Africa-Europe Bioclimatic Collaboration 21

Africa-Europe BioClimatic buildings for XXI century

REPORT ON AVAILABLE METHODS AND TOOLS FOR THE GENERATION OF FUTURE WEATHER FILES

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ABC 21 project

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Executive summary

Climate change is one of the greatest challenges of contemporary society and one of its main reasons is undoubtedly the increase of the global surface temperature by 1.09 °C from 1850-1900 to 2011-2020. The ongoing changes in air temperature and precipitation in different parts of the globe are already having consequences in worldwide energy use, economy, and human health. Climate change is expected to result in an increased frequency and intensity of hot extreme weather events affecting agriculture, water resources and energy systems.

In the last decades, the study of climate projections and future weather parameters has been receiving greater attention from researchers all over the world. The analysis of the present climate is based on the observation of climate variables and the application of statistical methods for understanding the current trends, instead the analysis of future climate is based on future scenarios and the projections of climate models. These latter are constantly being updated by different modelling groups that coordinate their research in the framework of the Intergovernmental Panel on Climate Change (IPCC). The Sixth IPCC Assessment Report (AR6) published on 9 August 2021, is underpinned by climate models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) of the World Climate Research Programme (WCRP). CMIP6 is the most up-to-date, scientifically advanced database for climate science and services. The AR6 has described five scenarios of projected socioeconomic global changes up to 2100, called Shared Socioeconomic Pathways (SSPs). Previously, in CMIP5, projections were elaborated according to four greenhouse gas concentration scenarios, called Representative Concentration Pathways (RCPs). This set of scenarios drives climate model projections of changes in the climate system by providing the input to both Global Climate Models (GCMs) and finer resolution Regional Climate Models (RCMs).

GCMs are complex numerical models which represent physical processes in the atmosphere, ocean, cryosphere and land surface using a three-dimensional grid over the globe, with a typical spatial resolution of 150–600 km^2. In case of building energy simulations, the GCMs should be downscaled to applicable spatial (less than 100 km^2) and temporal resolution (less than monthly value). There are two main approaches to downscale GCMs:

- Dynamical downscaling methods: The horizontal resolution of GCMs is relatively low, which restricts their ability to capture the characteristics of regional climate. Regional Climate Models (RCM), applied over a limited area and driven by GCMs can provide information on much smaller scales supporting more detailed impact and adaptation assessment and planning, which is vital in many vulnerable regions of the world. The results obtained from the GCMs and RCMs represent averages over regions or numerical grids, with the size of these grids depending on the model resolution.
- Statistical Downscaling methods: an alternative to RCMs is to use statistical techniques to downscale GCM models to a finer grid. Statistical downscaling develops and applies statistical relationships between regional or local climate variables and large-scale climate data using deterministic or stochastic approaches (by combining various scenarios). This technique assumes that large-scale meteorology and geographic features influence local weather and climate. The climate model data may also need to be temporally downscaled (time scale adjustment) if the resolution is too coarse for the required purpose of the final

application. Both RCM and GCM downscaled data can either be incorporated into a weather generator, which will produce future synthetic series of weather data (stochastic weather generator), or by means of a mathematical transformation produce a future time series based upon historic weather observations (morphing).

Weather generators are useful tools that allows to simulate future climate using downscaling methods. However, they have several limitations and uncertainties. The major limitation is the assessment of extreme events. Although the evaluation of them is crucial for the generation of future weather, it is rare that the historical database contains data that can correctly report single events. Another limitation is the surface interpolation. It can come from eventual gap data or/and the interpolation methodology used.

The most common tools to generate future climate are: CCWorldWeatherGen tool, WeatherShift, Meteonorm, MarkSimGCM.

Their features, advantages and limitations are compared as follows:

- Characteristics

Features	CCWorldWeatherGen	Meteonorm	WeatherShift	MarkSimGCM
Downscaling method	Morphing	Stochastic weather generation	Morphing	Stochastic weather generation
GCM	HadCM3	18 models	14 models	17 models
Projected Time periods	2020,2050,2080	2010-2200	2035,2065,2090	2030 and 2050
IPCC Report	AR3(2001), AR4(2007)	AR4(2007)	AR5 (2014)	CMIP5
IPCC emission scenario	A2	(B1, A1B, and A2)	RCP 4.5 and 8.5	RCP 2.6, 6, 4.5 and 8.5
Baseline period	1961-1991	for radiation: 1981-90, 1991-10, 1996-15 for temperatures: 1961-90, 2000-09	1976-2005	Run for about 50 or 100 years of past data. The exact baseline period is not available.

- Advantages

CCWorldWeatherGen	Meteonorm	WeatherShift	MarkSimGCM
Free online tool. Morphing individual years leads to year-to-year variability in the Morphed files	Simple method. Enhance the spatial and temporal resolution instead of using complicated and time-consuming downscaling. Methods based on regional climate models. Relatively low price.	Exploits AR5 (2014)	Information about rainfall, maximum and minimum temperatures and solar radiation Specifically designed for tropical countries. Generates data for a specific location anywhere in the world that can be used for crop, livestock and natural resource modelling and risk assessment.

- Limitations

CCWorldWeatherGen	Meteonorm	WeatherShift	MarkSimGCM
Possible differences in the reference time frames between HadCM3 and the EPW data, inaccuracy in the outputs of the tool may occur. Unable to model changes in the weather patterns (daily, weekly, monthly or yearly) and extreme events of the different weather variables are not available in a Morphed file.	The use of interpolated and synthetic data. The interpolations rely heavily on surface observation data, which are not equally distributed. Uses weather stations rather than satellite-based estimations.	Modifies only the most important meteorological parameters (dry bulb temperature, dew point temperature, relative humidity, atmospheric pressure, global horizontal radiation, direct normal radiation, diffuse horizontal radiation, and wind speed).	The system cannot model completely new climates except by extrapolation of the regression models from the nearest cluster. Since there is a data gap from 1985 to 2010 and the curves might not be stable in this region, it is not possible to generate weather data before 2010.

From a recent reported literature study, the high-resolution morphing method is the most recommended one among the diverse methodologies that can be used to generate future climate, and it will be used for the generation of future weather files in ABC 21.

Abbreviations

Term	Name
AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
BES	Building Energy Simulation
CDF	Cumulative Distribution Function
CIDs	climatic impact-drivers
CMIP6	Coupled Model Intercomparison Project Phase 6
CORDEX	Coordinated Regional Climate Downscaling Experiment
DSSAT	Decision Support of System for Agrotechnology Transfer
EPW	Energy Plus Weather format
GCM	General Circulation Model or Global Climate Models
GEBA	Global Energy Balance Archive
HadCM3	Hadley Center Coupled Model 3 global climate model
IPCC	Intergovernmental Panel for Climate Change
NCDC	National Climatic Data Center
RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
RMSE	root-mean-square error
SSP	Shared Socioeconomic Pathway
TMY	Typical Meteorological Year
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

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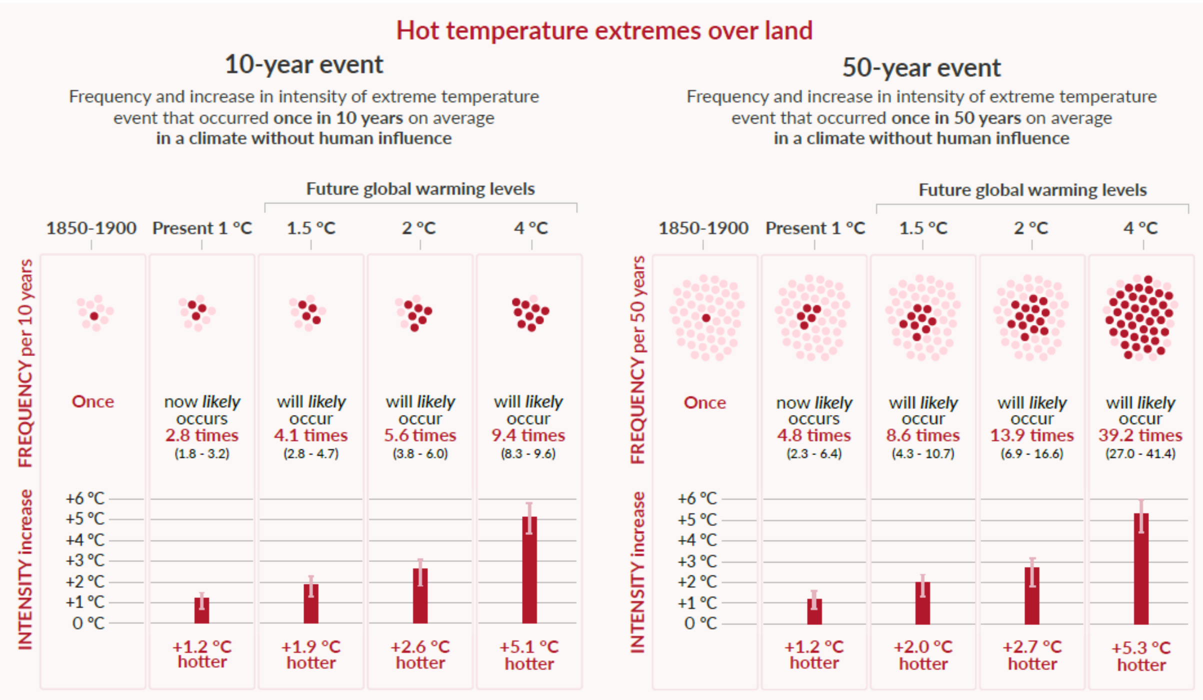
1. Introduction

ABC 21 aims to increase the energy performance, the quality of life and sustainability of West-African buildings through the identification, strengthening and effective deployment of affordable bioclimatic designs and local materials under the challenging African climate and urbanization context. The cooperation and the exchanges between African and European partners and Allies aim to provide a larger view on bioclimatic buildings with examples and experiences from different contexts to identify effective technical guidelines and tools for future-proof passive design in warm climates.

The project raises attention on the importance of improving the comprehension of the implications that climate change and future weather have on the design of the buildings, using a proper building energy modelling.

Climate change is one of the greatest challenges of contemporary society and one of the reasons is undoubtedly the increase of the global surface temperature by 1.09 °C from 1850-1900 to 2011-2020 [1]. The temperatures increase has been faster over land than over the ocean, with a warming of 1.59 °C compared to 0.88 °C, respectively. The ongoing changes in air temperature and precipitation in different parts of the globe are already having consequences in worldwide energy use, economy, and human health. Climate change is expected to result in an increased frequency and intensity of hot extreme weather events (Figure 1), affecting agriculture [2], water resources [3] and energy systems [4,5].



Projected changes in the intensity and frequency of hot temperature extremes over land [1]. ***Hot temperature extremes*** **are defined as the daily maximum temperatures over land that were exceeded on average once in a decade (10-year event) or once in 50 years (50-year event) during the 1850–1900 reference period (which is used as an approximation for pre-industrial conditions).**

Cities intensify human-induced warming locally, and further urbanization together with more frequent hot extremes will increase the severity of heatwaves [1]. The built environment will go through climate change threats such as those related to overheating issues. Buildings are responsible for approximately 36 % of the CO_2 emissions and 40 % of energy consumption in the European Union. In developed countries almost half of this energy is used in building heating, ventilation and air conditioning (HVAC) [6]. During their typical lifespan of 50 years or more, contemporary buildings will be subjected to a climate that will be progressively warmer and more volatile [7,8]. Unsurprisingly, several existing studies predict a future increase in annual cooling demand and a decrease in annual heating demand [9], with some dependency on the region of the globe [10]. If buildings are not prepared for the changing climate, in addition to extra costs for trying to maintain comfortable indoor conditions, there can be significant health risks for the occupants, with exposure to high indoor temperatures potentially leading to heat strokes or even mortality [11]. Therefore, it is necessary to study the future climatic scenarios to incorporate strategic plans within buildings to adapt to the future risks.

Task *3.2 – Indicators and weather files for future climate, as input for design of buildings and districts* is dedicated to create a state of the art on indicators and to analyse the availability and reliability of weather files to better represent current and future weather conditions and to improve the design of buildings and districts. The present deliverable aims to review the available methods and tools for the generation of future weather files, highlighting advantages and limitations of each method.

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2. Climate projections and generation of future weather data

The study of climate projections and future weather parameters has increasingly been receiving attention from researchers all over the world in the last decades. According to the Intergovernmental Panel for Climate Change (IPCC), climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (WMO). The relevant quantities are most often surface variables such as temperature, precipitation and wind. While the analysis of the present climate is based on the observation of climate variables and the application of statistical methods for understanding the current trends, the analysis of future climate is based on future scenarios and the projections of climate models [12].

Climate models are constantly being updated by different modelling groups that coordinate their research in the framework of IPCC. The Sixth IPCC Assessment Report (AR6)[1], published on 9 August 2021, is underpinned by climate models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) of the World Climate Research Programme (WCRP) and offers a novel tool named *Interactive Atlas* (Figure 2) for flexible spatial and temporal analyses of much of the observed and projected climate change information. Nowadays, CMIP6 is the most up-to-date, scientifically advanced database for climate science and services.

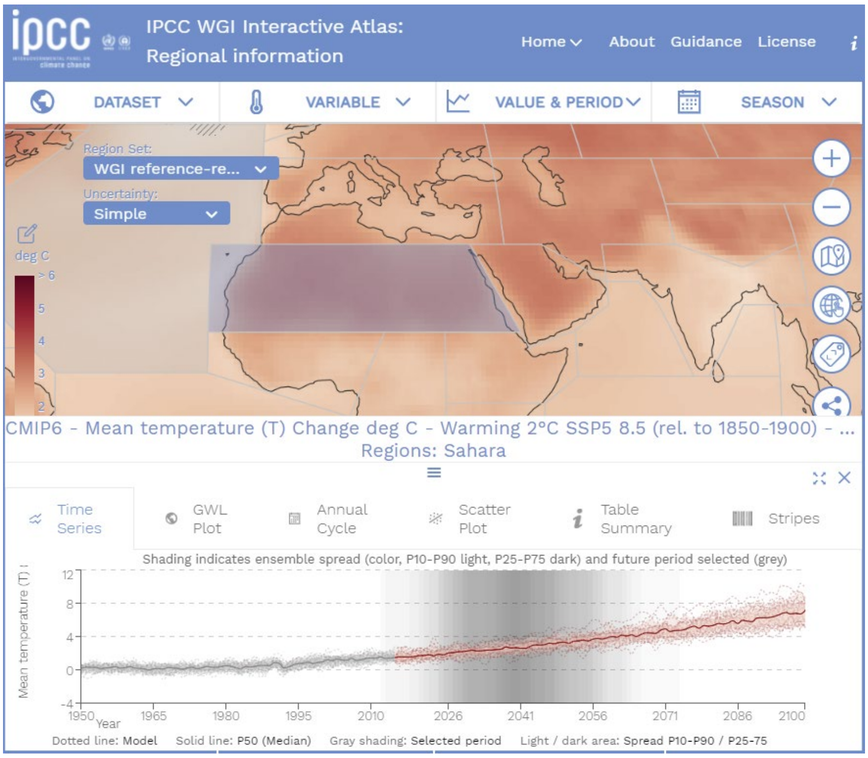

Figure 2: IPCC WGI Interactive Atlas: Sahara Region, model projection: CMIP6

[1] Disclaimer: The Summary for Policymakers (SPM) is the approved version from the 14th session of Working Group I and 54th Session of the Intergovernmental Panel on Climate Change and remains subject to final copy-editing and layout.

The climate change that people will experience this century and beyond depends on our greenhouse gases emissions, how much global warming this will cause and the response of the climate system to this warming. Since different social and economic developments can bring to different responses, the AR6 has described five scenarios of projected socioeconomic global changes up to 2100, called **Shared Socioeconomic Pathways (SSPs)**. Previously, in CMIP5, projections were elaborated according to four greenhouse gas concentration scenarios, called Representative Concentration Pathways (RCPs).
The five illustrative scenarios are referred to as SSPx-y, where ‘SSPx’ refers to the SSP describing the socio-economic trends underlying the scenario, and ‘y’ refers to the approximate level of radiative forcing (in W m^{-2}) resulting from the scenario in the year 2100 (Figure 3 - Figure 5):

- **SSP1-1.9** is characterized by very low GHG emissions, leading to warming below 1.5°C in 2100 and limited temperature overshoot over the course of the 21st century.
- **SSP1-2.6** has low GHG emissions and was designed to limit warming to below 2°C.
- **SSP2-4.5** is the intermediate scenario.
- **SSP3-7.0** has overall lower GHG emissions than SSP5-8.5 but, for example, CO_2 emissions still almost double by 2100 compared to today’s levels.
- **SSP5-8.5** represents the very high warming end of future emissions pathways from the literature.

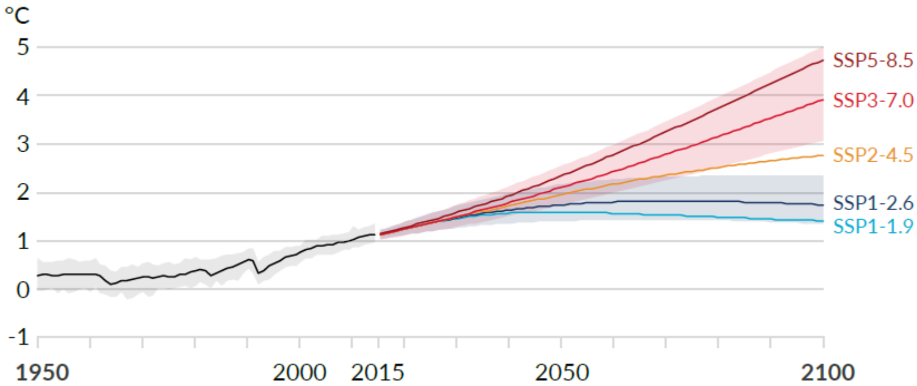

Figure 3: Global surface temperature change (°C) relative to 1850-1900, according to the IPCC AR6 [1]

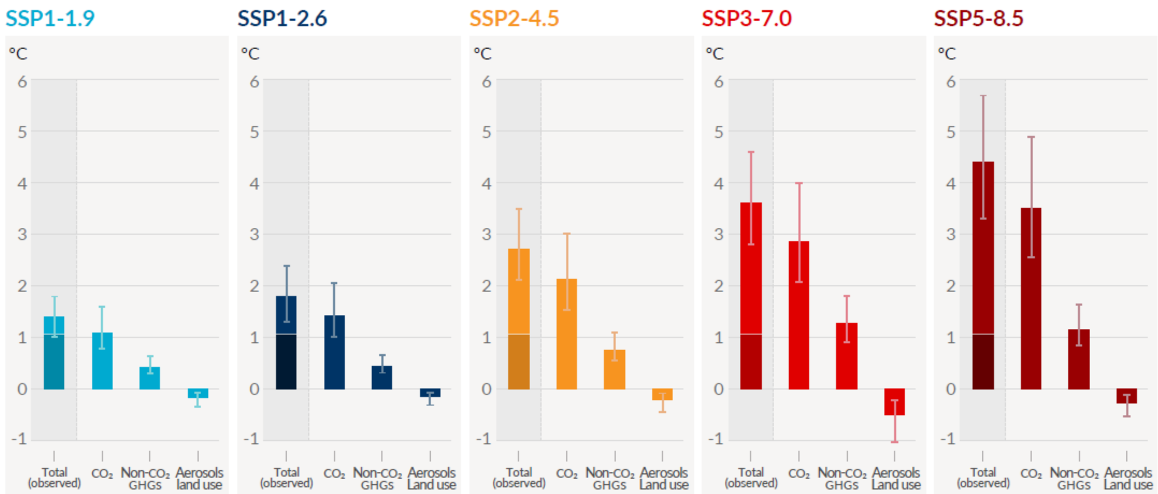

Figure 4: Change in global surface temperature in 2081-2100 relative to 1850-1900 (ºC), according to the IPCC AR6 [1]. Total warming (observed warming to date in darker shade), warming from CO_2, warming from non-CO_2 GHGs and cooling from changes in aerosols and land use

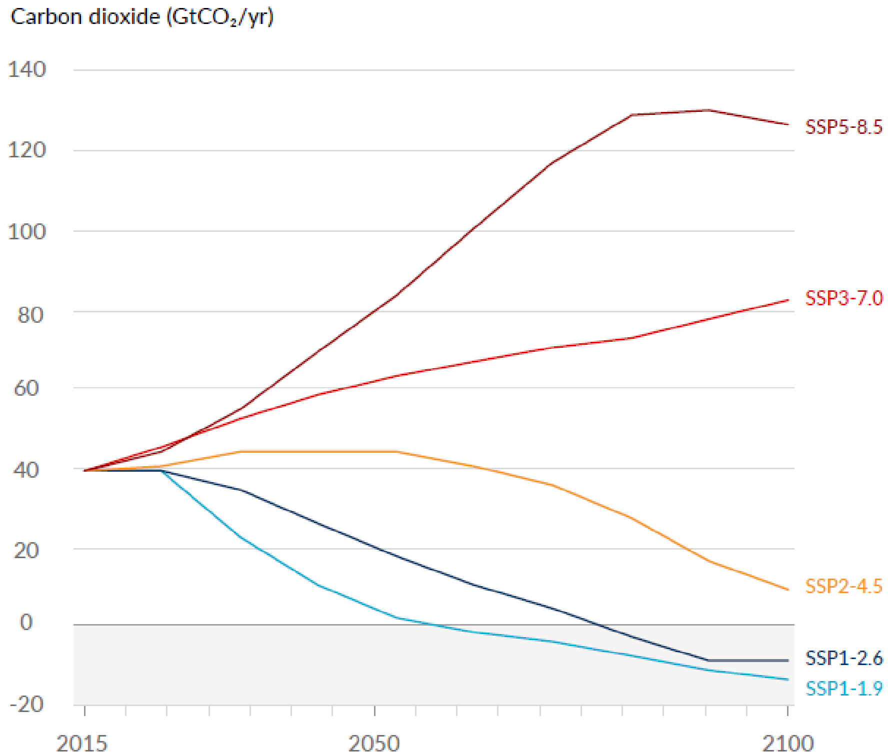

Figure 5: Annual anthropogenic (human-caused) emissions trajectories for carbon dioxide (CO_2) from all sectors ($GtCO_2$/yr) over the 2015–2100 period, according to the IPCC AR6 [1]

This set of scenarios drives climate model projections of changes in the climate system by providing the input to both Global Climate Models (GCMs) and finer resolution Regional Climate Models (RCMs). Current AR6 scenarios cover a broader range of future GHG emissions than the ones considered in AR5, including high CO_2 emissions scenarios without climate change mitigation, as well as a low CO_2 emissions scenario reaching net zero CO_2 emissions around mid-century. However, modelling studies relying on the RCPs used in the AR5, complement the assessment based on SSP scenarios, for example at the regional scale.
To investigate the energy performance of a building under future weather scenario, it is necessary to simulate its future performance using building energy simulation (BES) tools, which need accurate future weather datasets to provide reliable outputs.
Usually, BES software requires a yearly weather dataset established by hourly weather data to run the simulation. A typical weather file is created from historic records (usually around 20-30 years of data, depending on the data availability). This data is compiled by comparing the cumulative and the empirical distribution functions of different meteorological variables within the base dataset. The number and weighting of different meteorological variables considered is a feature of the weather file type (i.e., TMY, TRY, etc.). Table 1 lists the typical weather files used around the world. It is worth mentioning that despite having different sources or ways in which weather files are created to form distinct file types, several of them use common file formats such as the EPW format.

Table 1: A short list of weather file types [13]

Acronym	Complete Name	Region	Sites	Period
RMY	Representative Meteorological Year	Australia	69	1967-04
CSWD	Chinese Standard Weather data	China	270	1982-97
ISHRAE	Indian Typical Years from ISHRAE	India	62	1991-05
IGDG	Italian 'Gianni De Giorgio'	Italy	68	1951-70
SWEC	Spanish Weather for Energy Calculations	Spain	52	1961-90
UK TRY	Test Reference Year (CIBSE)	UK	14	1984-13
TMY (TMY3)[2]	Typical Meteorological Year (3rd edition)	USA and others	1020	1991-05
WYEC	Weather Year for Energy Calculations	USA/Canada	77	1953-01
IWEC	International Weather for Energy Calculation	Worldwide	3012	1991-05

Among the methodologies developed to create this one-year climate data, the most commonly used methodology is the Typical Meteorological Year (TMY). Deliverable *D3.4 - Report on availability of weather files and indicators for today and future weather in Africa and EU* describes the process of creation of TMY files, the weather data elements and quantities, and the typical resolutions used in this type of files.
Different TMY weather databases are available worldwide (see D3.4), even if, particularly in developing countries, the availability and quality of historical weather data is often limited. Recent works by the European Commission Joint Research Centre have led to the update of the TMY tool-PVGIS project, which is available for any location in Europe and Africa and provides free and open access to TMY data using recent periods of reference.
As all the main free databases are useful to represent past or current weather conditions, there is also an urgent need of datasets and easy access tools able to represent the future global and local warming trends. Further, some studies [12,14,15] have shown the variability of energy outputs and meteorological parameters depending on the chosen weather dataset and tool and highlighted the need of a standardized reference to create an official shared database for the different world locations, to reduce the gap between the simulated and real performance of buildings.
In the following chapters, the main methodologies and available tools for the generation of future weather files are critically analyzed and a description of the method that will be used in ABC 21 project is presented.

2.1 General Circulation Models (GCMs)

Future scenarios are the input data used to provide initial conditions for General Circulation Models or Global Climate Models (GCMs), which are models for forecasting climate change. GCMs are complex numerical models which represent physical processes in the atmosphere, ocean, cryosphere and land surface using a three-dimensional grid over the globe, with a typical spatial resolution of 150–600 km^2.
The IPCC Interactive Atlas includes global historical and future scenario data for CMIP5 (29 models, RCP2.6, 4.5, and 8.5 scenarios) and CMIP6 (35 models, SSP1-2.6, 2-4.5, 3-7.0,

[2] TMY3 is the last version of Typical Meteorological Year. Following, the previous editions:

Acronym	Complete Name	Region	Sites	Period
TMY	Typical Meteorological Year (1st edition)	USA and others	229	1948-80
TMY (TMY2)	Typical Meteorological Year (2nd edition)	USA and others	239	1961-90

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and 5-8.5 scenarios) for temperatures, precipitation, derived extreme indices, and climatic impact-drivers (CIDs). CMIP6 also includes information on snowfall and wind, oceanic variables (sea surface temperature, sea ice concentration, surface pH and sea level rise) and other relevant variables or information (e.g., ozone, PM2.5, ERF due to aerosols).
In case of building energy simulations, the GCMs should be downscaled to applicable spatial (less than 100 km^2) and temporal resolution (less than monthly value). There are two main approaches to downscale GCMs: dynamical and statistical downscaling.

2.2 Dynamical downscaling methods

The horizontal resolution of GCMs is relatively low, which restricts their ability to capture the characteristics of regional climate. Regional Climate Models (RCM), applied over a limited area and driven by GCMs, can provide information on much smaller scales supporting more detailed impact and adaptation assessment and planning, which is vital in many vulnerable regions of the world.
The results obtained from the GCMs and RCMs represent averages over regions or numerical grids, with the size of these grids depending on the model resolution. The finer scale and implied increase in geographic and land surface information of RCMs allows for greater geographic resolution. These models provide an accurate representation of the atmospheric processes under thermal contrasts and local topography, and thus describe the spatial and temporal variability of local climate [16]. These variabilities are usually associated to microclimates which have significant influence on building energy simulation of urban environments since they are subjected to different climates from centres to rural areas [17].
RCMs provide weather data with suitable temporal (down to 15 min) and spatial resolutions (down to 2.5 km^2) for direct use in building and energy simulations. However, large efforts in computational analysis are needed due to the amount of data to be analysed, the different time scales required to consider different physical phenomena in buildings, and the huge number of possible scenarios. Consequently, RCM data are less used in building simulations [18].
To overcome these issues, a simplified method to assess the impact of climate change on the energy performance of buildings using weather datasets out of RCMs with the hourly temporal resolution has been developed [18]. The method is based on synthesizing three weather datasets for each 30-year period: (1) typical downscaled year (TDY), (2) extreme cold year (ECY) and (3) extreme warm year (EWY). Each weather dataset is created based on comparing the cumulative distribution of the outdoor (dry-bulb) temperature and finding the typical and extreme months. This method provides an accurate estimation of future conditions and allows to decrease the number of simulations without neglecting the extremes and variations of the original RCM data.

2.2.1 The Coordinated Regional Climate Downscaling Experiment (CORDEX)

CORDEX, which stands for Coordinated Regional Climate Downscaling Experiment and works under the umbrella of the World Meteorological Organization (WMO) World Climate Research Programme (WCRP), coordinates activities for the application of RCMs for different regions of Earth. There are 14 CORDEX domains worldwide, which represent the regions for which the regional downscaling is taking place. Figure 6 and Figure 7 show European and African domains, respectively.

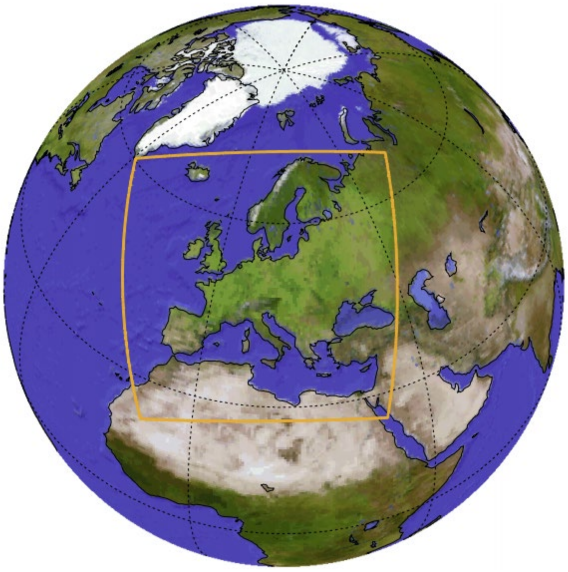

Figure 6: European domain in CORDEX

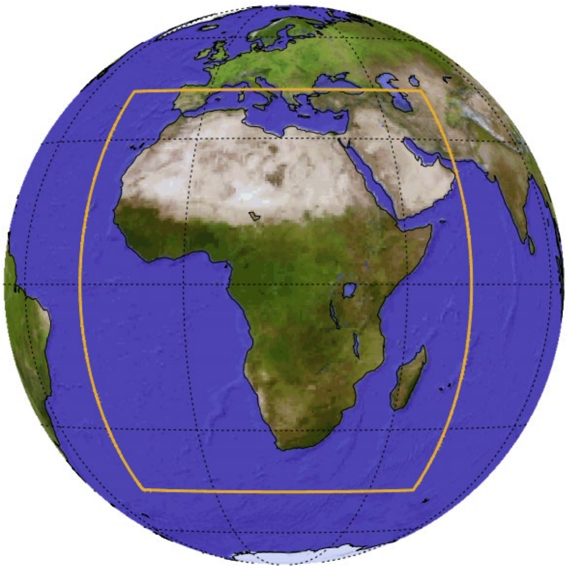

Figure 7: African domain in CORDEX

CORDEX is updated with new climate data from global domains available and includes an extensive RCM database [19]. It provides different scale of resolution: for European context of 12.5 km, for the Middle East and North Africa 25 km, while the rest of the world 50 km. The time scales on which data in multilayer format are available include monthly, daily, six hours, three hours and hourly during the historical period from 1976 to 2005 and for the future period, from 2006 to 2100. However, only a few simulations are available for some domains, thus limiting the level of analysis and assessment that can be performed using CORDEX data in some regions. Moreover, there are regions where several domains overlap, thus providing additional lines of evidence. Ongoing efforts, such as the multi-domain CORDEX-CORE simulations are promoting more homogeneous coverage and thus more systematic treatment of CORDEX domains [1].

The Mediterranean region has been object of different studies about regional downscaling because of its complex morphology [20]. EURO-CORDEX [21] and Med-CORDEX [22] are recent examples of dynamical downscaling, while earlier projects are ENSEMBLES [23,24], PRUDENCE [25], CIRCE [26] and ESCENA [27]. EURO-CORDEX projections are driven by CMIP5 GCMs and data are available for scenarios RCP 4.5 or RCP 8.5, depending on the

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model [28,29]. However, the EURO-CORDEX projections present differences with respect to projections driven by CMIP6 [30] and the EURO-CORDEX community is currently discussing the EURO-CORDEX simulation protocol for downscaling CMIP6 GCMs and the selection of CMIP6 GCMs for the GCM-RCM simulation matrix.

In Africa, the CORDEX-Africa initiative has been developed to analyse downscaled regional climate data over the CORDEX-African domain, train young climate scientists in climate data analysis techniques and engage users of climate information in both sector specific and region/space-based applications. Thanks to regionally downscaled CORDEX Africa outputs, new literature is now available for the African climate, providing projections of both the mean climate and extreme climate phenomena [1].

CORDEX Datasets and climate projections are included in the IPCC Interactive Atlas (together with global datasets such as CMIP5 and CMIP6) allowing for flexible spatial and temporal analyses. Figure 8 presents examples of data available selecting CORDEX Europe and CORDEX Africa Datasets. Different key variables from the atmosphere (daily mean, minimum and maximum surface temperatures and precipitation), extreme indices, climatic-impact drivers, RCP scenarios and baselines can be selected.

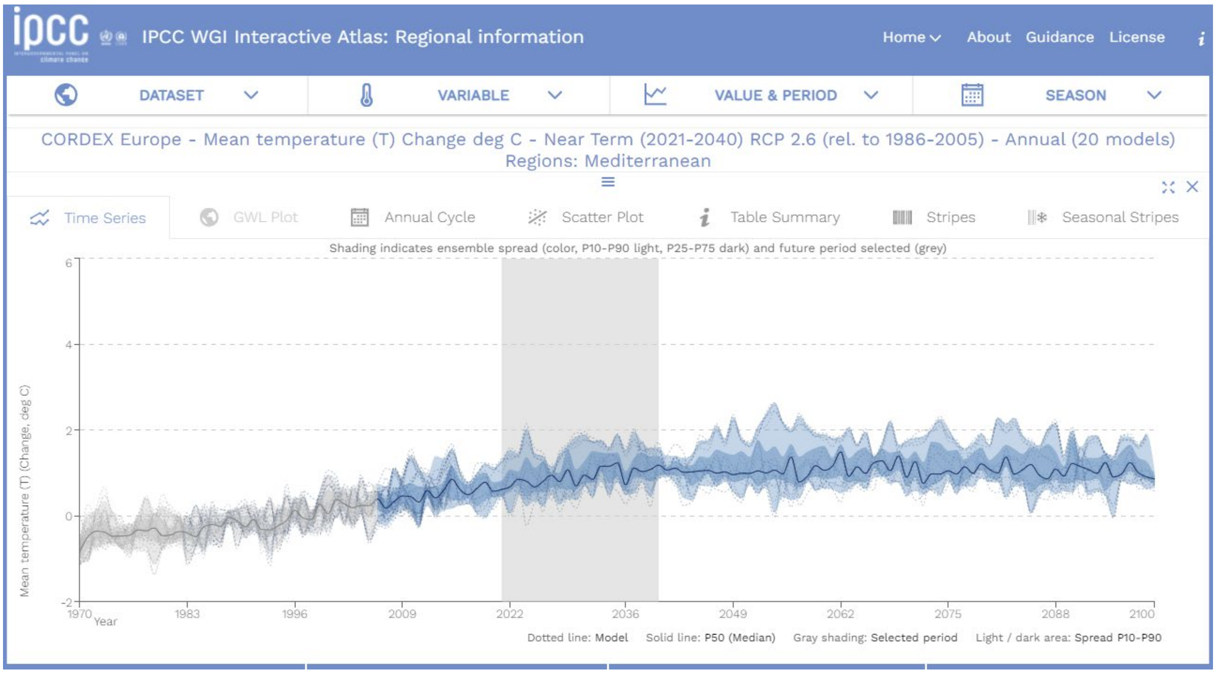


Figure 8: Mean temperature change trend according to CORDEX Europe dataset available through the IPCC Interactive Atlas

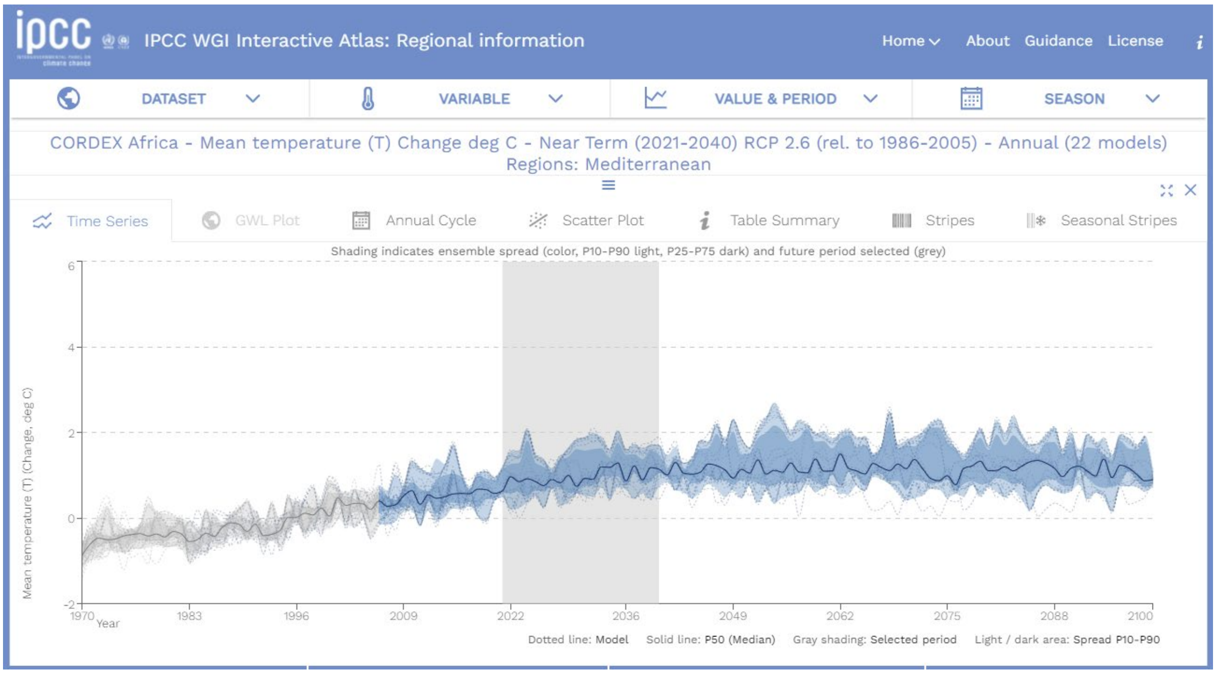


Figure 9: Mean temperature change trend according to CORDEX Africa dataset available through the IPCC Interactive Atlas

2.3 Statistical Downscaling methods

An alternative to RCMs is to use statistical techniques to downscale GCM models to a finer grid. Statistical downscaling develops and applies statistical relationships between regional or local climate variables and large-scale climate data using deterministic or stochastic approaches (by combining various scenarios). This technique assumes that large-scale meteorology and geographic features influence local weather and climate. The climate model data may also need to be temporally downscaled (time scale adjustment) if the resolution is too coarse for the required purpose of the final application. Both RCM and GCM downscaled data can either be incorporated into a weather generator, which will produce future synthetic series of weather data [31,32], or by means of a mathematical transformation (morphing) produce a future time series based upon historic weather observations [33]. The creation of future weather files can be approached in two ways: by combining climate projections with a weather generator to allow the creation of typical future weather years, or by a mathematical transformation (morphing) of the time series of existing current weather files using climate change anomalies from a GCM or RCM.

This downscaling approach is a computationally less demanding alternative that facilitates achieving various sets of results. The simplicity of this method, in comparison with dynamical downscaling, persuades many researchers to favour it. This method is mostly applied to GCM projections, while it may also be applied to RCM output as being a better representative for the local climate. In the two following sub-sections, major approaches for applying statistical downscaling are explained in more detail.

2.3.1 Stochastic Weather Generation

Stochastic weather generators produce synthetic time series of weather data of unlimited length for a location based on the statistical characteristics of observed weather at that location. An advantage of the stochastic time generation method is to allow the integration of the distribution used for the climate change signal [34]. Furthermore, it is liable for potential variations in weather patterns and climate flexibility [35]. A limitation of this method is the requirement of a large amount of data to train the model [32]. Meteonorm is a well-known tool which is based on this method (see section 3.3)

2.3.2 Morphing (Time Series Adjustment)

Morphing is the most common statistical downscaling method for the adjustment of time series towards the future. It has been widely used by researchers in Europe for projections of local building energy use, while in Africa, similar research is still few. Morphing modifies existing TMYs by synthesizing statistically downscaled results of GCM's large-scale outputs. In order to transform this baseline to a future time series, monthly climate change signals given by a GCM or RCM are used.

In order to morph data, it's possible to follow three different procedures [34]:

1. When the absolute monthly mean change derived from GCM or RCM is predicted for a singular variable (i.e., atmospheric pressure) for the month m the **shift** is applied according to equation (1):
2. When a relative monthly mean change derived from a GCM or RCM is predicted for a singular variable (i.e., wind speed) for the month m the **stretch** is applied according to equation (2):
3. When both absolute and relative monthly mean changes derived from GCM or RCM are predicted for a given variable (i.e., dry-bulb temperature) for the month m, the **combination of shift and stretch** is applied according to equation (3):

$$x_m = x_o + \Delta x_m \quad (1)$$

$$x_m = \alpha_m \cdot x_o \quad (2)$$

$$x_m = x_o + \Delta x_m + \alpha_m (x_o - x_{o,m}) \quad (3)$$

Where:

- x_o= given variable
- Δx_m= absolute monthly mean change
- α_m= relative monthly mean change
- $x_{o,m}$= variable x_o average over month m for all the considered averaging years of future data provided by the climate models

The Morphing methodology can reflect changes on the average weather conditions but is unable to model changes in the weather patterns (daily, weekly, monthly or yearly) and extreme events of the different weather variables are not available in a Morphed file [11].

CCWorldWeatherGen and WeatherShift are two available tools that use the morphing method to create future weather data. More details about these tools and their application are presented in section 3.1 and 3.2.

3. Future weather Generation Tools

3.1 CCWorldWeatherGen tool

CCWorldWeatherGen is a free online tool Microsoft® Excel-based created by Southampton University's Sustainable Energy Research Group [36]. This tool uses the morphing methodology to create future meteorological datasets in Energy Plus Weather (EPW) format (see Figure 10).

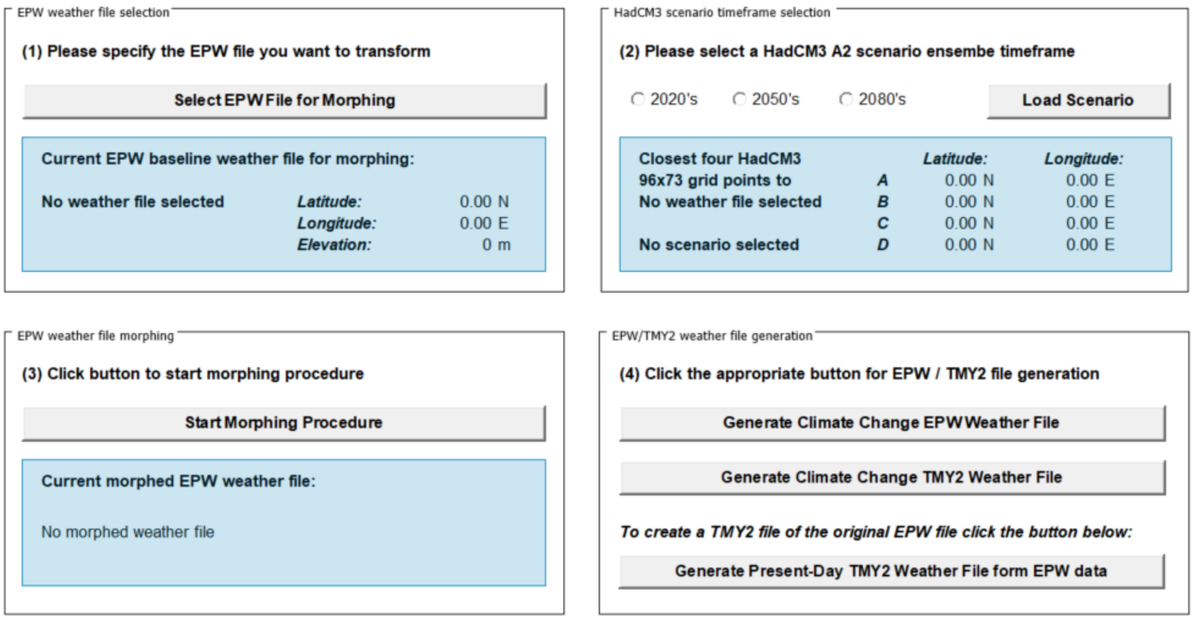


Figure 10: Extract of the CCWorldWeatherGen excel tool

The tool uses the Hadley Center Coupled Model 3 (HadCM3) global climate model, forced with IPCC A2 emission scenarios. HadCM3 provides the monthly value of relative changes regarding the period of 1961–1990 as input for the Morphing procedure. The Excel tool superimposes this input on the weather variables of the baseline weather data stored in an EPW file. The tool generates future weather data sets for 3 time slices: 2001–2040 (referred to as '2020s'), 2041–2070 (referred to as '2050s'), and 2071–2100 (referred to as '2080s').

Limitations and uncertainties

The tool specifies that ideally the EPW files used for the 'morphing' process should be formed of weather data derived from measured parameters of the years 1961-1990 in order to match the HadCM3 reference timeframe. Moreover, the reference interval should cover a period of 30 years. Therefore, the morphing approach cannot be applied to different and more recent dataset without incurring in major errors.

3.2 WeatherShift

The WeatherShift^{TM} tool is a weather-generator software developed by Arup and Argos Analytics [37]. This tool is based on morphing methodology and it exploits fourteen GCMs (Table 2) (out of a total of 40 models) with RCP 4.5 and 8.5 emission scenarios of the IPCC's Fifth Assessment Report (CMIP5). Weathershift uses multiple models which allow generating a Cumulative Distribution Function (CDF) for each variable through linear interpolation data.

In fact, the software applies the morphing method on eight climate-variables such as: the maximum, minimum and average daily temperature, relative humidity, daily total solar irradiance, wind speed, atmospheric pressure, and precipitation. This tool is able to generate future weather data for time periods of 20 years each, from 2011-2030 “the short term” to 2081-2100 “the long term”. The software requires a weather file formatted as TMY (TMY3), for this reason the reference period of the baseline is 1976-2005 [34]. Weathershift is paid-software but it offers also an online free visualization tool [38]. This latter provides four interactive graphs: Average Monthly Data, Trends by Season, Binned Data, Detailed Viewer. The variables that can be selected on the interactive graphs are: temperature, dew point, heat index, wind (chill and speed), relative humidity. All graphs provide four periods: the present climate and three future projection weather: 2026-2045 (referred as ‘2035s’), 2056-2075 (referred as ‘2065s’), 2081-2100 (referred as ‘2090s’).

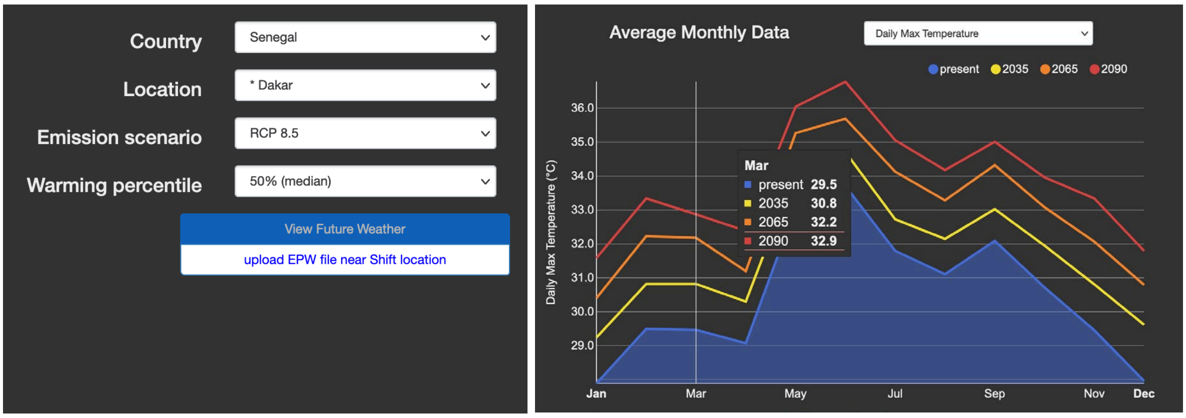


Figure 11: Online free visualization tool of Weathershift [38]

Table 2: Fourteen GCMs available in WeatherShift

N	Model	Institution	Resolution (Lat x Long ¡)
1	BCC-CSM 1.1	Beijing Climate Center, China Meteorological Administration	2.8125 x 2.8125
2	BCC-CSM 1.1(m)	Beijing Climate Center, China Meteorological Administration	1.12 × 1.12
3	CanESM2	Canadian Centre for Climate Modelling and Analysis	2.8 × 2.8
4	CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation and the Queensland Climate Change Centre of Excellence	1.8 × 1.8
5	GFDL-CM3	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5
6	GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5
7	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5
8	GISS-E2-H	NASA Goddard Institute for Space Studies	2.0 x 2.5
9	GISS-E2-R	NASA Goddard Institute for Space Studies	2.0 x 2.5
10	HadGEM2-ES	Met Office Hadley Centre	1.88 × 1.25
11	IPSL-CM5A-LR	Institut Pierre-Simon Laplace	3.75 × 1.8
12	IPSL-CM5A-MR	Institut Pierre-Simon Laplace	2.5 × 1.25
13	IPSL-CM5B-LR	Institut Pierre-Simon Laplace	3.75 × 1.8
14	NorESM1-M	Norwegian Climate Centre	2.5 × 1.9

Limitations and uncertainties

WeatherShift is able to manage only few climate variables (dry bulb temperature, dew point temperature, relative humidity, atmospheric pressure, global horizontal radiation, direct normal radiation, diffuse horizontal radiation, and wind speed) [39].

3.3 Meteonorm

Meteonorm is a software often used for creating meteorological data for BES, solar simulations and climate change studies [40]. It can be defined as stochastic weather generation and it uses spatial interpolation on the principal weather variables (i.e., dry-bulb temperature, dew-point temperature, global and horizontal irradiance and wind speed) in order to generate hourly weather data for any site of world [41]. The database stores climate data of more than 8000 weather stations with more than 1500 with measured global radiation [42]. Figure 12 shows the multiple choices available for selecting the location: weather stations, weather stations w/o global radiation, design reference year locations, cities and the user defined locations. If the statistical data are not accessible, Meteonorm works to interpolate the available data coming from the nearby sites.

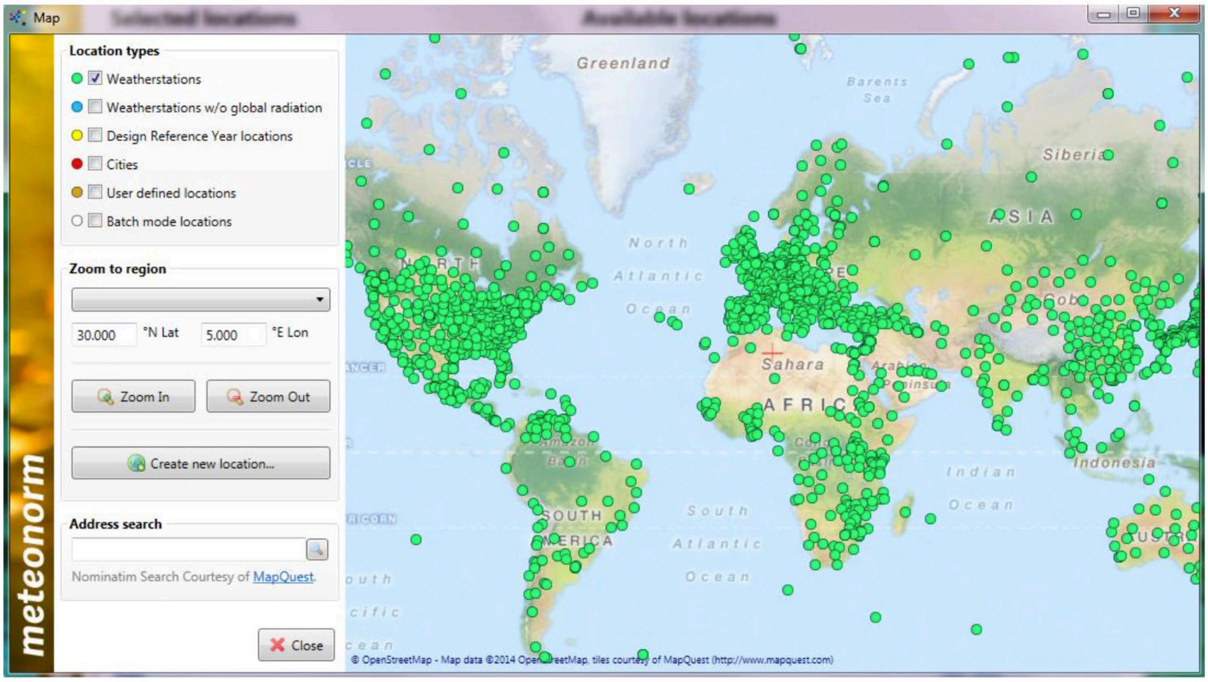


Figure 12: Software interface of Meteonorm at the selection of location [43]

The global radiation available on Meteonorm database comes from Global Energy Balance Archive (GEBA) [44], which stores monthly average variables recorded at the worldwide distributed stations. The other variables have been sourced from databases of World Meteorological Organization (WMO) and National Climatic Data Center (NCDC).
Meteonorm analyses the global radiation using a procedure by means the Markov transition matrices [45]. The values of temperature, instead, is generated starting from the global radiation and the daily temperature value of approximate 5000 site stored in the database [40].
The generation of future weather file is based on GCMs presented on the IPCC fourth assessment report (AR4) [46]. All 18 public climate model (Table 3) and the potential parameters' anomalies have been included in Meteornorm.

ABC21 is funded by the EU's H2020 programme

Table 3: Eighteen GCMs available in Metronorm [47]

N	Model	Institution	OGCM horizontal/ vertical resolution
1	CGCM3.1(T47)	Canadian Centre for Climate Modelling and AnalysiS	192 x 96 L29
2	CNRM-CM3	Météo-France/Centre National de Recherches Météorologiques	180 x 170 L33
3	CSIRO-Mk3.0	CSIROaAtmospheric Research	1.875 x 0.925 L31
4	ECHAM5/MPI-OM	Max Planck Institute for Meteorology	1 x 1 L42
5	GFDL-CM2.0	U.S. Dept. of Commerce/NOAAb/Geophysical FluidDynamics Laboratory	1 x 0.33-1 L50
6	GFDL-CM2.1	U.S. Dept. of Commerce/NOAAb/Geophysical FluidDynamics Laboratory	1 x 0.33-1 L50
7	GISS-AOM	NASAcGoddard Institute for Space Studies	90 x 60 L16
8	GISS-EH	NASAcGoddard Institute for Space Studies	2 x 2 cos(lat) L16
9	GISS-ER	NASAcGoddard Institute for Space Studies	72 x 46 L13
10	FGOALS-g1.0	LASGd Institute of Atmospheric Physics	360 x 170 L33
11	INM-CM3.0	Institute for Numerical Mathematics	2 x 2.5 L33
12	IPSL-CM4	Institut Pierre Simon Laplace	2 x 2 L31
13	MIROC3.2(hires)	Center for Climate System Research (The University of Tokyo),National Institute for Environmental Studies, and FrontierResearch Center for Global Change (JAMSTEC)	T106 L48
14	MIROC3.2(medres)	Center for Climate System Research (The University of Tokyo),National Institute for Environmental Studies, and FrontierResearch Center for Global Change (JAMSTEC)	256 x 192 L44
15	MRI-CGCM2.3.2	Meteorological Research Institute	2 x 0.5-2.5 L23
16	PCM	National Center for Atmospheric Research	384 x 288 L32
17	UKMO-HadCM3	Hadley Centre for Climate Prediction and Research, Met Office	1.25 x 1.25 L20
18	UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research, Met Office	1 x 0.33-1 L40

The data generation has to be set according with the following periods (Figure 13):

- Temperature (and all other parameters except for radiation): 1961 – 1990 and 2000 – 2009
- Radiation: 1981–1990, 1991–2010 / 1996–2015
- Future periods: (IPCC Scenarios) B1, A1B, A2.

Figure 14 shows the pre-defined data formats that can be generate with Meteonorm.
Each format is characterized by time-step, header lines, outputs' parameters, delimiter and units. An example of three format is reported within Table 4.

The results of the calculation can be viewed immediately, whereas the stored data are only accessible through external applications.

ABC21 is funded by the EU's H2020 programme

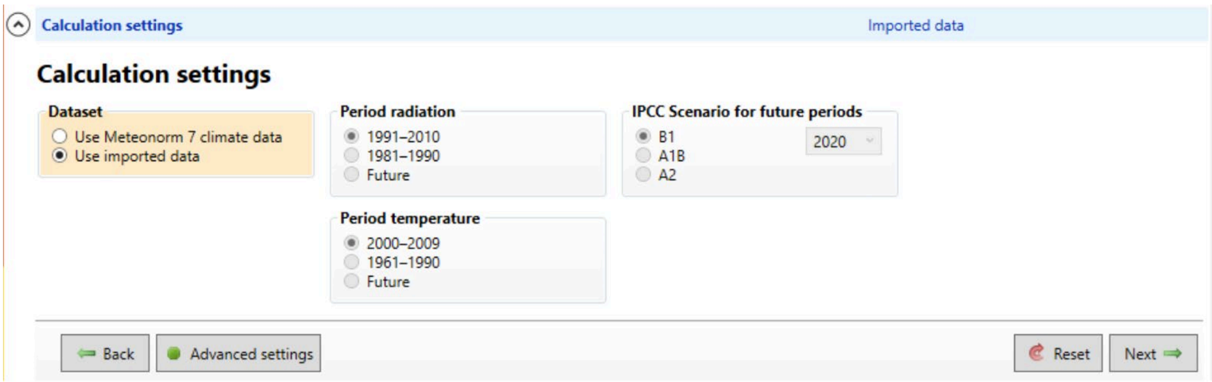


Figure 13: Calculation setting interface of Meteonorm [43]

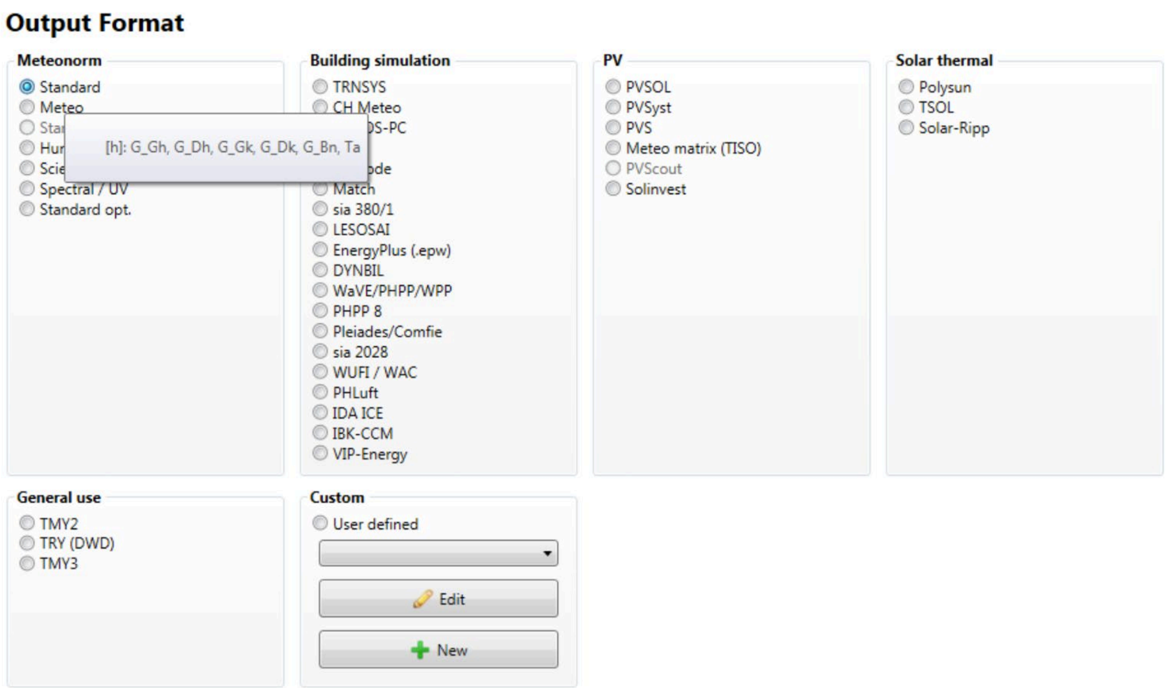


Figure 14: Output format of Meteonorm [43]

Table 4: Examples of outputs' parameters of Meteonorm [43]

Nr	Format	Timestep	Header lines	Parameters	Delimiter	Units
1	Standard	Hour	-	m, dm, h, hy, G_Gh, G_Dh, G_Gk, G_Dk, G_Bn, Ta	Tab	[W/m^2], [°C]
90	Meteo	Month	5	Ta, Ta_{min}, Ta_{dmin}, Ta_{dmax}, Ta_{max}, RH, H_Gh, SD, SD_{astr}, RR, RD, FF, DD, snow and wind loads	Blank	[°C], [%], [W/m^2], [h/day], [mm], [days], [m/s], [deg]
..	..	..	..	..	..	..
22	ENERGY PLUS ** (epw files)	hour	8	m, dm, h, Ta, Td, RH, p, G_G_{ex}, G0, G_Gh, G_Bn, G_Dh, LG, LD, L_Z, DD, FF, N, N1, Vis, Hc, Wc, PrecW, Aod, Sn, Ds**	Blank	[W/m2], [°C], [m/s], [cm], [h], [hPa]
9	TRNSYS	hour	2	dm, m, h, G_Bh, G_Dh, Ta, FF, RH	Blank	[W/m^2], [°C], [m/s]

Limitations and uncertainties

Mueller et al. validated the Meteonorm satellite irradiation dataset. From their results, uncertainties of 12-25% relative root-mean-square error (RMSE) for hourly values were found in particular for site located in Northern Europe [48].

3.4 MarkSimGCM

MarkSimGCM is a weather-generator released as a free online tool that uses statistical downscaling and it can be defined as stochastic weather-generator.

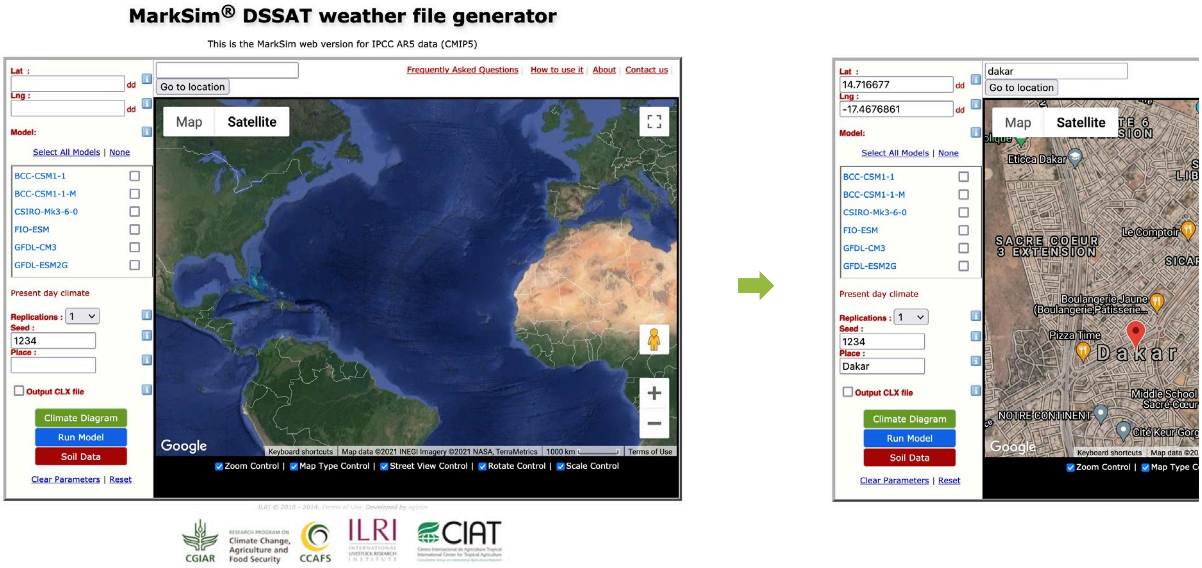


Figure 15: MarkSimGCM online interface [49]

This tool exploits a clustering process of 720 classes of world weather which define each set of regression equations used to determine the coefficients for the modelling. This constitutes stochastic downscaling following the Markov model to the GCM output and uses it to generate weather data for the site indicated [47].
Its last updated, in 2013, aims to include data from the seventeen climate modes (Table 5) reported in the IPCC's Fifth Assessment Report (CMIP5).

Table 5: Seventeen GCMs available in MarkSimGCM [47]

N	Model	Institution	Resolution (Lat x Long ¡)
1	BCC-CSM 1.1	Beijing Climate Center, China Meteorological Administration	2.8125 x 2.8125
2	BCC-CSM 1.1(m)	Beijing Climate Center, China Meteorological Administration	2.8125 x 2.8125
3	CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation and the Queensland Climate Change Centre of Excellence	1.875 x 1.875
4	FIO-ESM	The First Institute of Oceanography, SOA, China	2.812 x 2.812
5	GFDL-CM3	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5
6	GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5
7	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5
8	GISS-E2-H	NASA Goddard Institute for Space Studies	2.0 x 2.5
9	GISS-E2-R	NASA Goddard Institute for Space Studies	2.0 x 2.5
10	HadGEM2-ES	Met Office Hadley Centre	1.2414 x 1.875
11	IPSL-CM5A-LR	Institut Pierre-Simon Laplace	1.875 x 3.75
12	IPSL-CM5A-MR	Institut Pierre-Simon Laplace	1.2587 x 2.5
13	MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	2.8125 x 2.8125
14	MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	2.8125 x 2.8125
15	MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of	1.4063 x 1.4063

		Tokyo), and National Institute for Environmental Studies	
16	MRI-CGCM3	Meteorological Research Institute	1.125 x 1.125
17	NorESM1-M	Norwegian Climate Centre	1.875 x 2.5

Within the online platform, after the selection of the site (Figure 15) it is possible to directly generate a climate diagram or run a model.
The output coming from the tool can be summarized in two formats: annual charts of variables such as daily rainfall including maximum and minimum monthly air temperature (Figure 16), and a database compliant with the Decision Support of System for Agrotechnology Transfer (DSSAT) crop modelling system. countries [50]. For both formats it is possible to select and simulate all the seventeen models overmentioned.

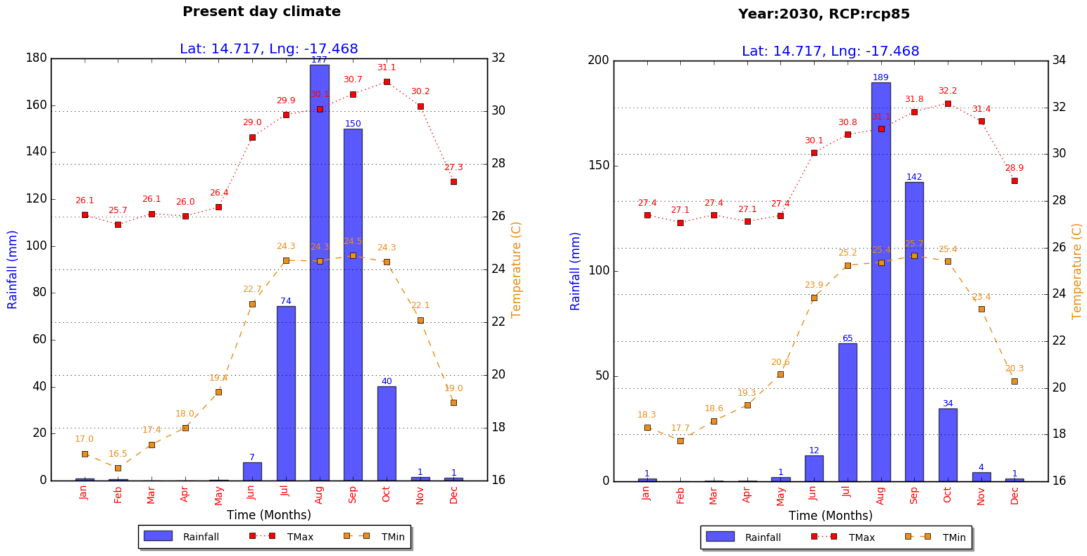


Figure 16: Example of MarkSimGCM output for Dakar (at current year, at 2030 using the model: BCC-CSM1-1 RCP 2.6 and RCP: 8.5) [49]

Limitations and uncertainties

This tool is limited for two aspects: the first one regards the few variables that can be simulated which do not recreate a complete future climate; the second one regards the impossibility of simulating climate before 2010 due to a data-gap from 1985 to 2010 which makes the simulation curve instable.

3.5 Common Limitations

Weather generators are based on statistics derived from historical weather data. Although the evaluation of extreme events is critical for the generation of future weather, it is rare that the historical database contains data that can correctly report single events [13]. More, historical climate data are not available for every region and reporting the same number of meteorological parameters.
Another possible problem concerns the surface interpolation. It can come from eventual gap data or/and the interpolation methodology used. The distribution and the density (intended as the number of stations per area) of weather stations on African territory are significantly lower than on other continents.

3.6 Summary comparison between weather generation tools

The Table 6 resumes the differences between weather generation tools comparing the main features.

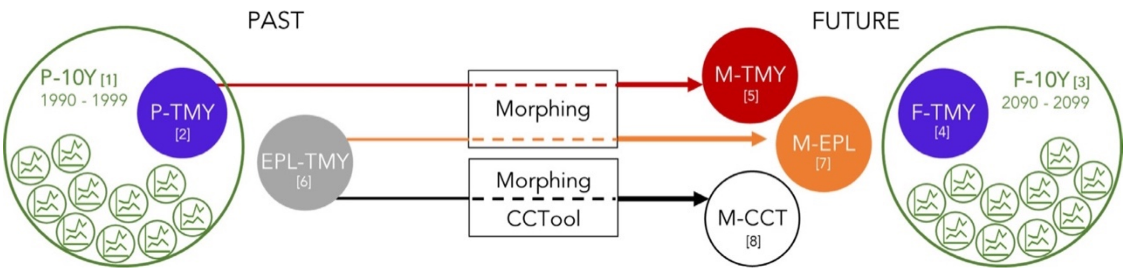
Table 6: Weather generation tools comparison

Features	CCWorldWeatherGen	Meteonorm	WeatherShift	MarkSimGCM
Downscaling method	Morphing	Stochastic weather generation	Morphing	Stochastic weather generation
GCM	HadCM3	18 models	14 models	17 models
Projected Time periods	2020,2050,2080	2010-2200	2035,2065,2090	2030 and 2050
IPCC Report	AR3(2001), AR4(2007)	AR4(2007)	AR5 (2014)	AR5
IPCC emission scenario	A2	(B1, A1B, and A2)	RCP 4.5 and 8.5	RCP 2.6, 6, 4.5 and 8.5
Baseline period	1961-1991	for radiation: 1981-90, 1991-10, 1996-15 for temperatures: 1961-90, 2000-09	1976-2005	Run for about 50 or 100 years of past data. The exact baseline period is not available.
Advantages	Free online tool Morphing individual years leads to year-to-year variability in the Morphed files	Simple method Enhance the spatial and temporal resolution instead of using complicated and time-consuming downscaling methods based on regional climate models. Relatively low price point	Exploits AR5 (2014)	Information about rainfall, maximum and minimum temperatures and solar radiation Specifically designed for tropical countries. Generates data for a specific location anywhere in the world that can be used for crop, livestock and natural resource modelling and risk assessment.
Uncertainties and limitations	Possible differences in the reference time frames between HadCM3 and the EPW data, inaccuracy in the outputs of the tool may occur unable to model changes in the weather patterns (daily, weekly, monthly or yearly) and extreme events of the different weather variables are not available in a Morphed file	The use of interpolated and synthetic data. The interpolations rely heavily on surface observation data, which are not equally distributed. Uses weather stations rather than satellite based estimations	Modifies only the most important meteorological parameters (dry bulb temperature, dew point temperature, relative humidity, atmospheric pressure, global horizontal radiation, direct normal radiation, diffuse horizontal radiation, and wind speed).	The system cannot model completely new climates except by extrapolation of the regression models from the nearest cluster. Since there is a data gap from 1985 to 2010 and the curves might not be stable in this region, it is not possible to generate weather data before 2010

4. The methodology for generation of future weather data in ABC 21

The generation of future weather files can be performed using different methodologies, as described in chapter 2. RCMs provide an accurate representation of atmosphere describing the spatial and the temporal variability of local climate. Statistical downscaling develops and applies statistical relationships between regional or local climate variables and large-scale climate data. Both RCM and GCM downscaled data can either be incorporated into a weather generator, which will produce future synthetic series of weather data (stochastic weather generator), or by means of a mathematical transformation produce a future time series based upon historic weather observations (morphing).

Bravo Dias et al. [51] (Figure 17) have recently shown through a comparative study that a high-quality Morphed TMY weather file has a similar performance compared to a typical meteorological year of future climate (F-TMY) (mean difference: 8% versus 7%). Additionally, they have assessed that low-quality Morphing (e.g., based on different baseline climates, low-grid resolution and/or outdated climate projections) leads to BES average differences of 16%-20%.



The high-resolution climate simulation dataset	Free available climate files and a morphing tool
▪ P-10Y: a 10-year file of past hourly data (1990–1999); ▪ P-TMY: a past TMY file, produced using P-10Y (1); ▪ F-10Y: a 10-year file of future hourly data (2090–2099); ▪ F-TMY: a future TMY file, produced using F-10Y (3); ▪ M-TMY: a morphed TMY file, produced using P-TMY (2), and differences between F-10Y (3) and P-10Y (1).	▪ EPL-TMY: past TMY download from EnergyPlus weather database; ▪ M-EPL: a morphed EPL-TMY, produced using EPL-TMY (6), and differences between F-10Y (3) and P-10Y (1). ▪ M-CCT: a morphed EPL-TMY, produced using EPL-TMY (6), using the CCWorldWeatherGenerator tool;

Figure 17: Evolution of weather file for generating future climate using different methodology [51]

Following this study, the methodology for the generation of future weather data in ABC 21 will be based on the use of high-quality morphed TMY.

5. Conclusion

The project raises attention on the importance of better understanding the implications that climate change and future weathers have on the design of the buildings, using a proper building energy modelling.

Climate models are constantly being updated by different modelling groups that coordinate their research in the framework of IPCC. The Sixth IPCC Assessment Report (AR6) has recently been released and CMIP6 is now the most up-to-date, scientifically advanced database for climate science and services.

Future scenarios are the input data used to provide initial conditions for General Circulation Models or Global Climate Models (GCMs), which are models for forecasting climate change.

In case of building energy simulations, the GCMs should be downscaled to applicable spatial (less than 100 km^2) and temporal resolution (less than monthly value). There are two main approaches to downscale GCMs: dynamical and statistical downscaling.

The simplicity of statistical downscaling, in comparison with dynamical downscaling, persuades many researchers to favour it. Moreover, there are several weather generation tools that can be exploited to generate future climate, the most common are: CCWorldWeatherGen tool, WeatherShift, Meteonorm, MarkSimGCM.

These tools are based on downscaling methods: CCWorldWeatherGen tool and WeatherShift use morphing methodology while Meteonorm and MarkSimGCM use stochastic weather generation.

Among the diverse methodologies that can be used to generate future climate, the high-resolution morphing method seems to be the most recommended and will be used for the generation of future weather files in ABC 21.

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