Urban climate – Impact on energy consumption and thermal comfort of buildings

Jan Remund[1] and Urs Grossenbacher[2]

[1] Meteotest AG, Bern (Switzerland)

[2] INES GmbH, Bern (Switzerland)

Abstract

Climate change and the urban heat effect is expected to have a large influence on the energy consumption and thermal comfort of buildings. However, using meteorological data which incorporates effects of climate change and characteristics of cities is not currently a standard practice in building simulation.

By default, Typical Meteorological Years (TMY) based on 20-year meteorological statistics from nearby meteorological stations often outside cities are used. This may lead to important discrepancies between simulation results and actual energy consumption and/or indoor climate data for buildings in urban areas.

These effects are analyzed within Building energy part of H2020 climate-fit.city project. First, adapted urban and future meteorological data modelled using the VITO UrbClim model and standard meteorological data were compared. Second, these data were included within the Meteonorm software. In a first phase, this was carried out for the cities of Bern and Vienna. In the future, this data will be included for other urban areas in Europe.

In a third step the urbanized TMY data sets generated by Meteonorm were used to simulate energy consumption and indoor climate conditions with models of three typical buildings. The whole-year simulation runs were made in series for several urban locations and – as a reference scenario – with the standard TMY.

First results show that meteorological data are modelled generally well; however at some sites differences are statistically significant. In some locations Meteonorm based data show lower discrepancies, in some the ERA-Interim / Urbclim model based. The differences regarding building energy needs are relatively low. Heating energy consumption is 6% lower within cities and cooling energy 15% higher. The hours outside comfort levels within cities are higher, however only to a small extent. Currently, only results from Bern and Vienna have been analysed. For other cities in other climate regions, the results and conclusions may be different.

Climate-fit.city is a EU project within the framework of Horizon 2020

Key-words: climate change, urban heat, building energy simulation, thermal comfort

1 Introduction

Climate change, and in particular the urban heat effect, is expected to have a large influence on the energy consumption and thermal comfort of buildings. However, using meteorological data which incorporates effects of climate change and characteristics of cities (e.g. susceptibility to the 'urban heat island' phenomenon) is not currently a standard practice in building simulation.

By default, Typical Meteorological Years (TMY) based on 20-year meteorological statistics with time lags of several years and from nearby meteorological stations are used. These stations are often located outside the city centers (e.g. at airports). From this, it follows that neither climate change nor urban effects are taken into account in building performance simulation. This may lead to important discrepancies between simulation results and actual energy consumption and/or indoor climate data for buildings in urban areas.

These effects are analyzed within Building energy part of H2020 climate-fit.city project. In a first step, adapted urban and future meteorological data, modelled using the VITO's UrbClim model (De Ridder et al., 2015) and standard (non-adapted) meteorological data were compared. In a second step, these data were compressed and included within the Meteonorm software. This will enable the software to model the urban and climate change effects for any location within the urban areas. In a first application, this was carried out for the cities of Bern and Vienna. In the future, this data will be included for other urban areas in Europe. In a third step the urbanized TMY data sets generated by Meteonorm (www.meteonorm.com) were used to simulate energy consumption (heating, cooling) and indoor climate conditions (operative temperature) with models of three typical buildings.

doi:10.18086/eurosun2018.09.15 Available at http://proceedings.ises.org

The whole-year simulation runs were made in series for several urban locations and – as a reference scenario – with the standard TMY. The “urban” results where then compared with the reference scenario.

2 Objectives

The purpose of the project is to develop services to provide building design engineers more accurate and adequate meteorological data for the simulation of buildings located in cities. The objective is to construct/refurbish buildings with better indoor quality and lower energy demand.

For the Building Energy service, Meteotest enhances its Meteonorm software to account for urban climate conditions, in particular the urban heat island effect, using UrbClim output files. Concretely, this enables the stochastic generation of time series of a so-called Typical Meteorological Year (TMY), as well as extreme (hot/cold) years, both for the current situation and under future climate conditions.

The first phase is equal to the test phase of urbanized Meteonorm (a.k.a. Meteonorm Version 7.3 / MN 7.3). INES will employ urbanized Meteonorm data for Bern and Vienna to simulate building cooling and heating loads and thermal comfort levels using the IDA-ICE (https://www.equa.se/en/ida-ice) building simulation software. The results will be compared to simulation based on standard TMYs.

The objective of the first phase is to show low deviations at sites with meteorological stations used to produce standard TMY (the data used historically for building design) and to prove the working hypothesis that for sites within cities significant deviations are seen when compared to the standard meteo stations (and therefore urban adaptation is needed).

In the second phase of the H2020 project (2019), more cities in Meteonorm will be upgraded with urbanized data. The final target is to include urbanized Meteonorm data for all larger urban areas in Europe and on other continents and thus enable more accurate building performance simulations for urban areas.

3 Data & Methods used

3.1: Generation of urban climate data

VITO delivered ERA5 (2010-16) and ERA-Interim (1987-2016) based UrbClim NetCDF files for Bern and Vienna in hourly time resolution. Parameters used were temperature, wind speed, relative humidity, global radiation (directly from ERA5/Interim) and precipitation (directly from ERA5/Interim – and not used for modelling).

Based on the input values, Meteotest calculated TMY based on Sandia method (Wilcox and Marion, 2008).and condensed the temperature information into Meteonorm (urbanized Meteonorm; see section 3.3.1). The results of Meteonorm were TMY datasets in hourly input format of IDA-ICE. This includes the parameters air temperature, relative humidity, wind speed, wind direction, direct horizontal radiation and diffuse horizontal radiation.

3.2: Condensing UrbClim output into "urbanized Meteonorm"

Starting point for condensing UrbClim output into “urbanized” Meteonorm are ERA/UrbClim high resolution fields calculated by VITO. To produce TMY datasets as well as input data for urbanized Meteonorm, 30 years of hourly data are needed. The spatial resolution of the Urbclim data is 100 m.

In a preliminary step, ERA5 and ERA-Interim based datasets were bias corrected. This was done by defining the difference of the yearly average temperature and the factors of wind speed and global radiation at the site of the official meteo station (Bern/Zollikofen and Wien/Hohe Warte) for the period 2010-16. The correction values were then applied to the whole modelled grid (Table 1).

Tab. 1: Bias corrections for Bern and Vienna for ERA-Interim

Site	Temperature [°C]	Wind speed [-]	Precipitation [-]	Global rad. [-]
Bern/Zollikofen	1.4°C	1.00	1.0	1.076
Vienna/Hohe Warte	0.0°C	0.75	0.9	1.000

Meteotest condensed the bias corrected fields on a regular grid (1.6 km at the outer areas of the cities, 0.8 km in the surrounding of the center and 400 m within the city centers) to TMY and input data for the Meteonorm stochastic temperature model. At this stage higher resolutions (e.g. 100 m) have not been included as the data volume and calculation time would have been too high.

A total of approximately 400 locations were saved for Bern and 950 for Vienna each. For Bern 9 additional test locations were modelled and 5 for Vienna (see Figure 1 and Figure 2). These were used for comparing the building simulation results. As shown, the topography in Bern and Vienna is rather complex; both are located next to a river (Aare and Danube) and are located at the foothills of the Alps.

TMY generation, directly based on ERA/UrbClim data, was used as an intermediate step. The resulting datasets have also been benchmarked along the urbanized Meteonorm data. TMY were calculated based on Sandia method described by NREL (Wilcox and Marion 2008). Preliminary tests with other methods have clearly shown, that lower accuracies were therefore not used (prEN ISO 15927-4:2005; https://www.iso.org/standard/41371.html).

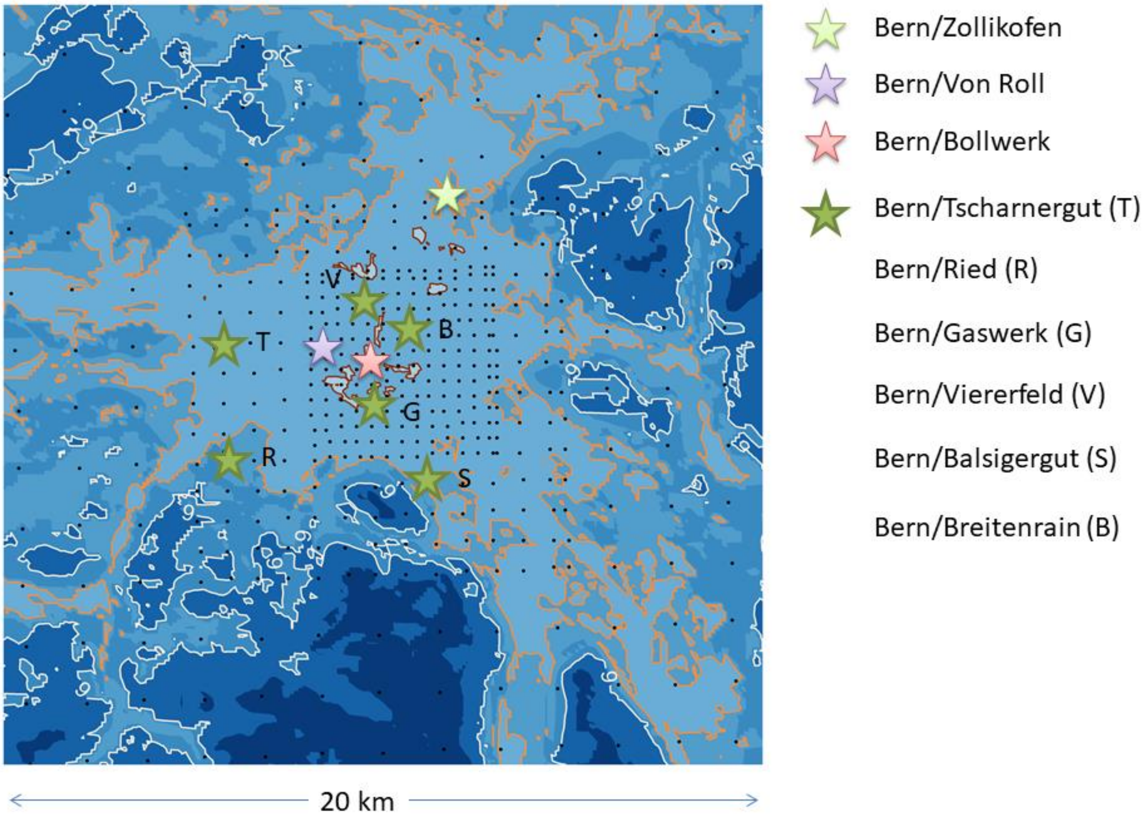


Fig. 1: Yearly average temperature in the Bern area (20x20 km) based on uncorrected ERA5/UrbClim model (red line: 11°C); black points: sites, where TMY and input data of the Meteonorm stochastic model have been used (1.6/0.8/0.4 km grid)

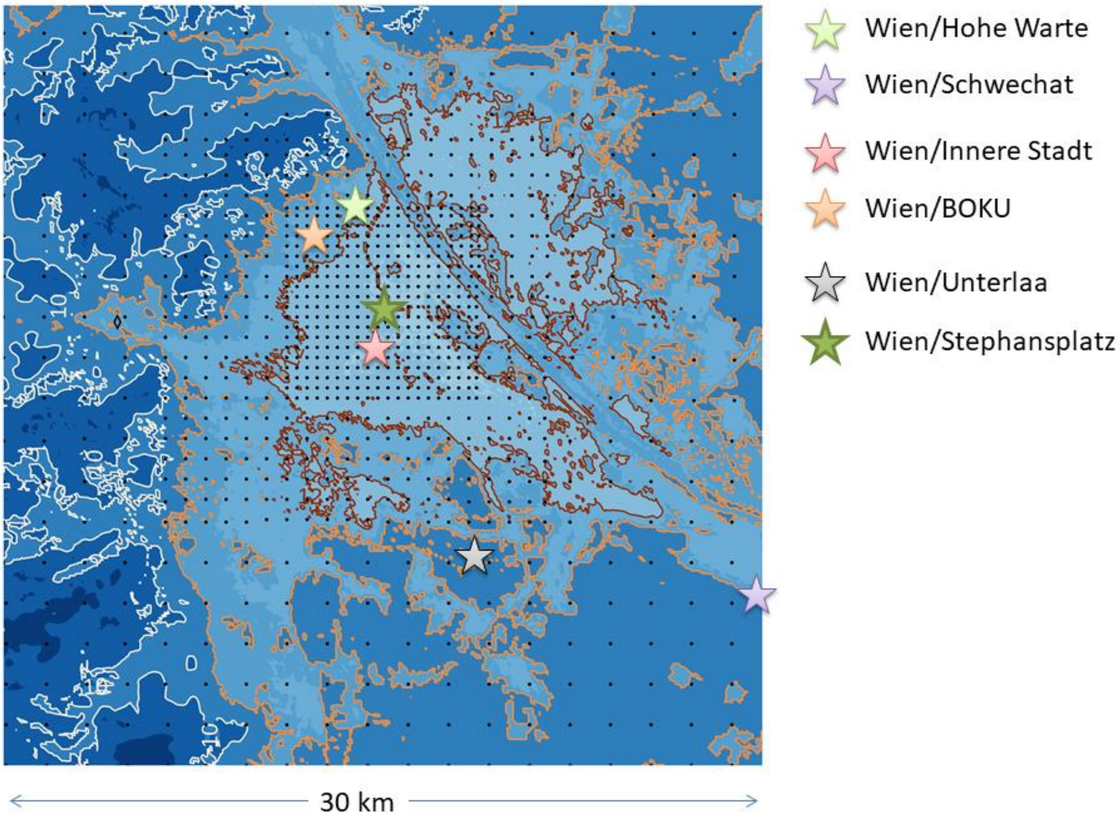


Fig. 2: Yearly average temperature in the Vienna area (30x30 km) based on uncorrected ERA5/UrbClim model (red line: 11°C); black points: sites, where TMY and input data of the Meteonorm stochastic model have been used (1.6/0.8/0.4 km grid)

In Meteonorm a Markov chain model (Remund et al. 2018) is used to generate daily temperature values. This model is based on temperature distributions from meteo stations (approximately 6000 stations). To get urbanized Meteonorm temperatures, distributions of approx. 400 input sites for Berne and 950 for Vienna were added from ERA/UrbClim models (at the points in the Figures 1 and 2 above). The following temperature parameters are used as statistical values for the model:

1. Monthly distribution of the daily temperature (7 points of the monthly distribution are stored: 1/31, 3/31, 6/31, 15/31, 25/31, 28/31, 30/31 quantiles)
2. Monthly mean temperature
3. Monthly mean of daily minimum and maximum hourly temperatures
4. Mean monthly minimum and maximum hourly temperatures
5. Mean standard deviation and difference of day to day variation, separated for days below and above the average daily difference between maximum and minimum temperatures. This approximately corresponds to a separation into clear and overcast days or days with high and low radiation
6. Mean minimum daily temperature per year
7. Mean 4-day minimum temperature per year
8. Mean maximum daily temperature per year
9. Minimum and maximum hourly value per month of all 10 years
10. Monthly deviation of average temperature in relation to meteo station (e.g. Zollikofen for Bern area); values are adapted for altitude differences

For sites within a city a general urban heat effect value of 1°C is assumed in Meteonorm. The last bullet point (10) is new and is used to correct the standard yearly urban heat effect value. At the new data points the urban heat effect is corrected to the local level.

3.3: Comparing meteorological data

At Bern and Vienna the following parameters have been tested:

- yearly average temperature
- average yearly maximum temperature
- number of tropical nights (daily minimum > 20°)
- number of hot days (daily maximum > 30°C)
- visual comparison of daily temperature profiles and daily temperature profiles between city and outside
- distribution tests (Kolmogorov-Smirnoff Index, Espinar et al., 2009)

4. Results

4.1: Meteorological data

A test based on urbanized Meteonorm (MN 7.3) was done by comparing the meteo datasets with measurements at meteo stations. TMY directly made from ERA/UrbClim time series (ERA5 / ERA-Interim), Meteonorm 7.2 (last version), Meteonorm 7.3 and measurements are listed in the tables. The table for Bern (Table 2) additionally includes SIA 2028 (1984-2003), the default TMY in Switzerland for building design (https://www.energytools.ch/index.php/de/downloads/grundlagenberichte/download/5-grundlagenberichte/47-klimadaten-sia-2028-de), whereas for Vienna (Table 3) additionally the official TMY (1993-2017) provided by Austria’s national meteorological service (ZAMG) is listed.

In the case of Bern, all datasets aside SIA 2028 have been adapted to Zollikofen (this is why all show low deviations for Zollikofen). SIA 2028 shows somewhat lower temperature values due to the older period (1984-2003).

For Bern the urban effect between Bollwerk, Von Roll and Zollikofen is about 1°C (measured as well as modelled). ERA5 and ERA-Interim underestimate the urban heat effect, whereas Meteonorm shows the same magnitude. For Vienna ERA-Interim shows correct levels of the urban effect (0.9°C), whereas Meteonorm overestimates the effect slightly.

Tab. 2: Yearly average temperature in °C for 3 sites with measurements in Bern

Model combination	Bollwerk	Zollikofen	Von Roll
ERA-Interim/urbclim TMY	9.9	9.7	9.7
SIA 2028 (1984-2003)		9.3	
MN 7.2	10.5	9.6	10.4
MN 7.3	10.5	9.6	10.4
Measured (2010-15/16)	10.6	9.6	10.7

Tab. 3: Yearly average temperature in °C for 3 sites with measurements in Vienna

Model combination	Wien/ City	Wien/ Hohe Warte	Wien/ Unterlaa
ERA-Interim/urbclim TMY	12.2	10.5	11.6
ZAMG (1993-2017)		11.1	
MN 7.2	12.9	11.1	12.3
MN 7.3	12.4	11.3	11.2
Measured (2010-15/16)		11.1	

In Tables 4 and 5 the numbers of hot days (daily maximum above 30°C) are listed as an example of temperature threshold values.

Tab. 4: Number of hot days 3 sites with measurements in Bern

Model	Bern/ Bollwerk	Bern/ Zollikofen	Bern/ Von Roll
ERA-Interim/urbclim TMY	3	1	5
SIA 2028 (TMY)		0	
MN 7.2	4	3	3
MN 7.3	3	3	3
Measured	12	9	14

Tab. 5: Number of hot days for 3 sites with measurements in Vienna

Model	Wien/ City	Wien/ Hohe Warte	Wien/ Unterlaa
ERA-Interim/urbclim TMY	16	11	12
TMY ZAMG TMY		7	
MN 7.2	13	7	9
MN 7.3	19	12	10
Measured	30	24	23

The number of hot days is underestimated by both ERA and MN datasets, but also by TMY at both sites. Urban effects are visible also in the modelled data. MN 7.3 gives more accurate results as MN 7.2 especially for Vienna. Official TMY's (sia and ZAMG) are showing also too low numbers of hot days (lower than Meteonorm based).

Daily profiles

Average daily profiles during summer half year (April-September) have been also compared graphically. Those profiles give a good impression of the urban heat effect. On one side the profiles at the three sites and on the other side the differences of the profiles from stations compared to the main meteo station are shown (here only the profiles are shown) (Figure 3).

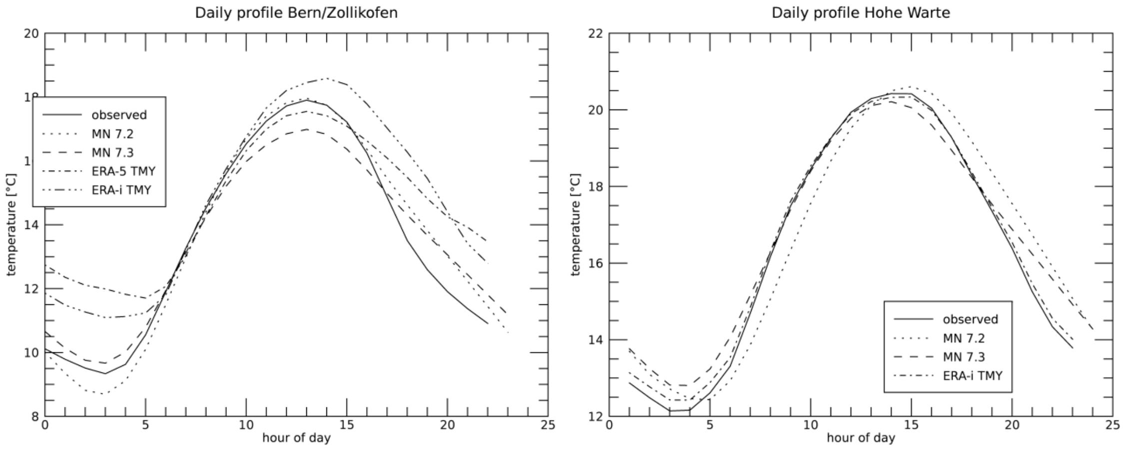


Fig. 3: Daily temperature profiles during summer at Bern/Zollikofen (left) and Vienna/Hohe Warte (right).

Meteonorm based profiles show a good agreement regarding profiles at Bern/Zollikofen; ERA based data show too high night time values. Meteonorm and ERA based profiles show a good agreement regarding profiles at Wien/Hohe Warte. Overall there is a diverse result: for Bern MN based date are closer to the measured values, whereas in Vienna the ERA based TMY are showing less difference to the measurements.

Distribution tests

Distribution tests were used to compare the different values (as TMY can't be compared hour by hour). Tables 6 and 7 contain the Kolmogorov-Smirnoff test index (KSI) over values (Espinar et al., 2009).

Tab. 6: KSI over (%) values for three sites in Bern

Model	**Bern/ Bollwerk**	**Bern/ Zollikofen**	**Bern/ Von Roll**
ERA-Interim/urbclim TMY	468	118	1216
SIA 2028 TMY	-	175	-
MN 7.2	0	0	65
MN 7.3	0	1.0	17

Tab. 7: KSI over (%) values for three sites in Vienna

Model	**Wien/ City**	**Wien/ Hohe Warte**	**Wien/ Unterlaa**
ERA-Interim/urbclim TMY	6	5	35
SIA 2028 TMY		508	
MN 7.2	564	336	685
MN 7.3	301	164	456

KSI values below 100% mean, that statistically no difference between the distributions exists. In Bern Meteonorm TMY have clearly lower KSI values than directly constructed TMY based on ERA/urbclim. However in Vienna ERA-Interim based TMY show clearly lower differences. MN 7.3 (urbanized Meteonorm) shows slightly lower differences than MN 7.2.

Figure 4 shows the cumulative distributions of modelled vs. measured temperature values at site Bern/Zollikofen and Wien/City. Whereas for Bern ERA based TMY show differences around 4°C, Meteonorm files are mostly below the threshold of 95% uncertainty (horizontal line at approx. 0.02). For Vienna/City ERA based TMY show smaller deviations than MN based (biggest deviations are also at 4°C).

Regarding distributions official TMY (sia 2028 / ZAMG) show larger discrepancies than ERA and MN based TMY's as they do for extreme values even for the station they have been made for.

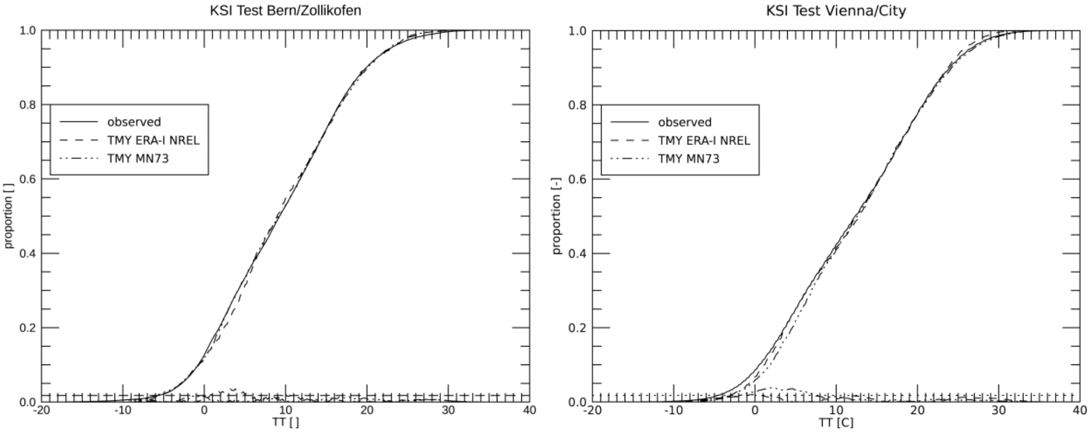


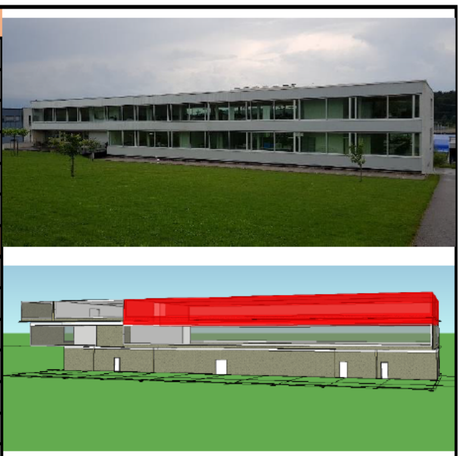
Fig. 4: Cumulative distributions of hourly temperature values at Bern/Zollikofen (left) and Vienna/City (right)

4.2: Building simulation

INES defined three types of buildings (apartment building from the 70’s, current apartment building, current office building). They compared the energy consumption (heating and cooling) and the indoor climate (EN-15251: typical hours per year in four comfort classes) for the different buildings and climate files.

Figure 5 exemplarily shows the definition for a current Office building. The photograph in the top right corner gives a visual impression and the 3D-view below shows the model in the IDA-ICE-editor. The highlighted zone represents the selected room for analyzing the thermal comfort criteria. In this case, an open space office on the top floor has been chosen. The table below the pictures gives an overview on the quality of the typical thermal insulation for buildings like this, in comparison with actual requirements for new constructions in Switzerland.

Building	
Country / City:	Switzerland / Berne
Project name	CH-Office New
Year of constructic	2012
Building category:	Office building
Area:	3'198 m²
No. of workplaces:	70
Building specification	
HVAC-System	
Heating system	Heating / Cooling slabs (concrete)
Cooling system	Chiller with dry cooler
Mechanical ventilation	Ventilation with heat recovery
Solar protection	External textile blinds
Control system	Building control system
DHW	Heat recovery from chiller / Gas boiler



Thermal envelope

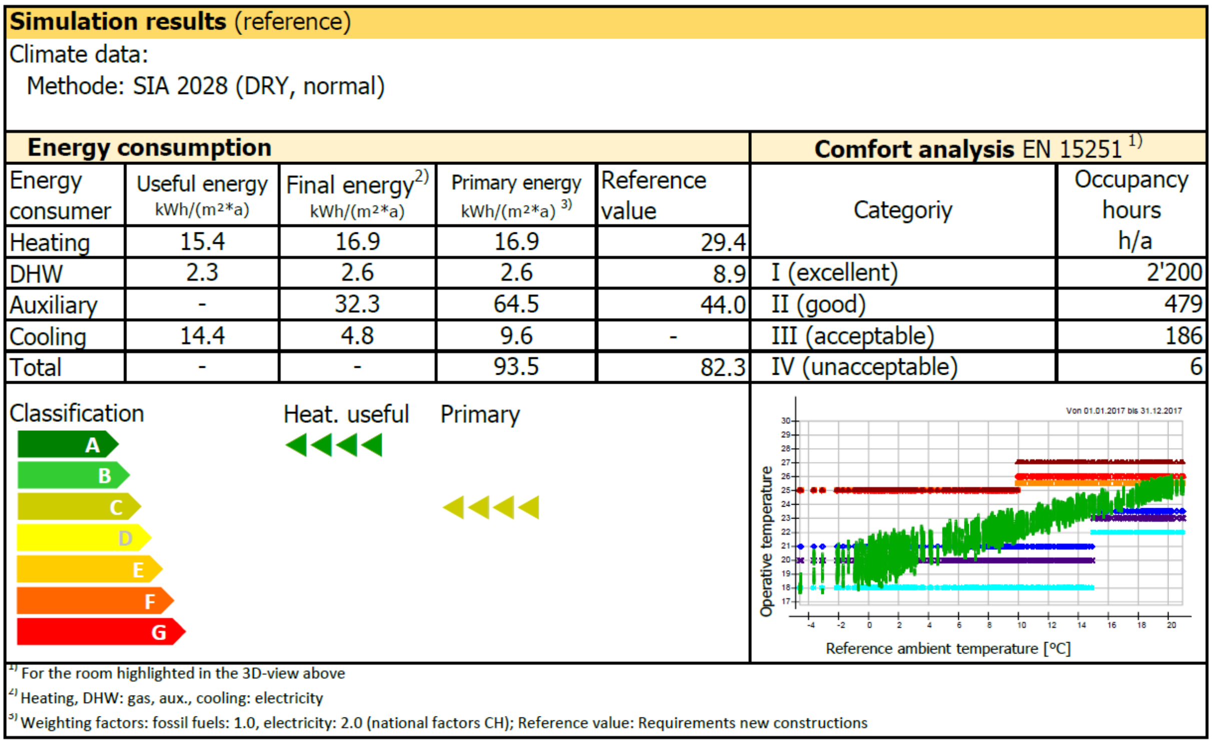
Element	U-Values W/m²*K	
	Current value	Requirement new constr.
External walls and floors	0.15	0.17
Roofs	0.15	0.17
Walls, slabs to ground or basement	0.20	0.25
Windows	1.10	1.00

Fig. 5: Characteristics of a current Swiss office building

After testing and validating the model by comparing the simulations results with real energy consumption data and other criteria, a series of simulation runs where performed, where the results using the standard TMY meteo data are considered as a reference scenario.

Figure 6 shows the simulation results using standard TMY meteo data:

- Energy consumption for space heating, domestic hot water, auxiliaries (Ventilation) and cooling
- Classification into energy efficiency categories by comparison with the national requirements for new constructions.
- Operative indoor temperature (in the highlighted zone) and the classification according EN-15251



Simulation results (reference)

Climate data:
Methode: SIA 2028 (DRY, normal)

Energy consumption

Energy consumer	Useful energy kWh/(m²*a)	Final energy 2) kWh/(m²*a)	Primary energy kWh/(m²*a) 3)	Reference value
Heating	15.4	16.9	16.9	29.4
DHW	2.3	2.6	2.6	8.9
Auxiliary	-	32.3	64.5	44.0
Cooling	14.4	4.8	9.6	-
Total	-	-	93.5	82.3

Comfort analysis EN 15251 1)

Categoriy	Occupancy hours h/a
I (excellent)	2'200
II (good)	479
III (acceptable)	186
IV (unacceptable)	6

Classification

Heat. useful

Primary

1) For the room highlighted in the 3D-view above

2) Heating, DHW: gas, aux., cooling: electricity

3) Weighting factors: fossil fuels: 1.0, electricity: 2.0 (national factors CH); Reference value: Requirements new constructions

Fig. 6: Simulation results for a typical Swiss office building with standard TMY meteo data.

The results from all the other simulation runs where then compared to the reference scenario. (Table 8)

Methode ***Criteria, Location***	***TMY official (normal)***	***MN 7.2***	***MN 7.3***	***TMY ERA-Interim***
Heating energy cons. useful				
Bern, Zollikofen	100.0%	89.6%	90.5%	90.6%
Bern, Bollwerk		79.1%	80.4%	88.1%
Bern, Von Roll		81.6%	83.2%	92.8%
Bern, Gaswerk		77.6%	78.8%	
Cooling energy cons. useful				
Bern, Zollikofen	100.0%	104.7%	104.1%	94.4%
Bern, Bollwerk		111.3%	112.0%	94.7%
Bern, Von Roll		110.3%	110.9%	93.5%
Bern, Gaswerk		118.4%	118.1%	
Thermal indoor comfort cat. I				
Bern, Zollikofen	100.0%	102.4%	107.4%	105.1%
Bern, Bollwerk		106.8%	93.8%	103.4%
Bern, Von Roll		104.9%	105.0%	101.9%
Bern, Gaswerk		100.3%	99.8%	

Tab. 8: Summary of a series of simulation results with relative difference to the reference scenario: Green figures: lower energy consumption / more occupancy hours in best comfort category, Red figures: higher energy consumption / less occupancy hours in best comfort category

Based on these results the following conclusions can be drawn:

- The use of urban climate data has a measurable impact on energy consumption and thermal indoor comfort.
- Currently, only results from Bern and Vienna have been analysed. For other cities in other climate regions, the results and conclusions can be very different.
- The differences in heating / cooling demand are up to ~15% in comparison to official TMY
- The differences within various urban locations are low: below 10%
- The differences are surprisingly low for buildings without air conditioning and cooling system. For the shown example of the office building it’s obvious, because it’s equipped with a cooling system

Relevance of urban climate effect on the Swiss building portfolio

Based on the simulation results obtained for different building models and statistical data concerning energy consumption and the Swiss building portfolio, the overall relevance of the urban climate effect can be estimated:

Due to urban climate, ...

- the energy consumption for space heating is 6 TWh/a lower than (hypothetical case) when all buildings would be exposed on rural climate conditions. (6.4% of overall consumption for space heating),
- the additional energy consumption for cooling is 480 GWh/a in comparison to a (hypothetical) case, where all buildings would be exposed on rural climate conditions. (6.0% of overall consumption for space cooling).

In the balance, the lower energy consumption for heating is much more important than the higher consumption for cooling. For Switzerland about 5.5 TWh are “saved” or 1.4 Mio tons of greenhouse gas emissions are not emitted. Of course, the GHG-figures are strongly influenced by the low carbon based Swiss energy mix (around 250 g CO2/kWh[2]).

5. Conclusions

This project showed that the use of urban meteo data has measurable impact on climate and therefore also on energy consumption and thermal indoor comfort. This simple fact might not be very surprisingly, but it is probably the first time that this aspect has been studied in a way to quantify the effect in high time and space resolution.

We understand this work also as a contribution to the actual discussion about the performance gap (difference between planned and real building performance). As long as the construction regulations requires the use of non-urban meteo data for the design process for buildings in urban areas, it is obvious, that there occurs a difference between planned and real energy consumption or/and indoor climate. Therefore, regulations should be modified at this point, where they define which meteo data must to be used for which location. For instance, this becomes relevant, when the planed yearly electricity consumption for air-conditioning has to be generated on-site (which is the already the case in some Swiss Cantons). The dimension of the PV-plant depends directly on the chosen meteo data for the simulation.

Up to now effects of future climate change hasn't been tested yet. This will be done during the next phase of the H2020 project.

6. References

Espinar, B., Ramírez, L., Drews, A., Beyer, H. G., Zarzalejo, L. F., Polo, J., & Martín, L., 2009. Analysis of different comparison parameters applied to solar radiation data from satellite and German radiometric stations. Solar Energy 83(1), 118–125. http://doi.org/10.1016/j.solener.2008.07.009

Remund, J., Müller, S.C., Kunz, S., Huguenin-Landl, B., Studer, C., Cattin, R., 2018. Meteonorm handbook. https://meteonorm.com/assets/downloads/mn73_software.pdf (last visited: November 27th 2018)

Wilcox, S, and Marion, W., 2008. “Users Manual for TMY3 Data Sets.” Technical Report. doi: NREL/TP-581-43156, https://www.nrel.gov/docs/fy08osti/43156.pdf (last visited: May 9th 2018)

Acknowledgements

Climate-fit.city is developed as part of the PUCS project, which has received funding from the European Union's H2020 Research and Innovation Programme under Grant Agreement No. 73004.