Selection of Weather Files and Their Importance for Building Performance Simulations in the Light of Climate Change and Urban Heat Islands

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Abstract

Building performance predictions and their reliability rely heavily on weather data inputs. Climate is affected by spatial and temporal differences related to climate change and urban heat island effects, but the weather files used in building performance simulations (BPS) often remain unchanged and may represent weather observations generated from inadequate space and time for their application. This study investigated Swedish weather data using statistical methods and analysed i) the local differences related to rural and urban microclimates and ii) the country-wide differences linked to climate change; by comparing recent observation data to the respective EnergyPlus Weather (EPW) files. The findings reveal that there are significant differences between rural and urban temperature means, and that outdated model years of weather data files make them unsuitable for BPS. The impact of using an inadequate weather file based on changes in recent climate in Sweden can lead to an overestimation of heating demand by 6.5 % on average, while the impact is higher for warmer climates – up to 12 %. The combined impact including climate change and urban heat island effects can lead to a heating energy overestimation by 12 % to 19 %, based on the Stockholm example. On the other hand, it was found that although the global radiation means saw a slightly increasing trend, its impact on the BPS remains inconclusive. The study highlights the importance of selection of adequate weather data for BPS keeping in mind the spatial and temporal influencing factors.

Keywords: weather data, EPW, statistical analysis, urban heat island, climate change, building performance simulations

1. Introduction

Weather data is a central input in building performance simulations (BPS) and sustainable urban planning. It defines the output of simulations relating to daylighting, energy use, and solar potential, and ultimately influences the decision-making process in the urban planning and building design practice. In a typical BPS process, a weather file selection is fixed to a single available weather file which is used repetitively in studies of a given geographical or administrative area and contains hourly values representing a typical meteorological year (TMY). One of the common weather file extensions used in building simulation software based on EnergyPlus and Radiance is the EPW (EnergyPlus Weather) file format. International EnergyPlus database is a large repository of EPW files from many different weather sources (EnergyPlus, 2021). It is often not possible to pick and choose between different weather files for a given location; there is usually only one that is the nearest available hence deemed the most suitable. For some locations and some data repositories it may also be difficult to obtain files with updated TMY with observation from the most recent years. In other terms, available weather file might not be fully representative due to spatial (location of the weather station) and temporal (years of observation included in the TMY) differences.

There are two key factors that drive the local spatial and temporal, as well as short-term and long-term, weather observation differences: urban heat island and climate change. Their effects on BPS have been previously studied, see e.g., (Burleyson et al., 2018; Crawl, 2008; de Wilde and Coley, 2012; Moazami et al., 2019). Studies also investigated the impact of future climate scenarios on BPS (Baglivo et al., 2022; de Masi et al., 2021; Moazami et al., 2019). Nik and Sasic Kalagasidis (2013) showed that the heating demand of Stockholm's residential buildings might expect a potential decrease of 30 % under a future climate scenario. On the other hand, a study by Guattari et al. (2018) investigating urban climate of Rome demonstrated that the average cooling need was 30 % higher, pertaining to urban heat island effects alone.

The urban heat island effect drives climate differences on a local scale. The phenomenon occurs due to conducive urban characteristics such as high build-up density, scarce vegetation, thermal waste, and the extensive use of heat-

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storing materials and dark surface colours; all of which causes the city centres to reach higher ambient and radiant temperatures, meanwhile possessing a decreased ability for radiative cooling due to a limited openness to the sky. Since the weather files are commonly built from stations located outside of the cities e.g., at rural airports, they typically do not account for this effect. In Sweden, six city locations are covered by the EnergyPlus database of EPW files, five of which come from rural airport-based weather stations outside of the city (Table 1). The source of the presented Swedish weather data files is IWEC (International Weather for Energy Calculations), which was developed by ASHRAE (ASHRAE, 2001).

Table 1. The available Swedish EPW file locations and the observation time spans they are generated from.

City and weather file name	Weather station location	TMY time period
Copenhagen (DK; also used in Malmö, SE)	Kastrup Airport	1983 to 1999
Gothenburg (SE)	Landvetter Airport	1983 to 1995
Karlstad (SE)	Sommarro area	1984 to 1996
Kiruna (SE)	Kiruna Airport	1982 to 1993
Östersund (SE)	Åre (Frösön) Airport	1982 to 1999
Stockholm (SE)	Arlanda Airport	1984 to 1993

While the heat island phenomenon triggers spatial microclimate differences, climate change alters the long-term weather patterns. The available EPW files in Sweden contain data based on real weather observations taken within a similar time span, ranging from 1982 to 1999, as shown in Table 1. Climate change is affecting locations globally in varying magnitudes, and it is important to understand how different places around the world are impacted. While future climate scenarios were previously applied in BPS studies in Sweden (Moazami et al., 2019; Nik and Sasic Kalagasidis, 2013), the disparities between recent weather observations and common Swedish weather files have not yet been studied.

To investigate the impact of the selection of weather files, a statistical analysis of Swedish weather data was conducted. The main objective of the research was to study the differences between the EPW weather data sets and recent weather observations, which might adversely impact future solar and thermal building performance predictions. The goal was to investigate firstly, whether there are significant statistical differences between the rural and the urban weather observations based on Stockholm's urban agglomeration, and secondly, whether the available EPW files for Swedish locations remain representative of the most recent weather patterns. The study looked at both hygrothermal as well as solar weather parameters (global radiation, sun duration) and analysed their potential impact on BPS. Since the impact of climate change on clouds is still largely unknown (Ceppi et al., 2017), it is important to study the solar aspects of climate. Lastly, the outcomes of the study address a key question for BPS: Is it important to continuously update the simulation weather files?

2. Methodology

2.1. Rural and urban differences - Stockholm

The first part of this study analysed dry bulb air temperature records measured in six selected stations located in Stockholm County. The analysis area was of a 35 km radius with Central Stockholm at its centre. The measured temperature data was obtained from SMHI (Sweden's Meteorological and Hydrological Institute) (SMHI, 2021a). Thirteen years of data records spanning between year 2008 and 2020 were extracted for the selected weather stations. The prerequisites for selecting suitable weather stations were: 1) the data was recorded hourly, 2) the station was active in years 2008-2020, and 3) the station was located in the Greater Stockholm area. The following weather stations were selected: Stockholm (A), Adelsö, Arlanda, Bromma, Tullinge, and Skarpö. To study their location on the map of Greater Stockholm area, see Figure 3. For each station and each annual hourly temperature data set, an annual temperature mean was calculated.

There were missing records in the retrieved data sets. Following the statistical significance level rule of 5 %, the annual data sets which had more than 5 % of data records missing were considered as significant loss of data and thus were removed from the analysis. There were four such data sets: Adelsö 2016, Arlanda 2008, and Skarpö 2014 and 2015.

A statistical analysis on the annual mean temperatures was conducted in RStudio (RStudio Team, 2021). A general linear model was used, and analysis of variance (ANOVA) as well as post hoc comparison tests (Tukey's method) were performed. Test assumptions regarding normality and homoscedasticity of the residuals were checked.

Weather data files used in BPS were introduced to assess their likeness to the measured data and to evaluate their ability to digitally represent the analysed climate of the recent time period in computer-based modelling. The weather data was obtained from two databases: EnergyPlus (EP) (EnergyPlus, 2021) with data source IWEC (ASHRAE, 2001), and OneBuilding (OB) (OneBuilding Climate, 2021). The former is a widespread source of weather data for BPS. Ladybug Tools (Ladybug Tools, 2021) users can connect directly via a web browser to a Ladybug interactive map providing many EP files to download, including IWEC files (Roudsari and Peng, 2021). As previously indicated, those files are often based on old measurements (Table 1). OB, on the other hand, is a free repository of TMY weather data that is updated continuously and covers many more locations. For this study, there was only one EP file available for the analysed area, while there were twelve different OB files – two for each of the stations, containing two different sets of model years on which the TMY data was based.

2.2. Spatial and temporal differences - Sweden

The second part of this study investigated weather data measurements from six Swedish locations: Stockholm, Gothenburg, Malmö, Östersund, Karlstad, and Kiruna (Fig. 1). The data was retrieved from SMHI's database (SMHI, 2021a), from weather stations that were located closest to the available IWEC weather file for a given city, and for eleven consecutive years: 2010-2020. The following weather parameters were analysed: air temperature (°C), relative humidity (%), global solar irradiance (W m^{-2}), and sunlight duration as fraction of an hour. Annual averages from the measured hourly-based data were calculated: for temperature and humidity – taking all data items, and for irradiance and sunlight duration – taking only data for those hours when the sun is up, which differs per location. Additionally, yearly temperature extremes were also investigated.

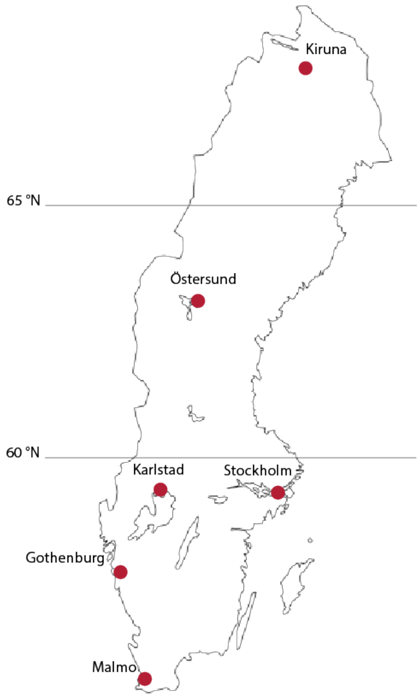

Figure 1. Locations of the weather stations for the analysis of Swedish weather.

The sunlight duration parameter was accounted for differently in the measured data and in the weather file data. SMHI uses a threshold of above 120 W m^{-2} in measured global radiation to determine that a given second was sunny (sunlight was present) and gives the results of these measurements hourly with maximum value of 3600 per hour (SMHI, 2021b). The SMHI sunlight duration data was normalised for this study, and all values were divided by the maximum to give a range between 0 and 1. The weather data from EPW files, on the other hand, provided information about the cloud coverage of the sky for every hour of the year, the invert of which was taken as sunlight duration.

There were some difficulties encountered during data extraction. Relative humidity data was missing or was of inadequate quality (category yellow by SMHI) for all locations for measurements in years 2010, 2011, 2012, and 2020: thus, only seven measurement years were considered for this parameter, except for Malmö where year 2020 records were available. Solar stations, those that measure global radiation and sunlight duration, were positioned in different locations than the weather stations which recorded the temperature and relative humidity; however, they were still located within the same precincts, except for Malmö, as the closest solar measuring station was in the nearby town of Lund.

Climatic differences between the selected Swedish locations but also differences between recent weather measurements and respective TMY data for these locations were investigated. The weather data files for all locations were sourced from EnergyPlus IWEC database. For Malmö, the Copenhagen file was used, as it was the nearest available location from IWEC.

Each parameter was first analysed separately using an additive linear model design. The assumptions for the ANOVA were checked for each data set. Temperature, relative humidity, and sun duration data sets proved normality and homoscedasticity on residuals; however, tests on radiation data set rejected the normality hypothesis. In order to be able to conduct further statistical tests, outliers of the radiation data were identified and removed. To ensure data normality, it was sufficient to remove just one radiation record, for Malmö 2017, which was the biggest outlier. ANOVA of every weather parameter data set showed that the locations and years had significant differences with high significance p-value levels. Post hoc comparisons were conducted on each weather parameter separately.

3. Results and discussion

3.1. Rural and urban differences - Stockholm

The annual temperature averages are shown in Figure 2. The parallel appearance of the lines indicated a block effect in the data; hence, a linear additive model with blocking was used. Next, one-way ANOVA was used to test whether the block design was appropriate. The ANOVA indicated that there was a significant ($p<0.001$) difference in the data corresponding to the year and the location, and that the grouping of data into blocks was adequate. The assumptions for ANOVA were tested using the Shapiro-Wilk and Levene tests, which did not reject normal distribution and homoscedasticity of the residuals, so the assumptions were met.

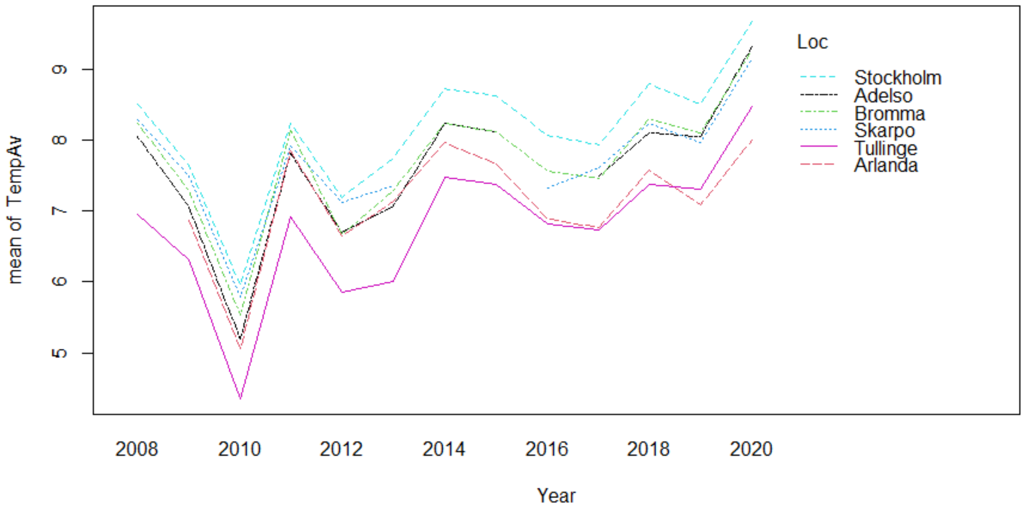

Figure 2. Interaction plot with Stockholm weather stations temperature means. Some lines appear broken because of missing data.

The Tukey's post hoc comparison test results with the level of significance $\alpha = 0.05$ are presented in Table 2. There are small standard errors and many degrees of freedom. The comparison of the location means showed that there are four groups of stations with significantly different temperature means, while three stations, Skarpö, Bromma, and Adelsö, did not have significantly different means according to the Tukey's test. The table also includes an annual temperature mean for the IWEC weather file from Stockholm Arlanda which was added to contrast the statistical means with the TMY mean.

Table 2. Tukey's post hoc test results with statistical grouping of means (descending order).

Location	emmean (estimated marginal mean)	SE (standard error)	DF (degrees of freedom)	Lower CL (confidence level)	Upper CL	Group
Stockholm	8.12	0.0540	56	8.01	8.23	A
Skarpö	7.76	0.0597	56	7.64	7.88	B
Bromma	7.71	0.0540	56	7.60	7.82	B
Adelsö	7.59	0.0567	56	7.47	7.70	B
Arlanda	7.16	0.0567	56	7.05	7.27	C
Tullinge	6.76	0.0540	56	6.66	6.87	D
IWEC (Arlanda)	6.49					

The weather station located in the Stockholm's city centre, named 'Stockholm', resulted in the highest estimated temperature mean. It was also significantly different from other stations. The result confirms the initial hypothesis that the air temperatures are higher in city centres, closer to the densely built and populated urban areas (Fig. 3), which might be ascribed to the known heat island effect.

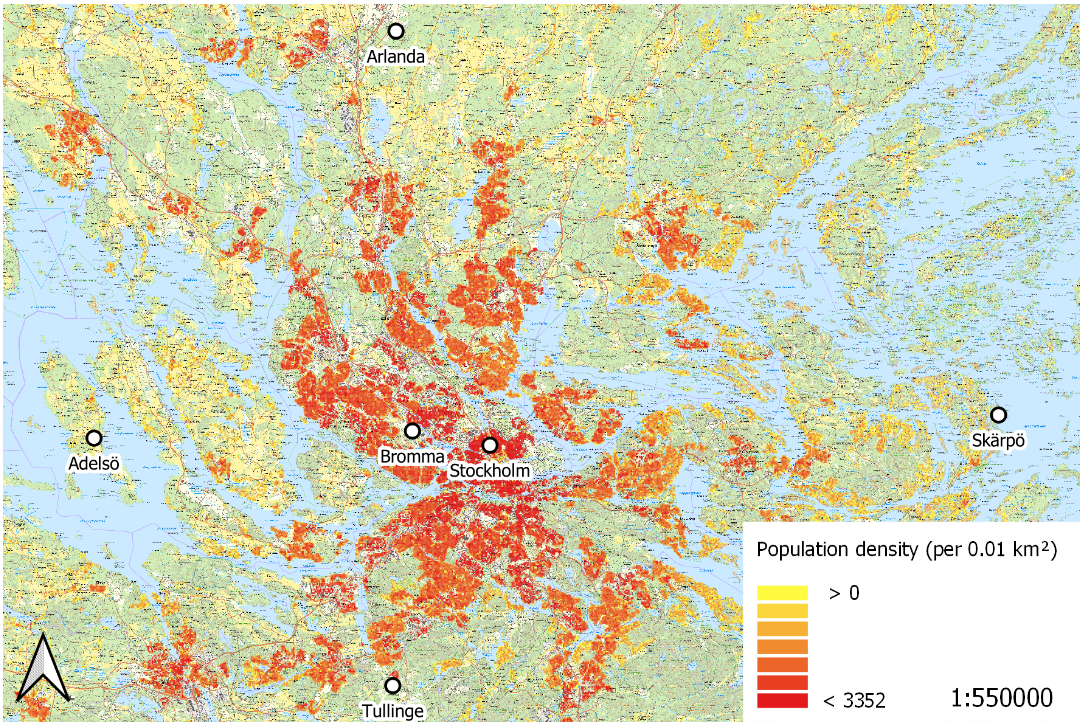

Figure 3. Stockholm's weather stations and population density (source: Lantmäteriet).

Weather stations of Bromma, Skarpö, and Adelsö were placed together in one group, which was the second highest group by temperature means. This means that there is no significant difference between these station's temperature means. While Bromma was located close to the agglomeration's centre, the other two were located outside of the strict city centre. The reason the means are not different could be attributed to the geographical and topographical location of the two rural stations. Skarpö and Adelsö are located close to large sea reservoirs, which might affect local climate and cause milder temperatures. The results might also be affected by the reduced data samples for the two said stations.

Arlanda and Tullinge were identified as the coldest locations within the analysed area. There was also a significant difference between them, with Tullinge being the colder station. It was noted that these two stations are located inland, further away from large water bodies than the warmer stations of Adelsö and Skarpö. This might again indicate the coastal effect on temperature averages, because all four of these stations were located far away from the city centre of Stockholm in rural locations that are not densely populated (Fig. 3).

The temperature means for all investigated weather stations and for all data sources (SMHI used this paper's statistical analysis, and IWEC and OB from online databases) were placed together in Table 3 and sorted by the ascending temperature mean. There was only one IWEC file available for the Greater Stockholm area, and its location was Arlanda. The OB weather files database offered two files for each station. The one which had the addition of '2004-2018' in the name was generated using this exact time period or shorter time span within it, while the other version was generated using an unspecified time span. The IWEC file's average of model years was the oldest.

The comparison table (Table 3) shows that for three out of six investigated locations the SMHI sourced temperature mean for the most recent years 2008-2020 expressed higher temperature mean than the weather files. In case of Skarpö and Bromma, the latest model years resulted in higher temperature means when comparing all three means for each location. The difference is especially pronounced for the temperature means that were modelled using larger time spans dating back to the 1980s, such as Bromma (OB) and Arlanda (OB). Their means were about 0.5 K lower than the two other respective means. It is noteworthy that the lowest temperature mean was obtained from the Arlanda IWEC file data, which is still a commonly used source of weather data for simulations.

Table 3. Weather station temperature data from different sources sorted by ascending temperature mean.

Weather station (source)	T mean /°C	Years
Stockholm (OB)	8.19	2002 - 2019
Stockholm (SMHI)	8.12	2008 - 2020
Stockholm 2004-2018 (OB)	7.98	2005 - 2017
Adelsö (OB)	7.78	2002 - 2019
Skarpö (SMHI)	7.76	2008 - 2020
Skarpö 2004-2018 (OB)	7.75	2004 - 2018
Bromma (SMHI)	7.71	2008 - 2020
Bromma 2004-2018 (OB)	7.70	2004 - 2018
Skarpö (OB)	7.66	1999 - 2018
Adelsö (SMHI)	7.59	2008 - 2020
Adelsö 2004-2018 (OB)	7.41	2004 - 2017
Arlanda 2004-2018 (OB)	7.27	2005 - 2018
Arlanda (SMHI)	7.16	2009 - 2020
Bromma (OB)	7.09	1980 - 2011
Tullinge (SMHI)	6.76	2008 - 2020
Arlanda (OB)	6.69	1981 - 2013
Tullinge (OB)	6.66	2002 - 2019
Tullinge 2004-2018 (OB)	6.66	2004 - 2016
Arlanda (IWEC)	6.49	1984 - 1993

The order of the Table 3 is similar to the post hoc classification from Table 2, with some exemptions which were discussed above. The overall difference between the lowest (Arlanda OB) and the highest (Stockholm OB) temperature mean from Table 3 is 1.7 K, which for an annual average difference of a relatively small geographical area is substantial. Based on simple hand calculations of building heat balance using a degree hours method (Letherman and Al-Azawit, 1986), such a discrepancy in annual average temperature could have a 12 % to 19 % incremental impact on the predicted heating energy use, depending on the indoor temperature setpoint through independently of the rate of heat loss. Miscalculated heat balance and mismatched energy performance predictions can lead to poor design and planning. This can, for instance, result in excessive and redundant insulation added onto the building envelopes in order to meet energy requirements, which may further cause potential overheating issues in the summertime (Porritt et al., 2012).

2.2. Spatial and temporal differences – Sweden

The temperature estimated means based on measurement data from SMHI and the corresponding TMY temperature averages from IWEC data were contrasted in Table 4 and sorted in a descending order by the emmeans. IWEC's temperature averages were between 0.65 K and 1.3 K lower than the mean based on the recent 11 years of measured data. There were significant differences between the locations, which resulted in 5 distinct statistically different groups (see also Fig. 4). Comparing the years instead, only year 2010 was colder than the IWEC TMY. Comparing relative humidity means in the same manner, the differences between SMHI and IWEC data means were negligible and inconclusive; there were very small differences between the investigated locations.

The temperature means from the recent weather observations were higher for all locations in respect to the IWEC weather files. Table 4 shows the impact of the difference on heating demand predictions; the percentages were calculated using the same simple degree hours method as previously (Letherman and Al-Azawit, 1986). An overestimation between 4 % and 12 % is expected, depending on the location. Colder locations are less affected by the rising annual temperatures, because the difference constitutes a smaller fraction of the temperature differential when considering the same heating setpoint temperature.

Table 4. Annual temperature means for SMHI observations for years 2010-2020 and IWEC weather files.

Location	Group	emmean (SMHI) /°C	IWEC average /°C	Difference /K	Heating energy difference
Malmö / Copenhagen	A	9.40	8.32	1.08	8-12%
Gothenburg	B	7.28	6.53	0.75	5-7%
Stockholm	BC	7.14	6.49	0.65	4-6%
Karlstad	C	6.75	5.92	0.83	5-7%
Östersund	D	3.86	3.15	0.71	4-5%
Kiruna	E	0.21	-1.09	1.30	6-7%

The comparison of annual maximum and minimum temperatures was presented in Table 5. All recent observations show higher maximum annual temperatures than those of the IWEC files, which may introduce overheating issues in buildings. The temperature minima, on the other hand, were both higher and lower depending on the location. Thus, no clear trend was observed, and the impact that the changes in temperature minimum might have on the heating peak load is smaller than of the heating energy difference - up to 7 % only.

Table 5. Annual temperature extremes for SMHI observations for years 2010-2020 and IWEC weather files.

Location	T_{max} emmean /°C	IWEC T_{max} /°C	Difference /K	T_{min} emmean /°C	IWEC T_{min} /°C	Difference /K	Heating power difference
Gothenburg	28.3	27.1	1.2	-14.1	-15.9	1.8	- 7 %
Karlstad	28.3	26.3	2	-18.3	-19.5	1.2	5 %
Kiruna	25.4	22.7	2.7	-31.6	-29.2	-2.4	- 4 %
Malmö / Cph.	29.6	26.8	2.8	-11.5	-9.6	-1.9	3 %
Östersund	26.7	26.5	0.2	-23.5	-25.7	2.2	5 %
Stockholm	29.1	27.1	2	-18.3	-17	-1.3	- 5 %

Radiation data from SMHI calculated emmeans and IWEC weather files was compared in Table 6. The recent SMHI measurements recorded higher averages than the older TMY model years with up to 10 % increase. This does not yet indicate a trend, but it is worth noting that for all locations there was an increase in the global radiation average. This phenomenon could be related to the potential discrepancy between the estimate-based radiation data, typically used in the weather file generation, and ground-based measurements. IWEC files are based on estimates from cloud coverage and other weather parameters (ASHRAE, 2001), while OneBuilding radiation estimates use satellite-based models (OneBuilding Climate, 2021). Satellite-based data allows to generate sky models and calculate surface irradiance at virtually any location, which increases data accessibility and improves applications promoting solar energy implementation (Huld et al., 2012), but the models can suffer accuracy loss (Psiloglou et al., 2020).

Similar comparison could not have been performed for the sunlight duration data, because SMHI and the TMY data had different ways of accounting for the direct sunlight duration.

Table 6. Annual global radiation means for SMHI observations for years 2010-2020 and IWEC weather files.

Location	Group	emmean (SMHI) /Wm^{-2}	IWEC average /Wm^{-2}	Difference / Wm^{-2}	Change
Malmö / Copenhagen	A	233	219.8	13.2	6.0 %
Karlstad	AB	227	221.4	5.6	2.5 %
Stockholm	B	226	204.7	21.3	10.4 %
Gothenburg	B	223	219.9	3.1	1.4 %
Östersund	C	201	196.4	4.6	2.3 %
Kiruna	D	177	163.7	13.3	8.1 %

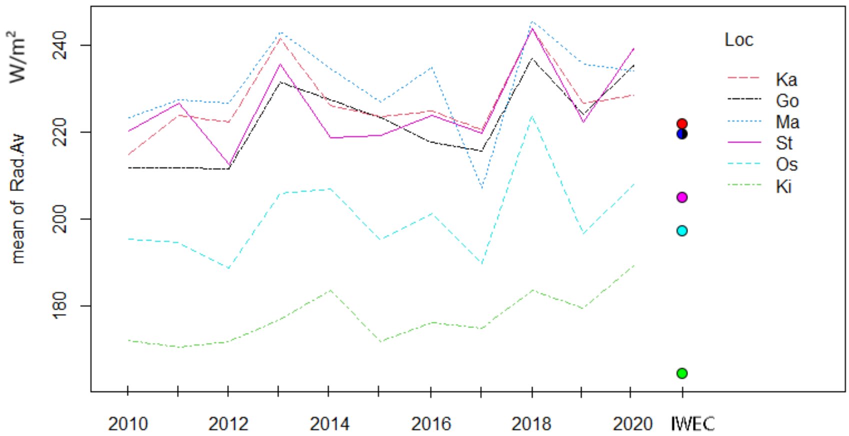

Figure 4. Annual global radiation average over measurement years and the IWEC year.

The graph presenting global solar radiation means from the last eleven years data in Figure 4 does not suggest that there are trends or changes in the means over time. What can be seen, however, is that the weather file IWEC radiation mean is generally quite low in comparison to the annual measurements. This increase may potentially have an effect on solar potential, energy, and daylight simulations; however, a previous study on weather data for daylight simulations showed that the impact is quite insignificant (Iversen et al., 2013).

All the individual post hoc comparisons of the Swedish weather locations were combined in one chart in Figure 5. This method of presentation is proposed for the purpose of comparing multi-parameter post-hoc comparisons. The graph can be read in multiple ways. First, it can be noticed that the order of locations by temperature as well as by solar parameters, particularly by radiation, roughly follows the latitude order from southernmost (Malmö) to northernmost (Kiruna) location. Special attention might be paid then to those locations which deviate from the latitude order in those parameters. One can also read the graph by looking at a certain location in respect to others. Gothenburg, for instance, is warm, but not exceptionally warm for its latitude as it does not deviate in respect to the latitudinal order. It is also rather humid and often cloudy since the radiation and sun duration are below latitudinal expectations for Gothenburg's latitude. It can be also assessed from the graph that Stockholm, Karlstad, and Gothenburg share similar climates. We think that this method for comparing climates proved easy to interpret and hence was chosen over the PCA biplots presentation method.

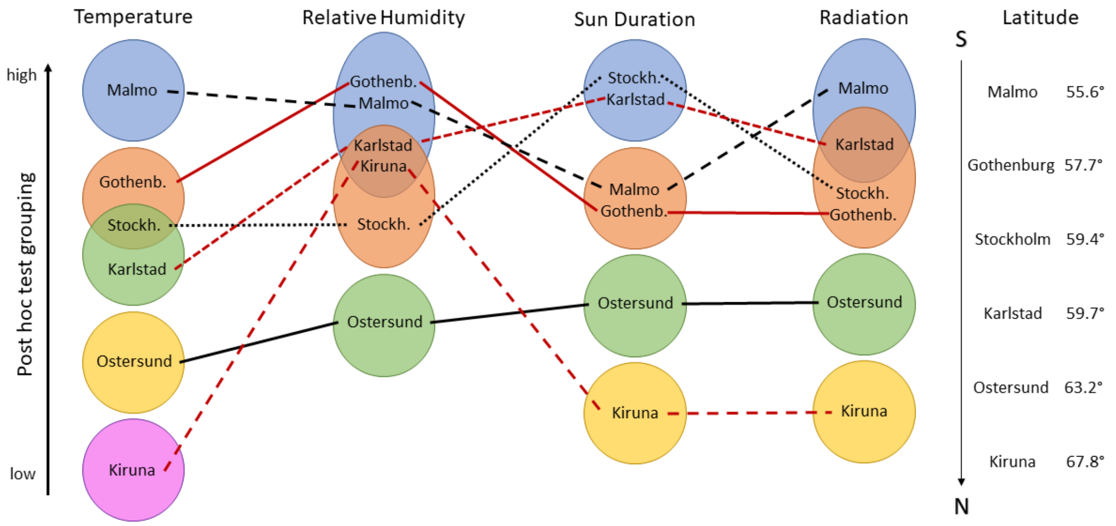

Figure 5. Combined post-hoc comparisons (data included IWEC yearly averages) and latitudes.

4. Conclusions

This paper analysed difference in weather files based on location of the weather stations and observations reference period on the example of the Swedish capital city agglomeration and Sweden as a country. The scope was to understand how the selection of weather files might affect BPS. The analysis showed the importance of keeping weather data for BPS updated, as it was seen that inadequate time and location that a weather file was generated from may have significant consequences on BPS.

The study brought to the attention of BPS analysts that there might be a substantial deviation in urban temperature from the respective rural-based weather data. Choosing an incorrect weather file for BPS can have a significant impact on simulation accuracy. BPS practitioners should be aware of the type of the location (rural/urban) that the selected weather file is from. In case of a mismatch in building site and weather station location type (e.g., a urban development and a rural weather file), adjustments may be advised to reduce the discrepancy. To transform a rural EPW file into a more accurately morphed urban file, one can use the Urban Weather Generator (UWG) (Nakano et al., 2015). Future studies should investigate the precision of the UWG transformations in relation to the actual rural-urban differences observed in real life.

There was a clear indication of potential impact from the temperature differences in different weather data sets and the implications they may have on heating and cooling. Climate change and urban heat islands contribute to higher average outdoor temperatures than those recorded in some weather files, which may lead to misestimation of the energy balance. For the heating demand of buildings in Sweden, poor selection of weather files may lead to an overestimation of up to 19 %. While there is a strong tendency for the yearly maximum to increase carrying potential consequences on cooling in buildings, the yearly minimum temperatures saw neither increasing nor decreasing trends, and thus, the impact on dimensioning of building heating systems is inconclusive.

Regarding solar weather parameters, it is uncertain whether the observed increase in average global radiation can be perceived as a trend. Previous research suggests that the impact on daylighting BPS is thus far limited and possibly negligible. Solar weather observations and the potential temporal differences due to climate change should be continuously inspected, and the consequences on BPS should be further investigated. Future work should examine the impact of the weather data differences on solar, thermal, and daylighting building performance using full-scale BPS.

5. Acknowledgements

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