalent temperature (eq. (3.19)). The lower temperature threshold is fixed and has a value of 12.8 ºC. This corresponds to the minimum supply air temperature for NV systems to avoid an unpleasant draft to occupants [**Fehler! Textmarke nicht definiert.**,50]. Y. Chen et al. [71] also includes an upper threshold for dew-point temperature (T_{dp}) of 17 ºC as humidity control.

$$T_{\mathrm{in\,max},j} = 0.31\bar{T}_{\mathrm{out},j} + 21.3 \quad (3.18)$$

$$\bar{T}_{\mathrm{out},j} = \frac{1}{720}\sum_{n=j-24}^{j-720} T_{\mathrm{out},n} \quad (3.19)$$

The indoor air velocity threshold is set to 0.8 m/s following the ASHRAE Standard 55 recommendations [50,71]. The maximum allowable indoor air velocity, $u_{\mathrm{in\,max}}$, is calculated according to Phaff et al. [72] that developed an empirical equation which considers the combined effect of outdoor wind velocity (u_{out}), temperature, and turbulence on NV:

$$u_{\mathrm{in\,max},j} = \sqrt{\mathrm{C}_1 u_{\mathrm{out},j}^2 + \mathrm{C}_2 H \Delta T_{\mathrm{max},j} + \mathrm{C}_3} \quad (3.20)$$

where C_1 is the wind speed coefficient, $\mathrm{C}_2$is the buoyancy coefficient, and C_3 is the turbulence coefficient. Their values are, respectively, 0.001, 0.0035 m·s^{-2}·K^{-1} and 0.01 m^2·s^{-2} [72]. The H is the vertical height of the opening, in m. Y. Chen et al. [71] do not mention the H value considered and probably may have used a height of 1 m as referred on the reference cases of Phaff et al. [72]. The ΔT_{max} is the maximum temperature difference, eq. (3.21), that corresponds to the difference between the upper-temperature threshold and the outdoor temperature.

$$\Delta T_{\mathrm{max},j} = T_{\mathrm{in\,max},j} - T_{\mathrm{out},j} \quad (3.21)$$

The NV hour concept relies exclusively on assessing the meteorological data not being explored an effective cooling potential or considering building-scale details [71]. Although NV hour can provide valuable information to evaluate the weather suitability for natural ventilation, this definition has some limitations. The first consists of using a humidity control criterion that establish an upper dew-point temperature that does not prevent the possibility of providing saturated air. The second relies on neglecting the vertical variation of wind speed that is justified with the lack of weather files not having data as surface roughness length, atmospheric stability, and upper air weather data for example [71]. The third is NV hour do not distinguish the suitability of passive cooling strategies for day and night period.

Climatic Potential for Natural Ventilation

The Climatic Potential for Natural Ventilation (CPNV) conceptually follows a similar approach to the NV hour, where is established when the climate has favourable conditions for natural ventilation. The difference between them relies on the definition of comfort. The CPNV does not account for how wind velocity affects the indoor air velocity during NV time. This considers that NV can occur if the outdoor air temperature and the humidity ratio are between the thresholds [67]. The CPNV is expressed as the ratio of the hours when NV could be performed and the total number of hours in a year (eq. (3.22)), where is assumed that indoor operative temperature is equal to the dry-bulb temperature, internal or solar heat gains are moderated, and the internal generation of humidity is low or negligible.

$$\mathrm{CPNV} = \frac{1}{t_{\mathrm{year}}}\sum_{j=1}^{t_{\mathrm{year}}} t_{\mathrm{NV},j} \quad \begin{cases} t_{\mathrm{NV},j} = 1 & T_{\mathrm{out},j} \in [T_{\mathrm{in\,min},j}, T_{\mathrm{in\,max},j}] \cap W_{\mathrm{out},j} \in [W_{\mathrm{in\,min},j}, W_{\mathrm{in\,max},j}] \\ t_{\mathrm{NV},j} = 0 & T_{\mathrm{out},j} \notin [T_{\mathrm{in\,min},j}, T_{\mathrm{in\,max},j}] \cup W_{\mathrm{out},j} \notin [W_{\mathrm{in\,min},j}, W_{\mathrm{in\,max},j}] \end{cases} \quad (3.22)$$

F. Causone [67] defines the upper and lower temperature according to the ASHRAE adaptive comfort model [50], where the prevalent mean temperature is given by eq. (3.19). The temperature comfort tolerance (ΔT_{comf}) depends on the satisfied occupant's percentage considered, 80% or 90% ($\Delta T_{\text{comf}} = 3.5$ or $\Delta T_{\text{comf}} = 2.5$, respectively [50]). However, for cases where NV is used for cooling purposes is suggested to shift down the lower temperature limit ($T_{\text{in min}}$) to 10-12 ºC [67,73]. Lower values are not recommended to prevent thermal discomfort for the occupants, but for unoccupied period lower temperatures may be used for night cooling if CPNV considers only buildings with high levels of heat gains [67].

$$T_{\text{in max},j} = 0.31\overline{T}_{\text{out},j} + 17.8 + \Delta T_{\text{comf}} \quad (3.23)$$

$$T_{\text{in min},j} = 0.31\overline{T}_{\text{out},j} + 17.8 - \Delta T_{\text{comf}} \quad (3.24)$$

According to F. Causone [67], the natural ventilation is only possible when outdoor humidity ratio mixed with the indoor humidity ratio have a final condition with a relative humidity value between 30% and 70%. The definition of a comfort band for humidity intents to prevent occupant's skin dryness, eye irritation and mucus membrane irritation, in very low humidity environments, and thermal discomfort caused by very high humidity environments [67]. The humidity ratio thresholds are calculated as a function of the indoor temperature and the relative humidity comfort range [67]:

$$W_{\text{in max},j} = 0.621945 \cdot \frac{p_{\text{ws},j} \cdot 0.7}{p - \left(p_{\text{ws},j} \cdot 0.7\right)}, p_{\text{ws}} = \begin{cases} f\left(T_{\text{in max},j}\right) & \text{low rate of moisture gen.} \\ f\left(T_{\text{in min},j}\right) & \text{high rate of moisture gen} \end{cases} \quad (3.25)$$

$$W_{\text{in min},j} = 0.621945 \cdot \frac{p_{\text{ws},j} \cdot 0.3}{p - \left(p_{\text{ws},j} \cdot 0.3\right)}, p_{\text{ws}} = f\left(T_{\text{in min},j}\right) \quad (3.26)$$

where p is the atmospheric pressure, and p_{ws} is the partial pressure of vapour under saturation conditions. The p_{ws} is a function of the air temperature and can be found in ASHRAE Fundamentals Handbook [3].

F. Causone [67] suggest that based on the methodology of CPNV is possible to produce a heat map (Figure 3.1) for a certain climate where it represents the periods when NV can occur and cannot due to it being too hot, too cold, too dry, too humid or any combination of these conditions. The heat maps will allow a comprehensive analysis of NV potential when different NV strategies are applied in different moments of a day.

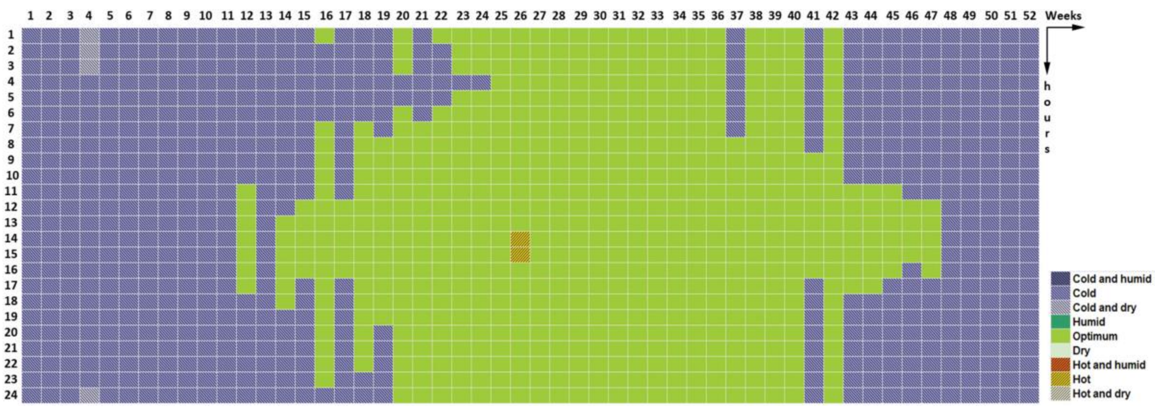

Figure 3.1 - Heat map representing the time of year when natural ventilation is pursuable in London. The week number is on the x-axis; the hours of the day are on the y-axis [67].

Suitability of air temperature for natural ventilation

J. Bravo Dias et al. [74] assessed the suitability of the outdoor environment promote natural ventilation defining four different intervals of dry-bulb temperature. When the outdoor temperature is between 10 ºC and 26 ºC NV can occur to increase the indoor air quality and thermal conditions. This interval is subdivided into two to account for different NV strategies. Between 10ºC and 16ºC is considered that outdoor air is suitable to improve indoor air quality through fresh air supply. While between 16 ºC and 26 ºC is considered that ventilative cooling can be performed to remove heat gains and improve or maintain thermal comfort. Below 10 ºC, outdoor air temperatures are too cold to provide fresh air, and above 26 ºC is considered too warm to use ventilative cooling strategy [74]. The suitability of air temperature for natural ventilation (S_{NV}) is expressed as a total number of suitable hours for NV in the typical year considering that NV can only perform during the working period (9h-18h) [74].

$$S_{\mathrm{NV}} = \begin{cases} T_{\mathrm{out}} \leq 10 & \text{Too cold} \\ 10 < T_{\mathrm{out}} \leq 16 & \text{Suitable for NV/fresh air supply} \\ 16 < T_{\mathrm{out}} \leq 26 & \text{Suitable for NV based ventilative cooling} \\ T_{\mathrm{out}} > 26 & \text{Too warm for NV} \end{cases} \tag{3.27}$$

This indicator has a simplified approach compared with the previous indicators, has the advantage of easy application. Nevertheless, do not account for the possibility of night cooling strategies or the relevance of humidity control for some climates, as already mentioned. Also, do not account for the effect of wind during the NV period.

3.3. Sources of indicators

In Table 3.2 is presented the databases available for weather indicators. Databases with limited or no information about the methodology or climate source were excluded. Degree-days is common to all databases, but different methods, base temperature and spatial resolution levels are adopted.

Table 3.2 – Examples of weather indicators databases.

Source	Type	Available for		Comment
		Europe	Africa	
ASHRAE Standard 169-2020	paid	yes	yes	Provides degree-days and design conditions. The indicators are based in local weather stations, but different record periods are considered.
Eurostat	free	yes	no	HDD and CDD at annual basis calculated according to [54]. Data available since 1979 to the present. The highest level of resolution corresponds to small regions (NUTS 3 level).
CMCC-KAPSARC	free	yes	yes	Provides the average DD and heat index for the period 1969-2013 for country level [75]. DD are calculated using the daily mean method from satellite-derived data and three base temperatures (15.6, 18.3 and 21.1ºC).
BizEE	free/paid	yes	yes	Provides degree-days for a base temperature defined by the user. The DD are calculated using the hourly basis method or the mean daily method according to resolution data available. The free version only allows the access to the last 36 months of current record [LINK]

Currently, there is no database for passive cooling indicators that covers all the ABC 21 cities with an acceptable spatial resolution. The future DD or NV cooling potential are only available for some locations in map format and produced from satellite-derived data [60,70,74].

Producing weather indicators for all ABC21 locations should use the weather data source recommended above (for current and future), and follow the same methodology and assumptions to guarantee uniformity.

The definition of innovative weather indicators can also be explored using the psychrometric chart developed by A. Marsh [76]. This tool imports a weather file to perform an analysis based on comfort adaptative models as ASHRAE Standard 55 and EN-15251, or an analysis using bioclimatic charts (Givoni Milne and Olgyay).

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4. Conclusion

Availability of Weather Files

Hourly data weather files for Africa and Europe can be found in several free and paid databases. Among the freely available databases, *Climate One Building* has the most accurate and recent weather data. Currently there are no databases for future weather files that incorporate the most recent predictions of upcoming climate change.

Future weather files can be produced using the morphing methodology, in the CCWorldWeatherGen tool or in a custom methodology that can use the predictions of future climate produced by several international research consortiums.

Availability of Weather Indicators

The methodology used to calculate cooling and heating degree-days can vary according to the resolution of the outdoor temperature data. For the cases when only the daily maximum and minimum temperature are available is recommendable combining the definition of the HDD of UKMO with ASHRAE method for CDD. Nevertheless, when hourly weather data is available, the most rigorous, accurate and firstly recommended form to calculate degree-days is the mean daily degree-day method. The concept of residual CDD is an innovative approach to account easily the expected impact of the NV system when used as passive cooling strategies. This definition could be useful to predict the energy savings when NV is performed.

Defining a base temperature value for more than one building and the location is a complex problem, as shown in Table 3.1. It is recommended to adopt the “comfort” base temperature approach where static and adaptative comfort temperature should be used. For a static comfort temperature, it is suggested, that the base temperature has a value of 18.6 ºC for HDD and 26 ºC for CDD. The DD based on this approach allows a comparison between the different climates of each location, where is possible to identify the intensity of the heat and cold seasons. However, the weather classification, according to ASHRAE [61], the base temperature is set to 10 ºC. The adaptative comfort temperature approach should be based on the adaptative comfort models proposed by EN 15251:2007 Standard [49] or ASHRAE Standard 55-2013 [50]. The DD based on adaptative models can be useful for bioclimatic buildings analysis due to represent the accumulated difference of temperature when the adaptative and passive strategies are ineffective.

The definition of DD is not restricted to a full year. DD can be only calculated for the heating season(3) or the cooling season(4). Therefore, the definition of technical guidelines for future-proof passive design should indicate the period to be considered for calculation of DD that are applied to estimation methodologies for building energy needs.

Assessing the suitability of the climate conditions for natural ventilation can be done in different ways. However, all the discussed passive cooling indicators present limitations. These can be overcome by combining the definition of CPNV and an upper limit of indoor air velocity during

(3) October through March in the Northern Hemisphere and April through September in the Southern Hemisphere [61].
(4) April through September in the Northern Hemisphere and October through March in the Southern Hemisphere [61].

NV time as defined for the NV hour indicator. Also, the CPNV should allow a comprehensive analysis of NV potential when different NV strategies are applied in different moments of a day.

The currently available weather indicators were produced using different methods, weather sources, assumptions, and spatial resolution levels. Whenever possible weather indicators should be calculated using the best available current and morphed future TMY files.

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