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Original research article

Building design in a changing climate – Future Swiss reference years for building simulations

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HIGHLIGHTS

- Future design reference years are created using climate change scenarios.
- Typical years as well as warm summers are generated for urban and extra-urban sites.
- The applied delta-change method was tailored to the requirements of the users.
- A case study applying the new data shows a substantial increase in cooling demand.
- The data set is publicly available as a climate service.

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ABSTRACT

With global climate change, temperatures in Switzerland are projected to rise in the coming decades, according to the national climate scenarios CH2018. Associated with the mean temperature increase, heatwaves are expected to become longer, more frequent, and more intense. The changing climate will affect the indoor climate as well as heating and cooling needs. In building design, these climatic changes have to be planned for today in order to ensure a comfortable indoor climate in the future.

In collaboration with practitioners, a reference climate data set for the future is created that specifically targets building designers and engineers. The data set consists of hourly weather data of one-year length based on the Swiss climate change scenarios CH2018. These future reference years are representative of two time periods in the future: one around 2030 and one around 2060. Climate change uncertainty is considered by using two emission scenarios (RCP2.6 and RCP8.5). Reference data for the future is provided not only for a typical year (called Design Reference Year, or DRY) but also for an above-average warm summer. The data is available at the sites of 45 measurement stations across Switzerland, including four stations inside major cities to take the urban heat island effect into account.

The generated climate data set is applied to a building model to provide an application example. The results point out that the cooling needs will substantially increase, which is why an adaptation of the building design to the changing climate is vital.

Practical implications

To optimize the building design and its services, basic climate information has to be available. For the current climate in Switzerland, such information was so far provided as reference years in a technical specification. Now, this technical specification is supplemented by climate data for the future in form of reference years based on climate change scenarios to adapt buildings' design to future climate conditions. The compiled data set comprises

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future reference years in form of hourly data for a total of 45 measurement stations across Switzerland. These stations mostly lie in rural areas (also called extra-urban areas – totally 41) with a few stations in urban areas (totally 4). The urban stations represent the well-known urban heat island effect in inner-city areas. The reference years for the future climate are based on the CH2018 Swiss climate change scenarios, which consider different assumptions for the future development of global greenhouse gas emissions (Fischer et al., 2022; CH2018, 2018; NCCS, 2018). With future scenarios all highlighting that summers in Switzerland will become warmer and heatwaves more extreme, it is evident that buildings in the future will have to be adapted to such climatic changes, and a future-oriented building design has to be adopted already today.

More technically, the following aspects were considered in the development of the future climate data for building simulations: Two future time periods i.e., one in the first half of the century (2020–2049) and one in the middle (2045–2074) together with a scenario including strong mitigation measures and another without. The reference years are created using a delta-change approach: observations are scaled into the future by using a climate-change signal – the delta – from the CH2018 scenarios. For each station, period, and emission scenario, a typical year is provided, the so-called Design Reference Year (DRY). This is complemented by a warm summer half year, the so-called "1 in 10" warm summer, representing summer conditions - with regard to temperature - as they are expected to be exceeded once every ten years. The purpose is to give building planners a possibility to explore the consequences of summer temperatures beyond average.

The produced data was used in building simulations designed to provide information for building planners. Besides evaluating the results of these building simulations in terms of the modeled indoor climate, this study evaluates the different methods of producing climate data (reference years) in terms of ambient climatological representativeness, and in terms of the modeled indoor climate. Both ways of evaluation create a high confidence in the generated data sets with respect of robustness and relevance.

At an international level, best practices on how to generate scenario data for building planers are currently missing. The presented study and methodology add to such an exchange by presenting the full methodological cycle to calculate typical hourly weather data for the future. This methodological chain could in principle be adopted to other regions of the Globe and might in the end support the formulation of best practices, as is currently discussed in the formulation of an ISO standard.

1. Introduction

Global surface temperature is projected to further rise during the 21st century (IPCC, 2021). This demands for adaptation strategies throughout all sectors to cope with recent and projected future climate changes in order to minimize ecological, economical and health risks. For Switzerland, the rising temperatures will be associated with more frequent, more intense and longer-lasting heatwaves in summer and milder winters, as is shown in the current climate scenarios for Switzerland, CH2018 (CH2018, 2018). These changes in ambient climate will also influence temperatures inside buildings. As people spend most of the time inside buildings, ensuring a comfortable indoor climate is a critical aspect of building design. Building structures are usually designed to last for 30–50 years before a refurbishment or renovation. During this lifetime, the installed heating and cooling systems are typically replaced only once. Hence, climatic changes of the years to come have to be considered in building design already today. In addition, the building sector is a major contributor to the national greenhouse gas emissions in Switzerland, accounting for approximately one third of the country's carbon dioxide emissions and 40 % of its total energy demand (SFOE, 2023). Therefore, a future-oriented and energy-efficient design of buildings is also of major importance for climate change mitigation.

Even if strong mitigation measures are put into place globally, summertime temperatures are projected to increase by an additional 0.9 °C to 2.5 °C by mid-century in comparison to the 1981–2010 mean climate in Switzerland. Without mitigation measures, the rise in Swiss summer temperatures would be even up to 4.4 °C (CH2018, 2018). A previous study (Settembrini et al., 2017), based on the predecessor climate scenarios CH2011 (CH2011, 2011), showed that with rising temperatures (considering a high emission scenario with balanced use of available energy sources), the heating demand from buildings is expected to decline by 20–30 % by 2060, whereas cooling demands will substantially increase. This trend is qualitatively seen globally (Ciancio et al., 2020; Deroubaix et al., 2021) although huge uncertainties remain especially on the future cooling demand. National efforts are taken to provide users with reliable information for planning in many places such as Belgium (Doutreloup et al., 2022), Finland (Jylhä et al., 2015), the United States (Shen, 2017), Taiwan (Huang and Hwang, 2016) and the United Kingdom (Liu et al., 2020) among others.

To adapt to future climate changes and design buildings optimally, climate projections tailored to the needs of building planners are necessary. Building simulations generally require meteorological input data with hourly resolution, encompassing multiple physically consistent climate variables. In order to keep computational and analytical workload at a feasible level for building planners, the data has to be condensed into one year. For the current climate, so-called "reference years" fulfill the mentioned criteria. The design reference years (DRY) for the current climate of Switzerland are documented and made available with the technical specifications SIA 2028:2010. These are based on an international standard procedure described in ISO 15927-4:2005. In Switzerland, the European norm (EN) is adopted in the Swiss norm (SN), hence the current national standard is called SN EN ISO 15927–4:2005. This standard is currently re-assessed at the national and international level to consider reference years for a future climate. The present work is carried out to exemplify a methodological framework to create future reference years and to provide such reference years consistent with the climate scenarios CH2018 to building planers in Switzerland. The stakeholders accompanying this study deliberately requested that the uncertainty of the resulting future climate data be limited to a small number of reference years analogous to the DRYs for the current climate.

The goals of this study are threefold: first, to derive hourly data for the future climate (also called future reference years). Therefore, the most suitable method is selected from a pool of available ones following a thorough evaluation. Second, the chosen procedure is adapted to represent future heatwaves. Third, the urban heat island (UHI) effect is considered by adapting the method to urban stations The latter is important, since buildings are mostly built in populated areas that are subject to urban climate effects.

This work presents and evaluates the developed procedure to generate reference years for the Swiss building sector under consideration of climate change. Using these data for dynamic building simulations, a case study puts the results into context at the example of a typical modern office building.

2. Data

In this study, the hourly climate data from 41 SwissMetNet stations, i.e., stations from the automatic measurement network maintained by MeteoSwiss, plus 4 additional urban stations, are used (Fig. 1, see Table A1 for more information on location and names of the stations). The SwissMetNet stations are located in extra-urban areas and are operated according to the standards of the World Meteorological Organization. The four stations operated in urban areas are used to

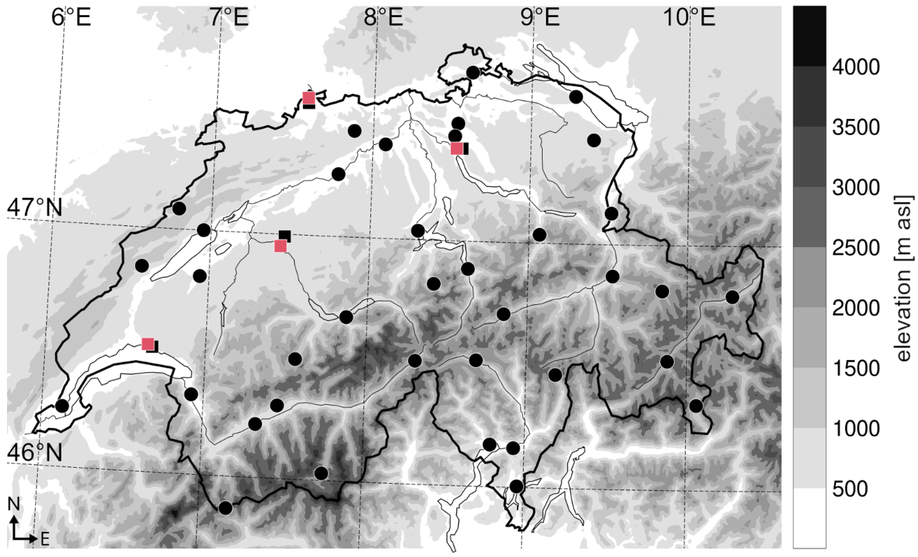

Fig. 1. Map of Switzerland with the location of the 45 stations used in this study. Urban stations are indicated by red squares and the corresponding extra-urban paired stations are indicated by black squares. The remaining extra-urban stations are indicated by black dots. The thick black line shows the border of Switzerland and thin black lines show rivers and outlines of lakes. The grey shadings show the topography of the study region in meters above mean sea level.

represent conditions within densely built areas (red squares in Fig. 1). The data from the urban stations were provided by the Department of Environmental Sciences of the University of Basel (station at Basel-Klingelbergstrasse BKLI) and by the National Air Pollution Monitoring Network (NABEL; stations at Zürich-Kaserne NABZUE, Bern-Bollwerk NABBER, Lausanne-César-Roux NABLAU).

The variables retrieved are 2-meter air temperature (°C), relative humidity (%), wind speed (m s^{-1}), wind direction (degrees), wind gust speed (m s^{-1}), cloud cover (Octas) and global radiation (W m^{-2}). Except for cloud cover and wind gust speed, hourly averages are used. Hourly averages are computed from measurements aggregated at 10-minute resolution by averaging over x-10 to x+40 for the hour x. For wind gusts, the hourly maximum of one-second gusts between x and 10 and x+40 is reported and for cloud cover three observations (taken always at x+40 with x being 06, 12 and 18 UTC) are linearly interpolated to hourly values. Cloud cover observations are reported in Octas and converted to percentage values. Using the Perez model (Perez et al., 1992, 1991), the diffuse radiation and direct normal radiation are deduced from the global radiation.

2.1. Climate scenarios CH2018

CH2018 is the latest generation of national climate scenarios for Switzerland (Fischer et al., 2022; CH2018, 2018). It presents projections for the future climate in Switzerland based on state-of-the-art global and regional climate models and using three alternative greenhouse gas scenarios (Representative Concentration Pathways; RCPs). They encompass a scenario with strong emission reductions, compliant with the 2 °C warming target defined in the Paris Agreement (RCP2.6), a high emission scenario that assumes no efforts to curb emissions until the end of the century (RCP8.5) and a scenario in-between that assumes stabilization of radiative forcing in the second half of the century (RCP4.5). The numbers of the RCPs indicate the level of the radiative forcing reached by the end of the century in W m^{-2}. The CH2018 scenarios are available for 1981–2099 and assess three future periods: 2020–2049, 2045–2074 and 2070–2099 against the historical reference period 1981–2010. In this work, we only consider the near future 2020–2049 and the mid-term future 2045–2074, which for simplicity are denoted by the central years, “2035” and “2060”, respectively. Also, the low and high emission scenarios are considered, but not RCP4.5, which is consistent with the Swiss adaptation strategy, helps to distill the information and capture the range of projected future climates in CH2018.

The CH2018 climate scenarios are based on an ensemble of regional climate model simulations provided by the Coordinated Regional Climate Downscaling Experiment for the European domain (EURO-CORDEX; Jacob et al., 2020, 2014). The output of the EURO-CORDEX regional climate models has a horizontal resolution of 12 km or 50 km, which is too coarse for local climate impact assessments. Further, the models partly show substantial biases, especially over the complex topography of Switzerland. Therefore, the EURO-CORDEX simulations were bias-corrected and downscaled using quantile mapping (QM) within CH2018 (Feigenwinter et al., 2018; Ivanov and Kotlarski, 2017; Rajczak et al., 2016). QM corrects the distributions of simulated climate variables by comparing raw model output against respective observational data in a historical period. For this purpose, CH2018 used station data and gridded observations to derive projections for the station network of Switzerland and for a 2 km grid. For the project presented here, we use the quantile-mapped station projections that are provided under the name “DAILY-LOCAL”. Note that there is a different number of model projections for each RCP, due to the number of EURO-CORDEX simulations available (see the CH2018 report for more details).

From CH2018, there is no scenario information for urban areas. Therefore, the bias-corrected station projections at the extra-urban locations are spatially transferred using observations from the corresponding urban stations and employing a second QM step as in Burgstall et al. (2021). For the QM the R-package qmCH2018[1] is used. The correction function for the QM is calibrated using the common observational period for both stations (urban and extra-urban). This correction function is then applied to the extra-urban CH2018 scenarios in order to transfer them to the inner-city locations. Wind as well as the radiation variables are not transferred because measurements at urban stations are highly influenced by the specific local conditions and may not represent a general urban effect. Furthermore, no cloud cover observations exist for urban stations and they are therefore taken from the extra-urban stations, if available.

[1] qmCH2018 v1.0.1, https://doi.org/10.5281/zenodo.3275571, https://github.com/SvenKotlarski/qmCH2018.

3. Methods

We introduce different methods and selection criteria to choose reference years (Section 3.1) and to generate hourly data for the future at extra-urban (Section 3.2) and urban locations (Section 3.3). Further, in Section 3.4, we describe in detail the methods to be evaluated later in Section 4.1.

3.1. Generation of reference years

Reference years (also called typical meteorological years) are used to represent the typical climatological conditions for a certain location. Usually, one year with hourly data shall represent the climate of a longer time period (usually a 20- to 30-year climatology) with reasonable accuracy. Therefore, segments from different years are assembled to form a one-year-long time series. Different statistics can be used to identify representative segments. For example, the mean and standard deviation of different segments can be matched to the climatology. In the following, we will describe another statistical method that is commonly used to select reference years.

3.1.1. Finkelstein-Schafer statistic

Finkelstein and Schafer (1971) describe a goodness-of-fit test for small sample sizes akin to the Kolmogorov-Smirnov test (e.g., Darling, 1957; Kolmogoroff, 1941; Lilliefors, 1969; Walsh, 1963). The Kolmogorov-Smirnov test compares a sample with a reference probability distribution or two samples with each other (in case of an unknown probability distribution function). Therefore, the differences between the cumulative distribution functions (CDFs) are computed along all x values. The Kolmogorov-Smirnov test then uses the largest absolute difference as the statistic. In contrast, the Finkelstein-Schafer statistic (FS from now) sums all absolute differences. The FS value is hence determined as:

$$FS = \sum_{i=1}^{n} \delta_i$$

For a sample size n and with δ_i corresponding to the absolute difference between the CDFs. The closer the two CDFs, the smaller the FS value.

The FS statistic is widely used to select reference years (e.g., Andersen et al., 1986; Doutreloup et al., 2022; Kalamees et al., 2012; Petrakis et al., 1998; Zang et al., 2012). It is also basis to the current reference years for Switzerland SIA 2028:2010 as well as in the technical standard ISO 15927–4:2005. In this context, the sample corresponds to daily values from one month from a chosen year and the reference distribution is given by daily values from all years for the selected month-of-the-year and for a specific location. This is illustrated in Fig. 2 for temperature for the month of August for the 1981–2010 time period (black) at the station of Zurich-Kloten (KLO) with specific years (samples) shown by the coloured dots. From Fig. 2 it can be seen that for the 1981–2010 time period, 2003 had a very warm August (all of the red dots are located to the right of the black curve, indicating hotter-than-normal daily temperatures) while 2006 experienced a relatively cold August (blue dots located on the left side of the black curve, indicating colder-than-normal daily temperatures). August in the years of 1990 and 2004 was average or normal for the time period, indicated by dots closely aligned with the black curve.

The FS value can be determined for only one variable at a time. The ISO 15927–4:2005 standard expands the method to select a reference year where the FS value is computed for three variables separately – air temperature, solar radiation and relative humidity. The months are then ranked according to the FS value of each variable. The sum of the ranks is determined, giving equal weight to the ranks from each variable. Among the three months with the lowest rank sum, the one with the most representative wind speed is chosen to the reference year. Running weighted means are used on the first and last 8 h of each month to smooth the transitions. The procedure suggested in ISO 15927–4:2005 has been adopted and adjusted to fit the purpose for different national reference years. The Swiss reference years SIA 2028:2010 use equal weighting for air temperature, solar radiation and relative humidity. However, to select one month out of the three months with the lowest rank sum the daily maximum (Tmax) and minimum temperatures (Tmin) are evaluated, choosing the month where the larger of the two differences (with respect to the climatology) is smallest.

3.1.2. Additional selection criteria to represent the future climate

For this study, additional selection criteria based on climate indicators are defined to serve the user's request that reference years shall represent future heatwaves and tropical nights with better accuracy. The set of additional indicators (and combinations of indicators) chosen here is:

a) Length of hot spells (continuous period with Tmax $\geq$ 30 °C)
b) Length of hot spells (continuous period with Tmax $\geq$ 30 °C) and number of tropical nights (Tmin $\geq$ 20 °C)

Option (a) is chosen for extra-urban stations, and option (b) for urban stations, as tropical nights occur more often in densely built areas. Criteria using only tropical nights and using the number of hot spells are found to result in a worse overall performance (not shown here). The additional criteria are not evaluated using the FS statistic but by computing the expected value from a 30-year time period in the future for each model simulation separately (and per RCP). The median over these n expected values is taken and used to select reference years (with n = number of model simulations).

3.2. Generation of future hourly data and selection of reference years for extra-urban stations

In the following, methods are introduced to generate hourly future data. As the CH2018 localized data is provided at daily granularity only, hourly data for the future needs to be created first. In a second step, the reference year that matches best the target climatology can be selected.

3.2.1. Delta-change approach

To create future reference years with the delta-change method, a climate change signal is first computed by comparing simulated climate in a historical time period and a future period, each spanning approximately 20–30 years. This minimizes uncertainties stemming from internal climate variability, while not being too much affected by trends. Here, deltas are computed for 2020–2049 or 2045–2074 with respect to the reference period 1981–2010, based on the available local CH2018 scenarios for each emission scenario separately. Depending on the variable, an additive (temperature) or multiplicative (radiation, relative humidity) delta is computed as the daily difference between the climatologies of the two periods. Daily delta values are smoothed by computing the seasonal values and using splines to calculate 365 homogenization values, such that the mean of the homogenized daily deltas corresponds to the original seasonal value. No delta is computed for wind and cloud cover due to the absence of a clear climate change signal in the CH2018 scenarios for these variables (CH2018, 2018).

The computed delta (left grey box in Fig. 3) is then applied to the observations to produce so-called scaled or future "observations" (light green box in Fig. 3) in hourly granularity.

Once hourly future observations are generated, a reference year is drawn from the multi-dimensional space spanned by n model simulations × 30 years (where n = 8 in Fig. 3). The aim is to select monthly segments (always one complete calendar month) that optimally represent a typical year as simulated by the climate models (target values; see right grey box in Fig. 3). The target values are computed per model simulation by using the FS statistic (see Section 3.1.1 and upper grey arrow saying "Finkelstein-Schafer" in Fig. 3) and considering the three

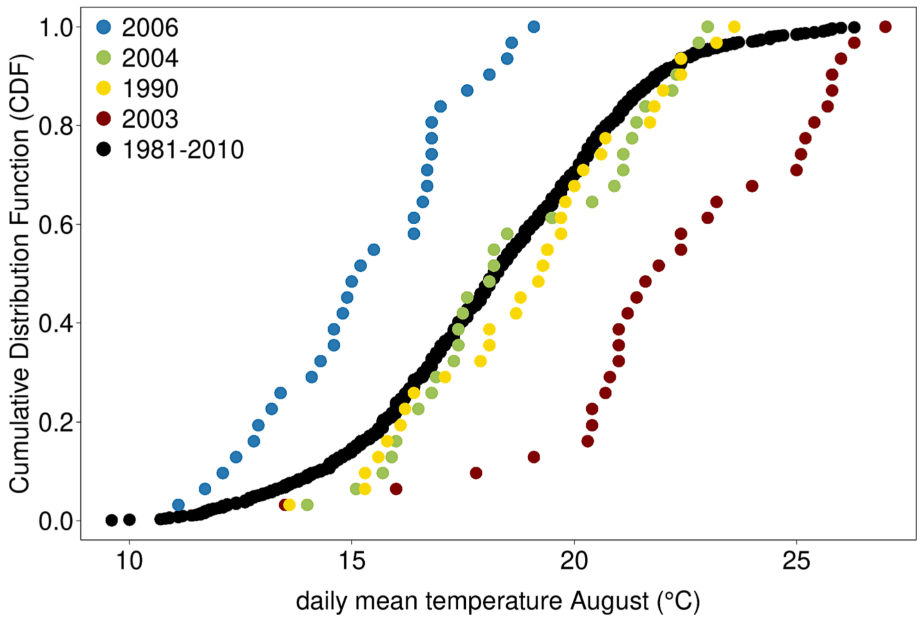

Fig. 2. Illustrative example of the Finkelstein-Schafer statistic showing the selection of the August month for the reference year for the station KLO from the 1981–2010 time series based on the cumulative distribution function of daily mean temperature.

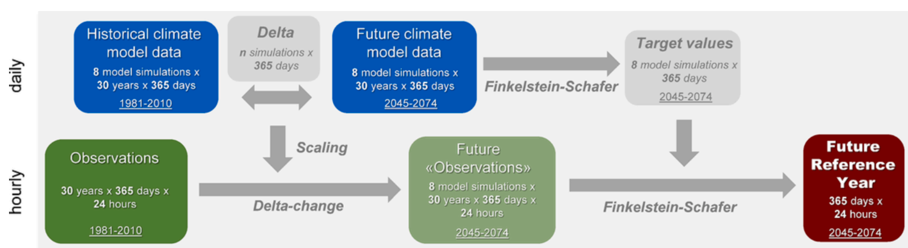

Fig. 3. Schematic for the delta-change method to create future reference years (at a specific station) at the example of the RCP2.6 emission scenario, for which 8 model simulations are available, and one future period (2045–2074). The climate model data (blue boxes) is taken from the DAILY-LOCAL simulations from CH2018. Delta (left grey box) represents the transfer between the historical time period (1981–2010) and the future time period. The future climate model data from CH2018 is used two times during the process: a) to compute the delta and b) to derive the target values (right grey box) that are to be represented by the future reference year. Note that the whole procedure is carried out for each of the variables temperature, relative humidity, and global radiation separately, before the future reference year is drawn based on the Finkelstein-Schafer values, as described in Section 3.1.1.

main selection variables: temperature, relative humidity and global radiation. The scaled observations are now compared to the target values month-by-month and ranked for each of the three selection variables using the FS statistic again (lower grey arrow saying "Finkelstein-Schafer" in Fig. 3). The future reference year is determined using the five months with the lowest rank sum and comparing their Tmax and Tmin to the scenarios, analogously to the generation of the historical Swiss reference years in Section 3.1.1.

The chosen month is a combination of the observed month from a specific year and the delta from a specific model chain used for the scaling (e.g., January in the chosen reference year can originate from the year 2000 scaled to the 2045–2074 time period with a delta based on model *x*). Note that a chosen month may not be the best available representation of one variable, e.g., temperature, if it in turn captures the other variables effectively.

"1 in 10" warm summer

Using FS and the delta-change approach, also reference years with a given rare occurrence can be determined. The "1 in 10" warm summer reference year represents conditions that are only exceeded once in ten years in the target period. To avoid splitting heatwaves, which can often span from one month to the next, a consecutive summer half-year is selected based on the generation of the DRY in Fig. 3. The target distribution is determined for the daily temperatures of the summer months (June, July and August; JJA in the following). Therefore, summer temperatures from each year are ranked using FS. This is done for each model chain separately, and the summers ranked 27th (the 4th warmest) are used to constitute the target distribution. Then, the scaled observations are ranked according to the closeness of their daily summer temperature distributions to the target (using FS again). The summer half-year from April 16th to October 15th is selected, and to complete the calendar year, the winter half year is taken from the corresponding DRY. Transitions between the DRY and the chosen summer half year are smoothed over the first and last eight hours using running weighted means.

3.2.2. *Analog approaches*

Analog methods do not require generating hourly future observations. Instead, the future reference year is directly assembled from observed episodes. Two analog methods are compared: one based on the method for test reference years (TRY[2]) for the future by the German Weather Service (DWD), and another, similar to the delta-change method but without scaling the observations.

[2] Test reference years 2017: https://www.dwd.de/DE/leistungen/testreferenzjahre/testreferenzjahre.html.

The TRY-based analog method uses 10–30 day weather episodes, adapting the method used by the DWD for Swiss stations. A climatology (365 days) is computed per emission scenario and future time horizon from all CH2018 scenario realizations. For future reference years, the method solely depends on temperature, selecting episodes from observations that represent the future temperature climatology as accurately as possible. The observational time period is extended to 1981–2019 to include more years (including remarkably warm years, e.g., 2015, 2018 and 2019) to choose from. The most representative periods are selected by minimizing the difference in the mean and standard deviation of the observed segments and the climatology. The differences are weighted 70 % for the mean and 30 % for the standard deviation. Different episodes lengths are evaluated to find the optimal segment. The reference year is then assembled from the chosen segments and transitions are smoothed over the first and last 5 h of each segment.

The second analog method uses the FS statistic to select monthly segments directly from observations without prior scaling. Similar to the delta-change method, the selection is based on temperature, relative humidity and global radiation, with the target data set consisting of all years from all model chains.

3.3. Reference years for urban stations using delta-change

Densely built city centers show local wind variations (due to channeling effects and higher roughness length) and radiation patterns (due to shading) as well as elevated temperatures due to the UHI effect (Oke et al., 2017). Especially during the nighttime and in summer, the UHI leads to higher temperatures in city centers compared to extra-urban areas (e.g., Fenner et al., 2014; Gehrig et al., 2018; Oke et al., 1991). To account for the UHI effect, reference years for four major Swiss cities, with sufficiently long observational records, are created using the delta-change approach. Therefore, urban – extra-urban station pairs are determined (NABBER – BER, NABLAU – PUY, BKLI – BAS and NABZUE – SMA; see Table A1 for station information). Similar to the extra-urban stations, reference years are selected using the delta-change method (see Section 3.2.1). Note however, that the reference period differs from 1981 to 2010 due to data availability (see Table A1). The delta is computed for the paired extra-urban station, assuming that the climate change signal is also valid for the urban station. Then the delta is applied to the urban measurements, except for radiation where we take the extra-urban measurements (as explained in Section 2.1). For urban stations, the target values are determined from the urban scenarios (except for radiation). Then the reference year is selected using FS. Since the radiation and wind effects are changing very locally, they are taken from the extra-urban station, and local effects are expected to be taken into account by the building models applying the data. An overview of where the variables in the reference year originate from for the urban and extra-urban reference years is given in Table 1.

3.4. Evaluation of methods

In order to evaluate the reference years and compare them to each other, mean errors are computed. Therefore, differences are taken between the monthly averages of the reference years and the monthly averages over the 30-year climatologies from the scenarios (or the observations for the historical reference years). The monthly differences are computed for each station separately and for the three variables temperature, relative humidity and global radiation. For the scenarios, the monthly averages are computed separately and the first (Q1) and third quartile (Q3) over all projections are determined. If the monthly average from the reference year lies within the interquartile range (IQR) from the scenarios, the difference is zero and if it lies outside the difference to Q1 or Q3 is computed. The bias is calculated taking the average over the monthly differences (hence, over one year) and used to determine the best method. The following methods are compared to each other:

1. Delta-change approach using equal weight on temperature, relative humidity and global radiation to select monthly segments. FS (see Section 3.1.1) is used to rank months from the scaled observations for each variable separately and the chosen month is determined based on the rank-sum (see Section 3.2.1). The so-generated typical future reference year will be called DRY-Delta-Change for the comparison.
2. Analog method using FS (see Section 3.1.1) to rank months from the observations and giving equal weight on temperature, relative humidity and global radiation to select monthly segments (see Section 3.2.2). Differs from DRY-Delta-Change by using observations directly (no scaling with a delta) and will be called DRY-Analog in the following.
3. Analog method using mean and standard deviation to select segments with variable length from the observations. Only temperature is used as selection variable and the weighting is 70 % for the mean and 30 % for the standard deviation (see Section 3.2.2). The generated reference year will be called TRY-Analog in the following.

4. Results

4.1. Validation and choice of method

The methods to generate hourly future reference years are evaluated based on how well the three main variables of interest, temperature, relative humidity and global radiation, are represented in the selected reference years. The evaluation is carried out at extra-urban stations for typical reference years and the emission scenarios RCP2.6 and RCP8.5. In Fig. 4, the bias of the historical reference years for Switzerland, based on the technical specifications SIA 2028:2010, is shown in order to put the bias of the future reference years in relation. Note however, that the bias for SIA 2028:2010 is determined from the observations as the deviations from the 1984–2003 climatology, which is the same time period that was used to create the historical reference years. The TRY-Analog method for future reference years results in the smallest bias for temperature, but also the largest biases for relative humidity and global radiation, particularly for RCP8.5. This is due to the fact that TRY-Analog – by purpose – is only tuned to represent future temperatures well. The DRY-Delta-Change method exhibits the smallest biases for relative humidity and global radiation. For temperature, a small negative bias can be found – especially for RCP2.6 – which is, however, within the range of the bias of the historical reference years. The DRY-Analog method shows overall positive biases for global radiation and negative biases for temperature, especially for RCP8.5 and the later time

Table 1
Overview of variables in the reference year. OBS refers to observations and DELTA to the delta-change scaling factor that is added to (+) or multiplied with (×) the observations. The lowercase suffix indicates whether the urban ($_u$) or extra-urban($_{ext\text{-}u}$) scenario or observation is used.

Variable Location	Temperature	Relative Humidity	Radiation	Wind	Cloud Cover
Extra-urban	$OBS_{ext\text{-}u} + DELTA_{ext\text{-}u}$	$OBS_{ext\text{-}u} \times DELTA_{ext\text{-}u}$	$OBS_{ext\text{-}u} \times DELTA_{ext\text{-}u}$	$OBS_{ext\text{-}u}$	$OBS_{ext\text{-}u}$
Urban	$OBS_u + DELTA_{ext\text{-}u}$	$OBS_u \times DELTA_{ext\text{-}u}$	$OBS_{ext\text{-}u} \times DELTA_{ext\text{-}u}$	$OBS_{ext\text{-}u}$	$OBS_{ext\text{-}u}$

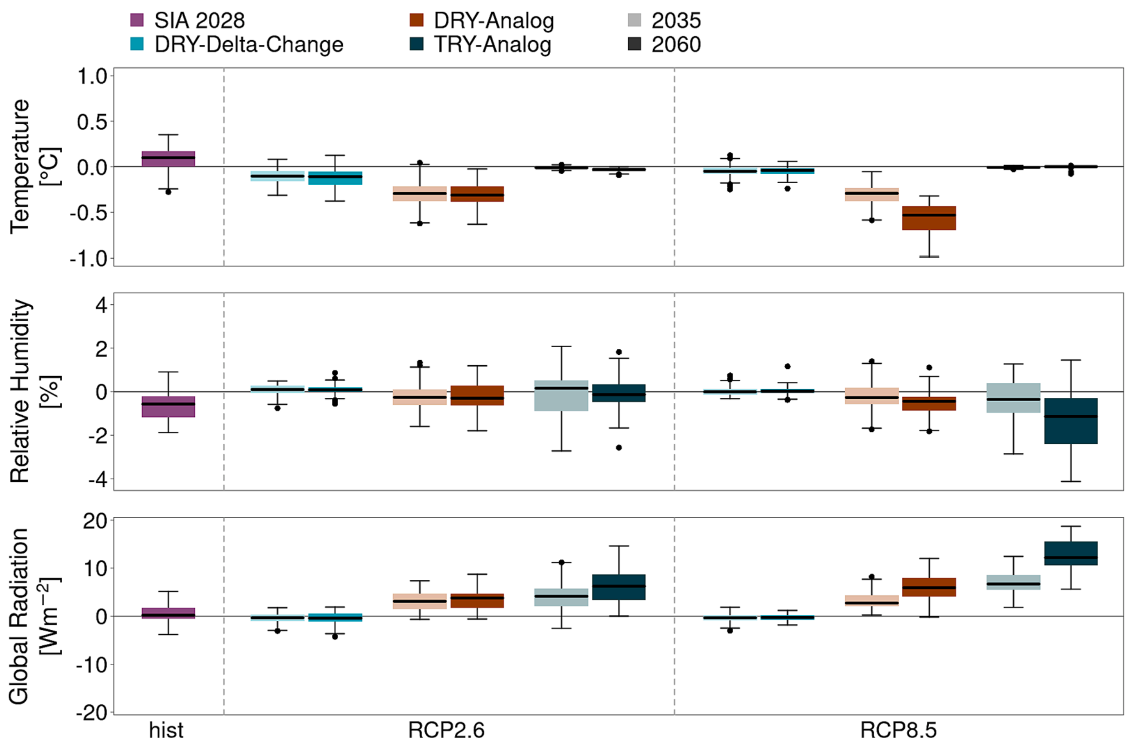

Fig. 4. Bias for the historical reference years ("hist") and for the different methods to create reference years for the future at individual extra-urban stations (40 stations in total for the historical reference years according to SIA 2028:2010, denoted by "SIA 2028", and 41 stations for the future reference years). Bars show the median, Q1 and Q3, and the whiskers indicate the Q3 + 1.5×IQR and Q1 − 1.5×IQR values (or the min and max values, whichever is smaller). Outliers are indicated by dots. Results for the reference years for the 2035 time period are shown in lighter shading and for the 2060 time period in darker shading.

horizon. This illustrates that the analog methods have difficulties finding suitable analogs for climates that are far from observed (e.g., 2060 with RCP8.5).

Based on the results in Fig. 4, DRY-Delta-Change is selected as the preferred method to generate reference years for the future. In order to better represent heatwaves and tropical nights, different variants of the delta change method are tested. To implement the additional selection criteria (see Section 3.1.2), the scaled observations are ranked according to the closeness to the median of the expected values over all model simulation. The expected values are computed as the mean (or the 90th percentile for the "1 in 10" warm summer) over 30 years for each model simulation separately. The selection of months in the final method is based on the main variables as well as the additional selection criteria by giving equal weights to temperature, relative humidity, global radiation and the length of hot spells for extra-urban stations. For urban stations, the ranking according to the length of hot spells and the number of tropical nights is each given 50 % weight, resulting in the total weight given to the two additional selection criteria being again equal to the

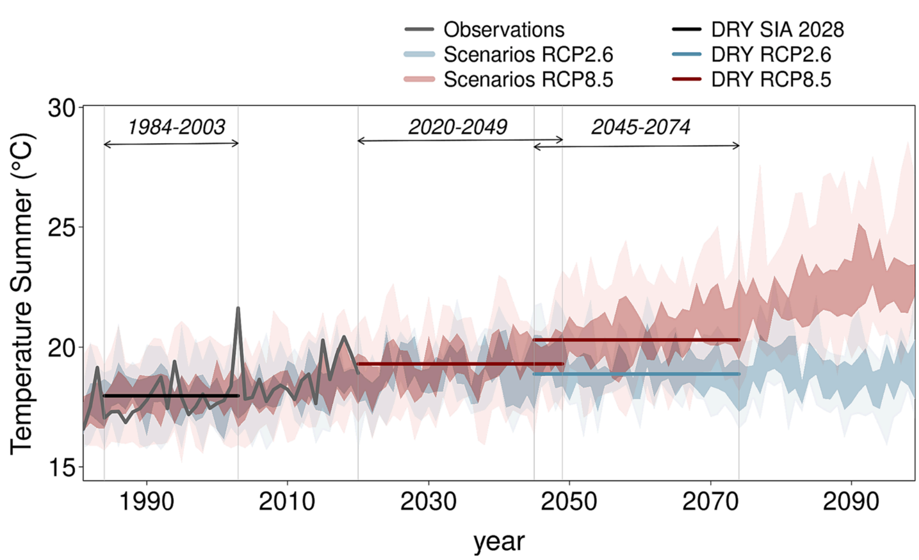

Fig. 5. Summer mean temperatures (JJA) for the years 1981–2099 at the station KLO in the extra-urban area of Zurich (see Table A1). Shading shows the full range (light shading) and 25th-75th percentile (darker shading) of the scenarios for KLO with RCP2.6 shown in blue and RCP8.5 in red. The dark grey line shows the observations from 1981 to 2020 at the station KLO. The black horizontal line shows the historical reference year for KLO, which is representative of the 1984–2003 time period. The blue and red horizontal lines show the selected future reference years for RCP2.6 and RCP8.5, respectively.

weight of one of the three main variables. The same selection criteria apply to the “1 in 10” warm summer. In the following, the results for the chosen final method are presented for the typical reference years (called DRY from now on) and for the “1 in 10” warm summer reference years.

4.2. Evaluation of reference years

Using the additional selection criteria from Section 3.1.2 to form future reference years results in similar climatological biases as shown for DRY-Delta-Change in Fig. 4, however in a better representation of hot periods (not shown). In Fig. 5, the average summer (JJA) temperature of the DRYs for the KLO station (located at Zurich Airport, see Table A1) is compared to the multi-model projections of CH2018 alongside the historical DRY and the observations for the same station. The mean summer temperatures for the future reference years fall within the IQR of the scenarios (darker shading in Fig. 5), demonstrating that the DRYs represent well the typical conditions projected in CH2018. It can also be seen that in the near-term future the emission scenarios do not differ a lot and the chosen RCP8.5 DRY could also represent the conditions of a lower emission scenario (RCP2.6) and vice versa. This holds not only for the KLO station but also for the other stations in Switzerland (not shown). Lastly, Fig. 5 also visualizes that since there is a warming trend within RCP8.5, the DRYs are on the higher side for the temperatures at the beginning of the chosen 30-year time period and at the lower side compared to the conditions toward the end.

In the following, the bias of the DRYs and “1 in 10” warm summer reference years with respect to a selection of climate indicators is shown. The bias is computed as the deviation from the Q1, resp. Q3 of the projected values from the CH2018 model chains. Note that the error statistics compute the biases over the whole year. Overall, the bias of the reference years is small with the median bias being close to zero, except for an underestimation of the hot spell lengths in the DRYs (Fig. 6). This can be attributed to the DRYs selecting monthly segments from different years, whereas the evaluation considers entire years, allowing hot spells to persist across months. Notably, the “1 in 10” addresses this point, which is why the performance is better.

It is noteworthy that while average errors over all stations are small, individual stations may experience large errors. This is because the reference years are selected from individual months and years with unique and random realizations of weather, which can never represent all aspects of a 30-year climatology. Addressing this issue would require longer reference data (e.g., 30 years), demanding more computation time for building simulations. Alternatively, the reference years would have to be selected manually for each individual station. Both approaches contradict the intention of reference years being one year based on a standardized procedure.

4.3. Comparison of urban and extra-urban reference years

Computing the number of events for a selection of climate indicators for the future reference years shows a general warming trend for later time periods and/or higher RCPs (Fig. 7 for the example of Zurich). Comparing an urban (NABZUE) and an extra-urban (KLO) site in Zurich reveals a substantial increase in the number of threshold exceedances for

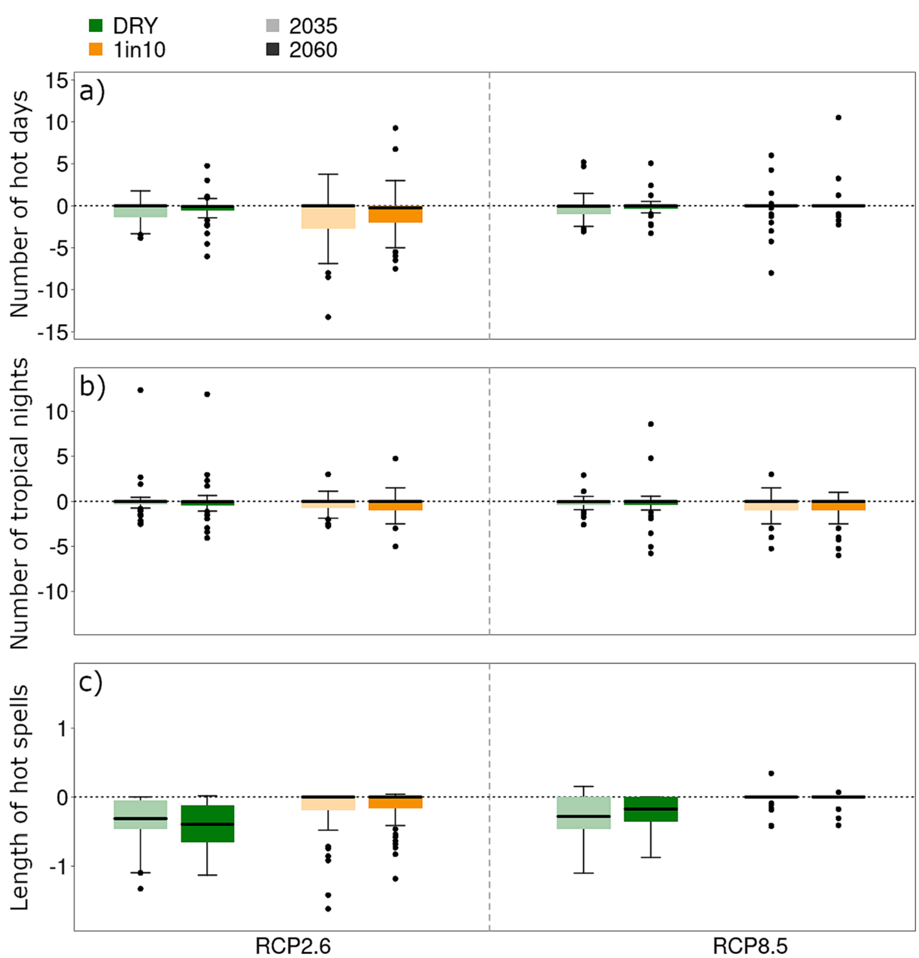

Fig. 6. Bias for the typical reference year (DRY, green) and the “1 in 10” warm summer reference year (1in10, orange) for the indicators a) number of hot days (Tmax ≥ 30 °C), b) number of tropical nights (Tmin ≥ 20 °C) and c) length of hot spells (continuous period with Tmax ≥ 30 °C). All 45 stations (41 extra-urban and 4 urban) are shown. Results for the reference years for the 2035 time period are shown in lighter shading and for the 2060 time period in darker shading.

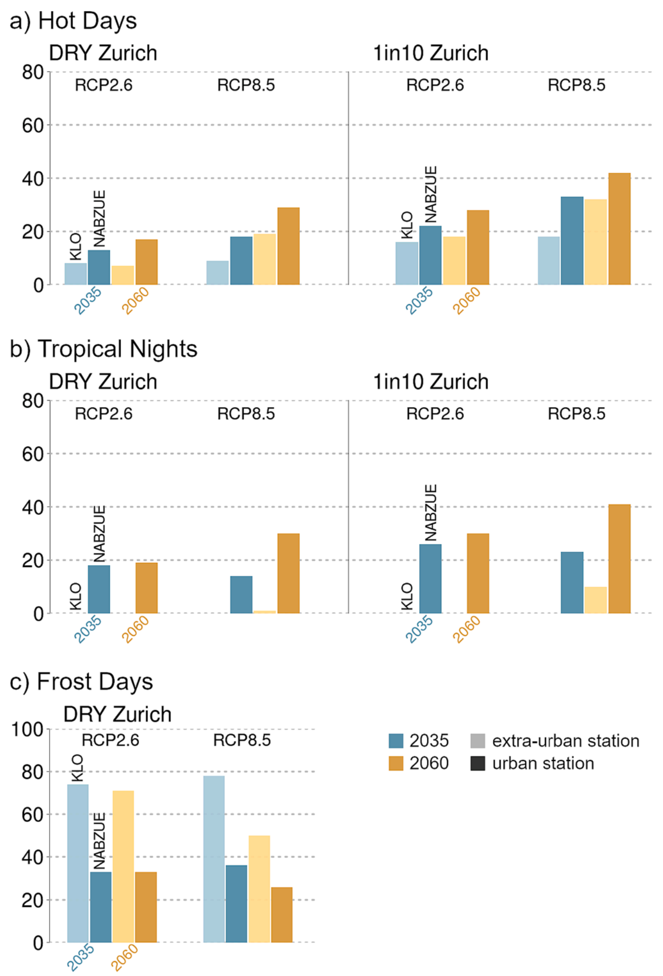

Fig. 7. Number of (a) hot days, (b) tropical nights and (c) frost days in the reference years for the two future time periods 2035 (blue) and 2060 (orange) and two RCPs. The extra-urban site, KLO, is shown in lighter colors and the urban site, NABZUE, in darker colors. The DRY is shown to the left and the "1 in 10" warm summer reference year (1in10) to the right. For frost days, only the DRY is shown since the winter months in the "1 in 10" warm summer reference year are the same as in the DRY.

the heat indices (hot days with Tmax $\geq$ 30 °C and tropical nights with Tmin $\geq$ 20 °C) at the urban site. Simultaneously, there is a decrease for the number of frost days (Tmin $\leq$ 0 °C) for all emission scenarios and time horizons. Tropical nights are projected to remain seldom at the extra-urban site, whereas at the urban site they occur more frequently already for RCP2.6 and the near future. This emphasizes the importance of considering urban stations for a comprehensive understanding of future climate conditions for building purposes. Note that only one reference year is considered here in contrast to Burgstall et al. (2021) who did a similar comparison between urban and extra-urban sites for 30-year periods.

4.4. Case study: Application in building simulations

In order to verify the plausibility and applicability of the generated reference years, they are used to simulate an office building by means of the dynamic building simulation software IDA-ICE[3]. IDA-ICE calculates the energy consumption and indoor comfort variables (air temperature, operative temperature, humidity and CO_2 concentration among others) over time in the defined zones. Therefore, the dynamic interaction between building, climate, building services and users are considered. The simulations are post-processed to evaluate the selected variables, such as energy consumption and thermal indoor comfort.

The focus of the simulations is on the mid-term future (2060) and the two emission scenarios RCP2.6 and RCP8.5. Both, the DRY and the "1 in 10" warm summer ("1in10") are evaluated for an urban (KLO) and extra-urban (NABZUE) site in Zurich (see Table A1 for station details).

4.4.1. Characteristics of the office building

A generic reference office building is defined considering the formal and constructive characteristics, occupation, equipment and schedules specified in the code of practice SIA 2024:2021. The simulated building (Fig. 8) has a heated gross floor area of 2,784 m^2. It has three upper floors, each one with four open-plan offices, five single offices and a corridor for central access. The ceiling height is 3 m. All floors have the same floor plan, except the basement. The basement is considered an unconditioned zone without internal loads. The proportion of glass is approx. 45 % of the façade area. The constructions comply with the limit U-values of Table 3 of SIA 380/2:2022.

4.4.2. Performance indicators

Dynamic building simulations are performed with the goal to calculate the energy and power demand for heating and cooling as well as the indoor thermal comfort in summer. To calculate and evaluate the energy and power for heating and cooling, the simulations are carried out with ideal heating and cooling units in each zone over one year. The energy demand for heating and cooling corresponds to the annual total energy required to operate the building with an ideal indoor climate (set to 21 °C in the winter half year and 26 °C in the summer half year). The power demand for heating and cooling is defined as the peak demand during one hour by taking the maximum hourly average over the simulated period.

To evaluate the indoor thermal comfort in summer, additional dynamic simulations are carried out for the summer half year, from 16th April to 15th October without active cooling. Natural ventilation (during day and night, when indoor temperature is higher than 22 °C and outdoor temperature is lower than indoor temperature) is implemented through two laterally arranged windows to avoid overheating. The operative temperature, also called "perceived temperature", which is defined as the average of the mean radiant and ambient air temperatures, is used as a criterion for assessing comfort. The overheating hours result from the number of hours in which the operative temperature exceeds the defined limit values according to Figure 4 in SIA 180:2014. The limit curve is shown in the appendix in Fig. A1. The occupancy time of the office building was taken into account according to SIA 2024:2021 from 7 to 18 local time with an occupancy between 20 % and 100 %.

The following three cases are distinguished:

Mean value of overheating hours: floor area-weighted mean value of the number of overheating hours of all zones during the occupancy period.

Max. Overheating hours: Maximum number of overheating hours occurring in a zone during the occupancy period over the entire observation period.

Min. Overheating hours: Minimum number of overheating hours occurring in a zone during the occupancy period.

4.4.3. Simulation results

The building simulation results obtained with the future weather data are compared to those employing the currently used historical weather data according to SIA 2028:2010.

Energy and power demand for heating and cooling

Fig. 9 shows the energy and power demand for heating and cooling for the office building at the urban and extra-urban sites for Zurich.

The results do not contain any major outliers. Although the historical period has the highest heating energy demand, the heating power

[3] IDA Indoor Climate and Energy Version 4.8 SP2 (IDA-ICE) by EQUA Simulation AB, Stockholm, Sweden.

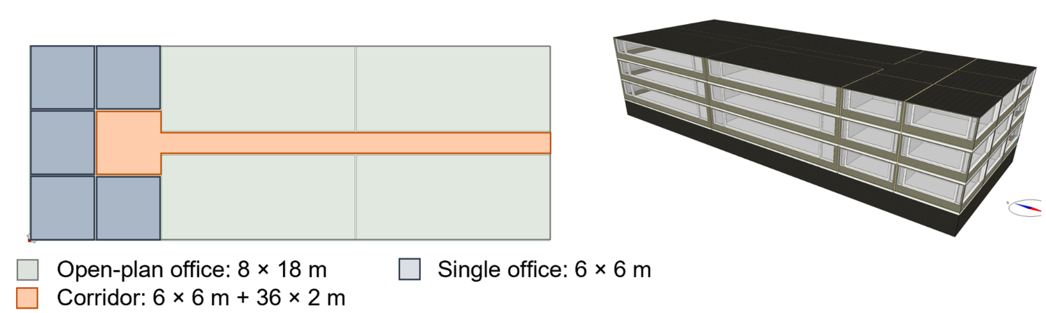

Fig. 8. Floor plan with zoning (left) and 3-D representation (right) of the office building.

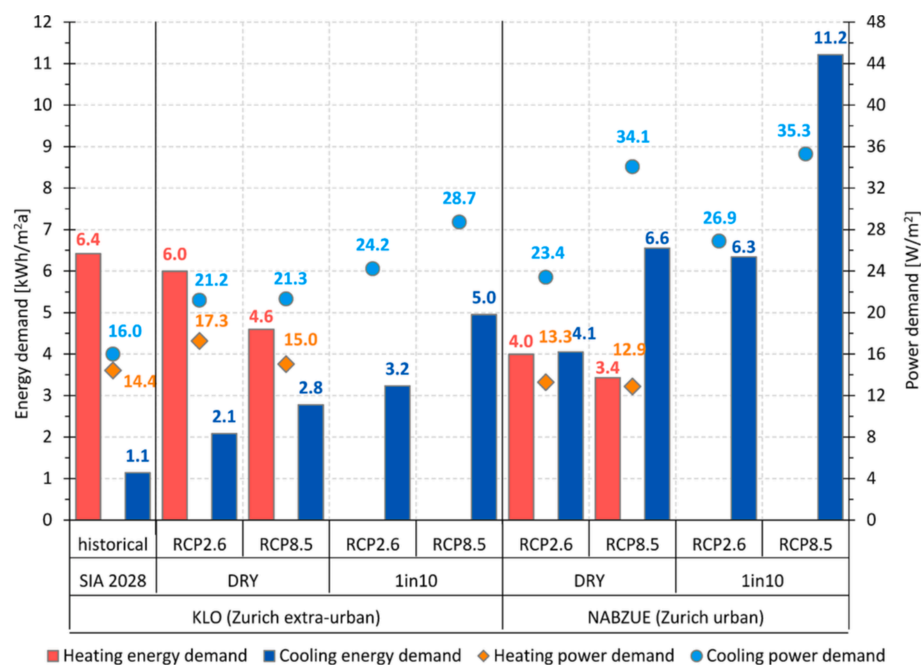

Fig. 9. Yearly energy and power demand for heating and cooling of the simulated office building. The simulations are carried out for the historical weather data (SIA 2028) and the 2060 time period for two emission scenarios (RCP2.6 and RCP8.5) and for a typical reference year (DRY) as well as the "1 in 10" warm summer reference year (1in10). Heating energy and power demand is not computed for the "1 in 10" warm summer reference year as the winter half is taken from the DRY. Note the different y-axes for energy demand (left) and power demand (right).

demand is lower than for the future reference years for the extra-urban station in Zurich. This is due to the realization of weather chosen in the corresponding reference years. The individual cold waves in the future reference years apparently have such characteristics (persistence and intensity) that during peak time (i.e., the most severe one-hour time period of the year) more heating power is required to guarantee ideal temperatures in the office building. Hence, during winter times the heating power demand can be very high even if the total annual energy demand decreases in the future. For both sites, the heating energy and power demand is higher in the future DRYs for RCP2.6 compared to RCP8.5. The cooling energy and power demand behaves just the opposite way. Also, more cooling is required in the "1 in 10" warm summer reference years compared to the DRYs of the same emission scenario.

Comparing the same type of reference year between the extra-urban and the urban station highlights the generally warmer climate of the city center due to the UHI effect. The heating energy and power demand are higher at the extra-urban site, while the cooling energy and power demand are lower.

Overheating

The simulations of the overheating hours shown in Fig. 10 are carried out assuming continuous day and night natural ventilation as explained in Section 4.4.1. Similar to the cooling energy and power demand, for both stations more overheating hours are expected for the RCP8.5 DRY compared to the RCP2.6 DRY, and likewise for the "1 in 10" warm summer reference years.

For the extra-urban station, a maximum of 108 overheating hours is achieved in one zone and 66 h averaged over all zones applying the historical data. On the contrary, a maximum of 350 overheating hours is obtained in one zone and 283 h averaged over all zones for the "1 in 10″ reference year and the RCP8.5 emission scenario. Given that currently 100 h are considered as acceptable, this means that in the future, even with optimal day and night natural ventilation, cooling will be necessary if no additional (architectural) measures are taken.

At the urban station for Zurich, a marked increase of 31 % to 63 % of the maximum overheating hours is observed compared to the extra-urban station.

5. Summary and conclusions

The aim of this work is to create climate reference years for the future (design reference years – DRYs) at hourly resolution to supplement the existing historical weather data for building design according to the

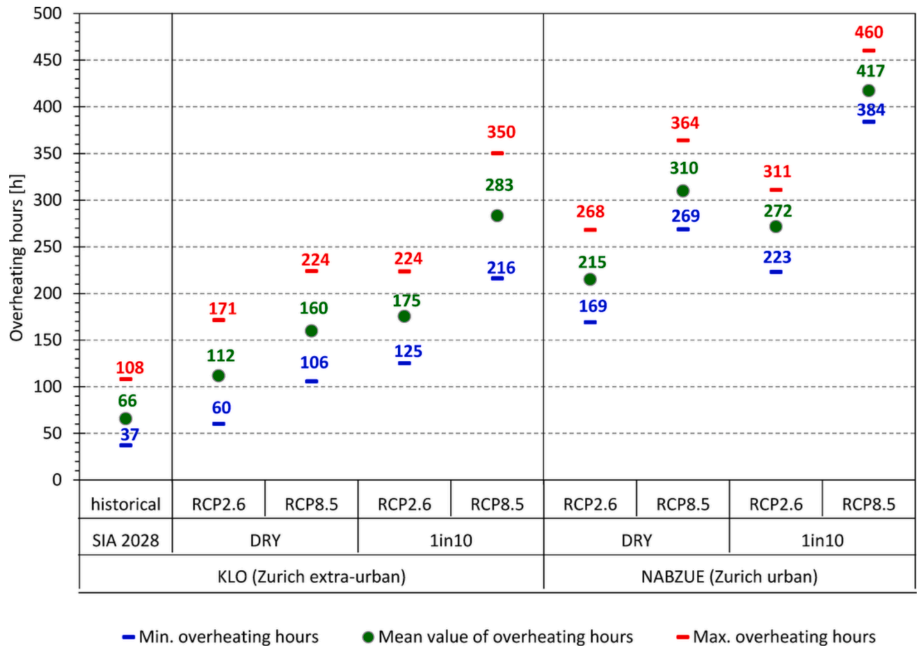

Fig. 10. Overheating hours from 16th of April to 15th of October during the occupation time (1,430 h in total) of the office building.

Swiss SIA 2028:2010 norm. In this study, we first evaluated different methods to develop DRYs for the future based on the Swiss climate change scenarios (CH2018). The best method is then used to create future typical reference years and reference years with a warm summer at the locations of 45 measurement stations in Switzerland. Two future time periods and two emission scenarios are considered. The DRYs are created taking into account temperature, relative humidity, and global radiation, and in addition, the monthly average duration of heat events for the extra-urban stations. For urban stations, the number of tropical nights is considered as an additional criterion. The “1 in 10” warm summer considers the temperature of the months of June to August as well as the duration of heat events over the entire summer half year. For urban stations, the number of tropical nights is considered in addition. These reference years are evaluated climatologically and applied in building simulations in a case study.

5.1. Choice of the method

Since the available local scenarios for Switzerland, CH2018, are only available at daily resolution, a method has to be found to generate hourly data for the future. The chosen method uses a delta-change approach, meaning that hourly observations are transferred to a future time period. To achieve this, a climate change signal is computed from the daily CH2018 scenarios and added to observations from the past. This delta-change method is contrasted to two other methods that are both using an analog approach, which means that the reference years are selected directly from hourly observations without the intermediate step of scaling the observations. All methods can be assumed to preserve physical consistencies between the variables, as slices from actual (analog) or scaled (delta-change) observations are used. In all cases, the target to be represented is given by the CH2018 scenarios, allowing direct comparison of the methods. It is found that the analog methods show overall larger biases than the delta-change method, especially for the highest emission scenario and the later time period. This is because temperatures that are typical for the future were sometimes rarely observed in the past. Hence, the analog methods have to make a trade-off between too low temperatures or too high global radiation (which balances the negative temperature bias), usually resulting in a reduced quality of the reference year for both variables. Since it is important to the users that the three variables temperature, relative humidity and global radiation are treated with the same priority, the delta-change method was proven to be most appropriate, as it ensures a reasonable simultaneous representation of the three variables by the future reference years without systematic biases.

For the delta-change method, additional criteria are implemented to better represent consecutive hot periods (as well as tropical nights for the inner-city locations). These final reference years are shown to represent the future climatology of temperature, relative humidity, and global radiation equally well as the original method and they are not inferior in quality to the existing historical DRYs from the technical specifications SIA 2028:2010.

Another way to create hourly data from daily scenarios would be temporal disaggregation. However, since the physical consistency between variables is crucial for the use in building simulations, this would require complex multivariate disaggregation techniques, which is out of scope and not yet a standard procedure. Temporal disaggregation could potentially also solve the issue of different climate change signals to daily minimum and maximum temperatures and the daily temperature cycle, which are not considered here. Currently, there is no hourly scenario data available for Switzerland and climate models providing hourly outputs cannot be trusted enough regarding the diurnal distribution mainly of precipitation events (which also affects the other variables relevant here). With convection-resolving climate models becoming more common (Ban et al., 2021), hourly reference years might be drawn directly from climate scenarios at some point in the future.

5.2. Urban and extra-urban stations

The comparison of the DRYs for the pair of urban and extra-urban stations in Zurich shows that the urban station is substantially warmer with more warm events and less cold events. This agrees with available literature on the UHI and its implications on the climate in cities today and in the future (e.g., Burgstall et al., 2021; Gehrig et al., 2018). The UHI effect is particularly visible in the number of tropical nights in the future reference years with the urban station in Zurich experiencing around 15–25 more tropical nights compared to the extra-urban station. Results for the other urban stations in Switzerland are qualitatively the same although the difference to the extra-urban site is sometimes less pronounced, due to the degree of urbanization present at the two sites (for example if the extra-urban station is in the outskirts of the city).

Here, only four urban sites are considered because observational records of other Swiss cities are not sufficiently long yet. It is possible that the UHI effect differs for other cities not covered in this study.

5.3. Results from the case study

The results from the case study show an increase in cooling demand and a decrease in heating demand in the future. For the historical data, around one seventh of the total annual energy demand of the simulated office building originates from cooling and the rest from heating. Applying the future weather data to the same building shows that cooling energy will make up one quarter to one third of the total energy demand in a typical year. In a warm summer, the same energy amount will be required for cooling as is used for heating in a typical winter. At the urban site, cooling energy demand can even be substantially higher than heating energy demand, especially for high emission scenarios and in warm summers. Similar numbers were found by Salvati and Kolokotroni (2023) for a residential building in the city of London and the mid-century assuming a strong emission scenario. The results are also in line with Remund and Grossenbacher (2019) for a residential building in the city of Bern, where an even stronger relative increase in future cooling need was found due to more warm nights (when office buildings are normally not occupied and do not need cooling).

Today, typical office buildings can be designed without active cooling if suitable measures are taken (solar protection and, especially, unrestricted – regarding duration and opening area – day and night cooling through natural ventilation). According to SIA 382/1:2014, office buildings fall at least into the category “cooling desirable” in the future. If unrestricted day and night cooling through natural ventilation is not possible, these office buildings will no longer be operable without active cooling. This is even aggravated at the urban site for Zurich, where a marked increase in the number of overheating hours can be observed compared to the surrounding stations. This means that office buildings in the city of Zurich can no longer be operated without active cooling in the future.

5.4. Outlook

The future reference years for Switzerland have been made publicly available in 2022. Since then, the current standards in Switzerland are under evaluation to incorporate these reference years. So far, practitioners can choose between the two time horizons 2035 and 2060. For the time horizon around 2035, only one emission scenario, RCP8.5, is officially provided, since the RCPs hardly differ in that period. For the period 2060, the RCP2.6 and RCP8.5 scenarios are provided to span the possible range of future climate development. It is planned to provide reference years also for the end of the 21st century in order to increase the planning horizon.

With this new set of data that is publicly provided, a new fundament is laid for climate adaptation in the building sector of Switzerland. Corresponding standards on an international level are currently being elaborated to include future climate data. With the work here, a feasible and pragmatic approach is shown on how to incorporate and consider the effects of a warmer climate to buildings that are planned today.

Data availability statement

The CH2018 scenarios are available through the National Centre for Climate Services: https://doi.org/10.18751/Climate/Scenarios/CH2018/1.0. The reference years for the future are available through the map.geo.admin.ch platform: https://s.geo.admin.ch/94e9d38450.

CRediT authorship contribution statement

Kathrin Wehrli: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Conceptualization. **Franz Sidler:** Formal analysis, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Investigation, Methodology. **Stefanie Gubler:** Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing, Software. **Gianrico Settembrini:** Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. **Markus Koschenz:** Validation, Writing – review & editing. **Silvia Domingo Irigoyen:** Formal analysis, Investigation, Methodology, Software, Writing – review & editing. **Sven Kotlarski:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Andreas M. Fischer:** Conceptualization, Project administration, Supervision, Writing – review & editing. **Gerhard Zweifel:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Overview of measurement stations. Typically, the 1981–2010 time period is assessed. Different time periods are used in case of shorter observational periods and for the city stations (last four stations at the bottom of the table).

Station	Abbreviation	Geographical coordinates N / E	Height [m. a. s. l.]	Observational time period assessed
Adelboden	ABO	46–30 / 07–34	1320	1984–2010
Aigle	AIG	46–20 / 06–55	381	1981–2010
Altdorf	ALT	46–52 / 08–38	449	1981–2010
Basel-Binningen	BAS	47–33 / 07–35	316	1981–2010
Bern-Zollikofen	BER	46–56 / 07–25	565	1981–2010
Buchs-Aarau	BUS	47–23 / 08–05	387	1985–2010
Chur	CHU	46–52 / 09–32	555	1981–2010
Davos	DAV	46–49 / 09–51	1590	1981–2010
Disentis	DIS	46–42 / 08–51	1190	1981–2010
Engelberg	ENG	46–49 / 08–25	1035	1983–2010
Genève-Cointrin	GVE	46–15 / 06–08	420	1981–2010
Glarus	GLA	47–02 / 09–04	515	1981–2010
Grand-St-Bernard	GSB	45–52 / 07–10	2472	1982–2010
Güttingen	GUT	47–36 / 09–17	440	1981–2010
Interlaken	INT	46–40 / 07–52	580	1981–2010
La-Chaux-de-Fonds	CDF	47–05 / 06–48	1019	1981–2010
La-Frêtaz	FRE	46–50 / 06–35	1202	1981–2010
Locarno-Monti	OTL	46–10 / 08–47	366	1981–2010
Lugano	LUG	46–00 / 08–58	273	1981–2010
Luzern	LUZ	47–02 / 08–18	456	1981–2010
Magadino	MAG	46–10 / 08–53	197	1981–2010
Montana	MVE	46–19 / 07–29	1508	1981–2010
Neuchâtel	NEU	47–00 / 06–57	485	1981–2010
Payerne	PAY	46–49 / 06–57	490	1981–2010
Piotta	PIO	46–31 / 08–41	1007	1981–2010
Pully	PUY	46–31 / 06–40	461	1981–2010
Robbia	ROB	46–21 / 10–04	1078	1981–2010
Rünenberg	RUE	47–26 / 07–53	610	1984–2010
San Bernardino	SBE	46–28 / 09–11	1639	1982–2010
St. Gallen	STG	47–26 / 09–24	779	1982–2010
Samedan	SAM	46–32 / 09–53	1705	1981–2010
Schaffhausen	SHA	47–41 / 08–37	437	1982–2010
Scuol	SCU	46–48 / 10–17	1298	1981–2010
Sion	SIO	46–13 / 07–20	482	1981–2010
Ulrichen	ULR	46–30 / 08–19	1345	1981–2010
Vaduz	VAD	47–08 / 09–31	460	1981–2010
Wynau	WYN	47–15 / 07–47	422	1981–2010
Zermatt	ZER	46–02 / 07–45	1638	1982–2010
Zürich-Affoltern	REH	47–26 / 08–31	444	1981–2010
Zürich-Kloten	KLO	47–29 / 08–32	425	1981–2010
Zürich-Fluntern	SMA	47–23 / 08–34	556	1981–2010
Zürich-Kaserne	NABZUE	47–23 / 08–32	409	1998–2020
Bern-Bollwerk	NABBER	46–57 / 07–26	536	1999–2020
Basel-Klingelbergstrasse	BKLI	47–34 / 07–34	285	2003–2020
Lausanne-César-Roux	NABLAU	46–31 / 06–38	538	1991–2020

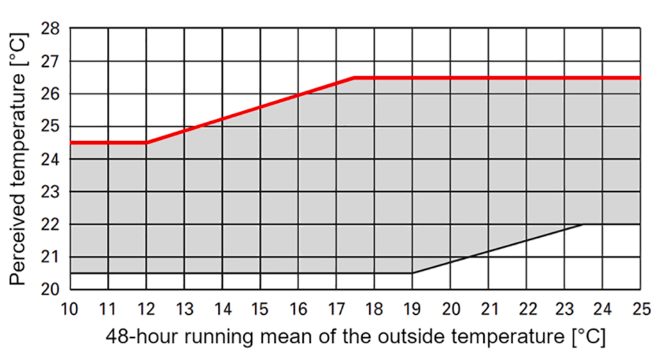

Fig. A1. Limit value curve according to SIA 180:2014, Figure 4. Overheating hours result from the number of hours in which the perceived temperature exceeds upper limit of the curve (red line).

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