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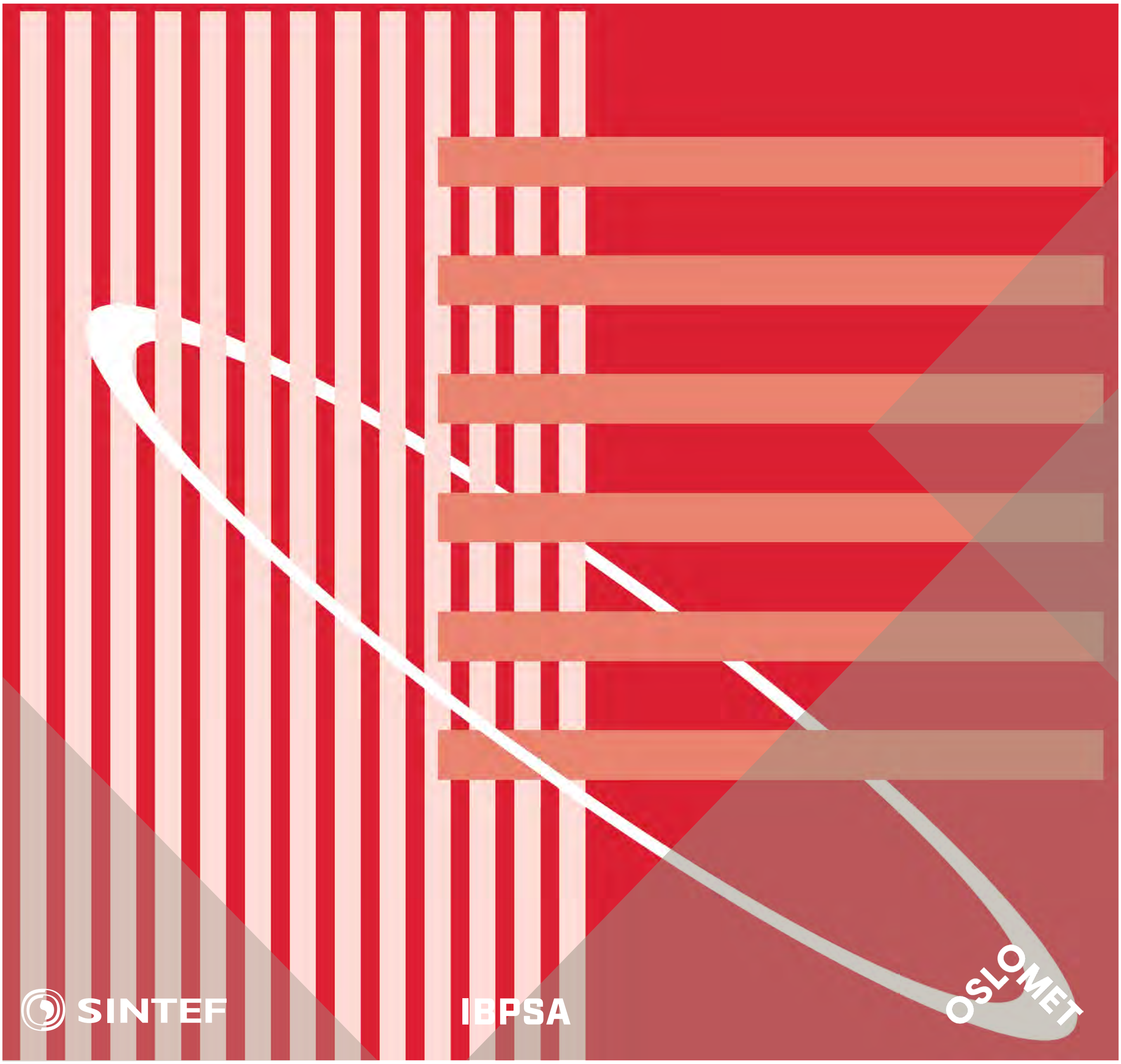

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Editors:
Laurent Georges, Matthias Haase, Vojislav Novakovic and Peter G. Schild

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The Effect of Local Climate Data and Climate Change Scenarios on the Thermal Design of Office Buildings in Denmark

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Abstract

The effect of climate change on Danish office building energy performance was investigated. Local mean weather data and national design reference year are morphed into future weather files, and the output from a total of 313,000 EnergyPlus simulations was analysed. The results indicate that the current Danish building design practice is not appropriate if buildings designed today are to be resilient to climate change.

Introduction

Thermal building performance simulation (T-BPS) can be used during the design phase to make reliable predictions of the thermal indoor climate and energy performance of proposed building designs under the weather conditions of the building site. In terms of weather conditions for simulation, the decade-long practice in Denmark is to use a so-called Design Reference Year (DRY) for any building no matter its geographical location. DRY is an artificial hourly dataset constructed according to a specific procedure described by Lund (1995). The result of the procedure is a dataset that expresses the mean weather conditions of the past years of actual weather used to construct the DRY. The first version of DRY from 1995 (Jensen and Lund, 1995) also included 'an appropriately representative sample of extreme values from the 15-year datasets'. The second – and current – DRY from 2013 (Wang et al., 2013a; Wang et al., 2013b) is also a 'mean year' that seems to have been constructed like the former DRY1995 but it is not clear from the documentation.

It is mandatory to use DRY2013 when documenting the annual energy and thermal indoor climate performance according to the Danish building code (BR18, 2018). The use of a 'mean year' can be regarded as an expression of mean expected energy and thermal indoor climate performance of a building design over a range of years. This could be informative to designers and building owners as long as they realise that it is a mean value, i.e. that the performance can be better or worse depending on the weather data of a specific year. In other words, designing a building to marginally comply with BR2018 using DRY correspond to designing a building to perform *better* than the demands in BR2018 for 50% of its lifetime years but that the building can also be expected to perform *worse* than the demands in BR2018 for 50% of its lifetime years. Realising this, the use of DRY for building design seems like a risky approach to avoid overheating. The Danish tradition is – for various reasons, see e.g. (Petersen and Knudsen, 2017) – to allow the building design to have a certain amount of hours above a summer comfort threshold. For example, a maximum of 100 hours above 26 °C and 25 hours above 27 °C for office buildings. This means that when using DRY for assessing compliance with this criterion will lead to building designs that can be expected to be additionally overheated every 2nd year on average.

The use of a 'mean year' as a boundary condition for T-BPS seems to have some limitations that building designers should be aware of. However, using a 'mean year' like DRY is just one of many ways of representing weather conditions; several studies have described and contrasted the these, see e.g. Barnaby and Crawley (2011), Al-Mofeez et al. (2012), Herrera et al. (2017), Ramon et al. (2018), and Yassaghi and Hoque (2019) to mention a few. Overall, there seem to be two strategies for setting up weather data files for T-BPS, namely 1) use of past weather data or 2) use of future weather. Within these strategies, different types of weather data files are regarded to serve different purposes in building design. The following two sections provide a brief overview of the two strategies and their different categories of weather files. The last section of this introduction outlines the contribution of this paper.

Past weather

The use of past weather for T-BPS can be divided into the following three categories[1]: 1) 'Multi-Year', 2) 'Typical Year', and 3) 'Extreme Year'. The weather data in these categories may originate from observed weather recordings, climate models, or climate generators. Using past weather data for building design implies the expectation that the data also represents future weather conditions. The following subsections contain a short description and purpose of the weather data in each category.

<u>Multi-year</u>

The 'Multi-Year' approach for T-BPS can be defined as the use of annual weather data for a consecutive number of past years for a specific location. A multi-year weather

[1] Ramon et al. (2018) suggests a fourth category named 'Representative Datasets' where a set is a 'typcial year' and an extreme cold and warm year for a specific location.

dataset should consist of 30 annual files (preferably for a period spanning from the current year minus 1 and 30 years back in time) as the World Meteorological Organization considers that climate statistics converge over 30 years (Brisson et al., 2015). Past weather data for building simulation can be obtained from observations, climate models e.g. from NCAR (NCAR, 2020) (see the webpage www.vejrdatafiler.dk (Broholt and Petersen, 2020) for an application example) or MESAN (MESAN, 2020) (see Shiny Weather Data (Lundström, 2020)), or climate generators (Eames et al., 2011).

Thermal simulations using 'Multi-Year' weather data provides insights into the variability of the building performance due to long-term variation in weather conditions. This variability is also useful for determining the risk profile for HVAC sizing. However, a multi-year simulation comes with a relatively long simulation time.

Typical Year

The 'Typical Year' approach for T-BPS can be defined as the use of a single-year dataset that represents the average weather conditions recorded for a consecutive number of past years at a specific location – hence considered to be 'typical' ('Average Year' or 'Representative Year' could be alternative names for this category). There are several methods to construct or select this type of weather data leading to different weather data files such as the Test Reference Year (TRY) (Levermore et al., 2006), Typical Meteorological Year (TMY, TMY2, TMY3) (Renné, 2016), Design Reference Year[2] (Lund, 1995), International Weather year for Energy Calculations (IWEC) (Thevenard and Brunger, 2002), Weather Year for Energy Calculations (WYEC, WYEC2) (Crow, 1981). The past weather data used for generating these files are most often observed data but could also be generated using climate models as in the Typical Downscaled Year (TDY) (Nik, 2016) or the probabilistic Test Reference Year (pTRY) (Liu et al. 2019).

This single-year approach is more computationally efficient than a 'Multi-Year' approach but only provides the average performance of a building over its lifetime as the data of a 'Typical Year' is essentially at the 50th percentile of the full distribution of possibilities; i.e. the probability that a data value within the dataset will be exceeded is 50% (Renné, 2006). The dataset does not contain extreme events and is therefore not suitable for 'stress tests' or HVAC sizing. A 'Multi-Year' or 'Extreme Year' approach should be applied for this purpose.

Extreme Year

The 'Extreme Year' approach for T-BPS can be defined as the use of a single-year dataset that is selected or constructed to contain extreme or near-extreme weather conditions for a specific location. There are several ways to select or construct an extreme year leading to different weather data files such as Design Summer Year (DSY) (Hacker et al., 2014), Hot Summer Year (HSY) (Liu et al., 2016), Extreme Warm Year (EWY) and Extreme Cold Year (ECY) (Nik, 2016), hot and cold extreme reference years (ERY_h and ERY_c) (Pernigotto et al., 2019), Typical Hot Year (THY) (Guo et al., 2019) or combinations of both like the Extreme Meteorological Year (XMY) (Ferrari, 2008)[3], Untypical Meteorological Year (UMY) (Narowski et al., 2013), the Design Reference Year[2] (DRY) (Watkins et al. 2013), or P10/P90 Extreme Year (Remund et al., 2018).

Thermal simulations using files from the category 'Extreme Year' are useful for 'stress test' of the building design and to size HVAC systems – like the 'Multi-Year' simulation; however, it is less time-consuming than a 'Multi-Year' simulation. The 'Extreme Year' approach cannot be used for assessing average expected performance or distribution of annual performance. A 'Typical Year' and 'Multi-Year' approach, respectively, should be applied for this purpose.

Future weather

All climate change scenarios published by the International Panel on Climate Change (ICPP) are anticipating an increase in the global outdoor temperature (Moss et al, 2008). This has been the main motivation for recent studies that seek to develop weather data files for T-BPS that considers climate change scenarios. One approach is the 'analog scenario method' that seeks to identify weather files from a location that currently has the climate conditions that are expected to be the future conditions at the current building location (Belcher et al., 2005). A similar approach, seen used in practice, is to identify a year from the past for the specific location that is warmer than normal. Limitations of these approaches are discussed briefly by Ramon et al. (2018). Another approach downscales data from General Circulation Models that take future climate scenarios into account from a spatial resolution of 150-600 km, see e.g. IPCC (2013), to a relevant spatial resolution for building simulations, e.g. by using dynamic downscaling, interpolation, stochastic weather generators or morphing (Wilby and Wigley, 1997; Belcher et al., 2005). The pros and cons of these downscaling methods are discussed by Ramon et al. (2018). The downscaling approach can be used to generate future weather files for T-BPS for both multi-year, typical, extreme years (see the section 'Past weather' of this paper for details on these definitions).

Contribution of this paper

Research on the consequence of future climate on thermal building performance in the Danish context is very rare. This paper presents the outcome of a simulation-based analysis of how climate change affects the thermal

[2] There are two different definitions of DRY. The first definition of DRY (Lund, 1995) is an expansion of the month selection method of the TRY and TMY method whereas Watkins et al. (2013) defines DRY as 'a year formed from individual more extreme weather months' and is proposed as a replacement of DSY.

[3] Another 'Extreme Year' definition also called XMY is provided by Crawley and Lawrie (2015).

performance of Danish office buildings. The analysis takes into consideration local differences in weather conditions across Denmark. This may challenge the current decade-long practice concerning T-BPS and building design where only one dataset, namely DRY, is assumed to represent weather conditions for all locations in Denmark. Furthermore, the results from a sensitivity analysis on how various building design parameters affect the variability of the simulation output are presented to investigate whether there is a shift in the ranking of design parameters most important to the simulation output variance due to climate change.

Method

Local TMY data files used for the analysis reported in this paper was downloaded from climate.onebuilding.org (climate.onebuilding, 2019). The TMY files available on this webpage are derived from observed hourly weather data from the US NOAA's Integrated Surface Database (ISD, 2019) using ISO 15927-4 (ISO, 2005). Only TMY files from locations in Denmark where a TMY file named 'TMYx.2003-2017…' are available were used; these files are derived from weather data from the 15 years 2003-2017 (other available files on the site use data from the period 1957-2017). Exceptions from this rule were location 'Aalborg airport' which was omitted due to an abnormal mean temperature of the dataset (9.4 °C) compared to neighbouring datasets, and Bornholm was only represented by one of its three data locations (namely 'Bornholm AP'). Furthermore, one data location in Germany near the Danish border was added ('Leck AP') to have a dataset that represents the most southwestern part of Denmark. This led to a total of 52 TMY locations.

The 52 local TMY dataset was morphed to future climate scenarios (the 2020s, 2050s, and 2080s) using the Climate Change Weather Generator tool (CCWorldWeatherGen, 2013). This tool uses the HadCM3 GCM (Pope et al., 2000) for the SRES A2 emission scenario as the basis for the morphing procedure (Jentsch, 2013). The SRES A2A scenario represents high growth and a global 3.5 °C warming relative to 1990 by 2100 (Nakicenovic et al., 2000). This led to 165 (3x52) TMY files.

A section of a one-story office building for six persons was modelled as one thermal zone in EnergyPlus, and uniform probability density functions (PDFs) of 24 input parameters were defined; see Petersen et al. (2019) for further details. A total of 1000 Latin hypercube samples was generated from the PDFs and implemented in 1000 individual EP models of the office section. These models were simulated for all 208 (4x52) TMY files resulting in a total of 208,000 EP simulations.

As mentioned in the introduction, Wang et al. [18] reported briefly on the construction of the Danish DRY2013 that has to be applied when documenting fulfillment of the energy performance and overheating criteria in the Danish Building Code (BR18, 2018). The report claims that the dataset is 'representative for the largest possible share of the Danish building stock given the available measurements' but does not contain any further documentation, specifications, or reference to the method used for establishing the DRY2013 dataset. Neither does the other reports about DRYs for Denmark (Wang et al. 2012; Nielsen, 2019). What can be derived from the reports is that the DRY2013 dataset contains one year of hourly weather parameters built from observed weather data for 12 typical months. The observed data comes from three different weather stations located in the eastern part of Denmark, and that only data from one station is used per parameter in the DRY2013 dataset. It is of interest to investigate how representative the use of DRY is for Denmark as a whole when compared to the local TMYs and the morphed local TMYs. The 1000 individual EP models were therefore also simulated using the DRY2013 weather file. The energy need for heating, cooling, and mechanical ventilation was extracted for all of the above-mentioned simulations and are presented in the result section.

The sensitivity analysis on how the 24 input parameters with an ascribed PDF affects the variability of the simulation output was performed by analysing the total-order effects (S_{Ti}) generated using the Sobol' method (Sobol', 1993) the same way as described by Kristensen and Petersen (2016). N=1000 Latin hypercube samples from the PDFs of the 24 input parameters were generated resulting in 26 000 EP models to be simulated. DRY2013 was morphed to the future climate scenarios DRY2020s, DRY2050s, and DRY2080s using CCWorldWeatherGen. The EP models were simulated with DRY2013 and morphed DRYs resulting in 104,000 simulations. The 95% confidence bounds of S_{Ti} for each weather scenarios were derived using 200 bootstrap samples.

Results

Morphed weather data analysis

Figure 1 illustrates the mean outdoor temperature of the morphed local TMYs on a map of Denmark. The grid is generated in Matlab using the interpolation option 'nearest' in the 'grid data' function. The grid size corresponds to approx. 7.5x7.5 km on the map. Figure 1, (top/left) shows that the annual average outdoor temperature for DRY is 8.1 °C while it is 1 °C higher (9.1 °C) for the average of all historical local TMYs. The average annual temperature across the TMY locations varies less than ±1 °C. In the morphed 2020s scenario (Figure 1, top/right), the average of all morphed local TMYs increased by 1.1 °C to 10.2 °C compared to the historical data. The increasing trend continues for the 2050s (Figure 1, bottom/left) with an increase of 1.2 °C

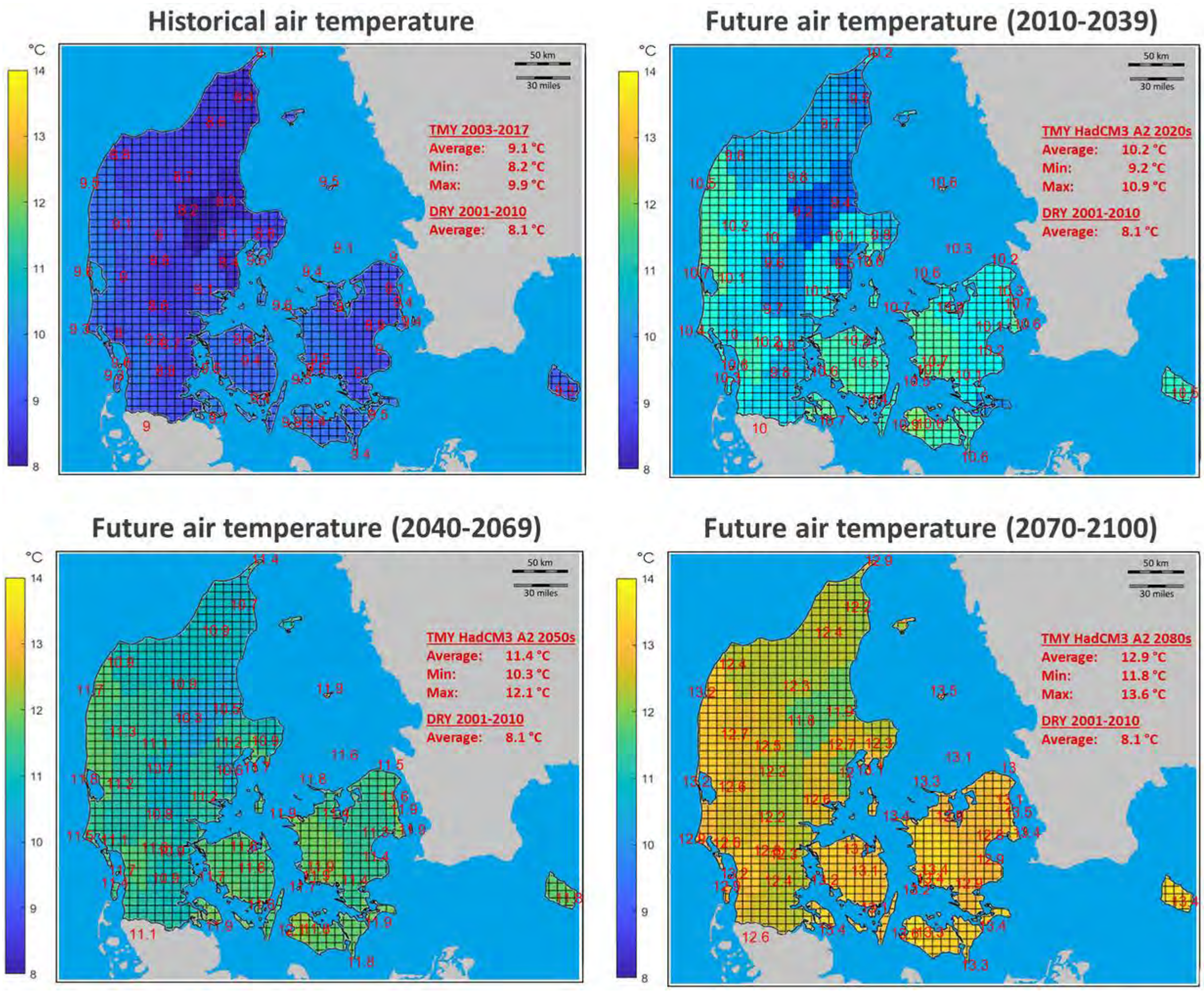

Figure 1: Local outdoor temperature now and in climate change scenarios.

to 11.4 °C, and another 1.5 °C to 12.9 °C for the 2080s (Figure 1, bottom/right). This corresponds to the mean warming of approx. 3.8 °C for Denmark by 2100. The slight deviation from the warming of 3.5 °C could be because that TMY data morphed in this study is not generated from the same 1961–1990 baseline climate data as the HadCM3 model runs. On the other hand, the HadCM3 'morphed' weather data that is based on the 'general circulation model', which is the case for CCWorldWeatherGen, are likely to underestimate future climate impacts under temperate climates with maritime influence (like Denmark) compared to more detailed 'regional climate model' data of the same emissions scenario family (Jentsch, 2013).

Figure 2 (left) illustrates the monthly mean temperatures of the datasets in the analysis including the former Danish DRY from 1995. DRY2013 is, in general, colder in the heating season months Oct-Mar than the TMY datasets; in fact, there are three months where the mean monthly temperature in DRY2013 is lower than the lowest average of all TMYs (Mar, Nov, Dec). Especially March seems unusually low; 3.1 °C lower than the lowest mean in the TMYs. The mean temperatures in the other months of the year are quite alike but DRY2013 is a little warmer in July and August. It is also noted that there is a rather large difference in mean for the TMYs in each month. The monthly mean temperatures in the climate change scenarios have – with few exceptions the same magnitude of increase as the mean annual temperatures.

Figure 2 (right) illustrates the monthly mean global solar radiation on a horizontal plane. The mean solar radiation for DRY2013 and DRY1995 are much lower in May-July compared to the mean of the TMYs but they are not outside their noticeable large min-max range. The climate change scenarios only result in slightly increased solar radiation in the summer and fall months.

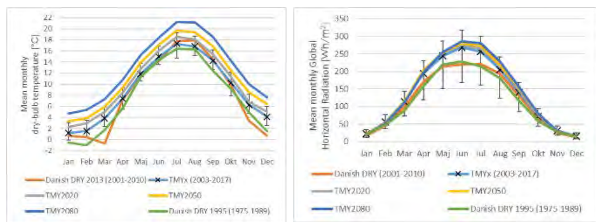

Figure 2: Monthly mean values of weather data.

Building simulation

Figure 3 and 4 illustrates the mean heating and cooling output, respectively, from the 1000 EP simulation for

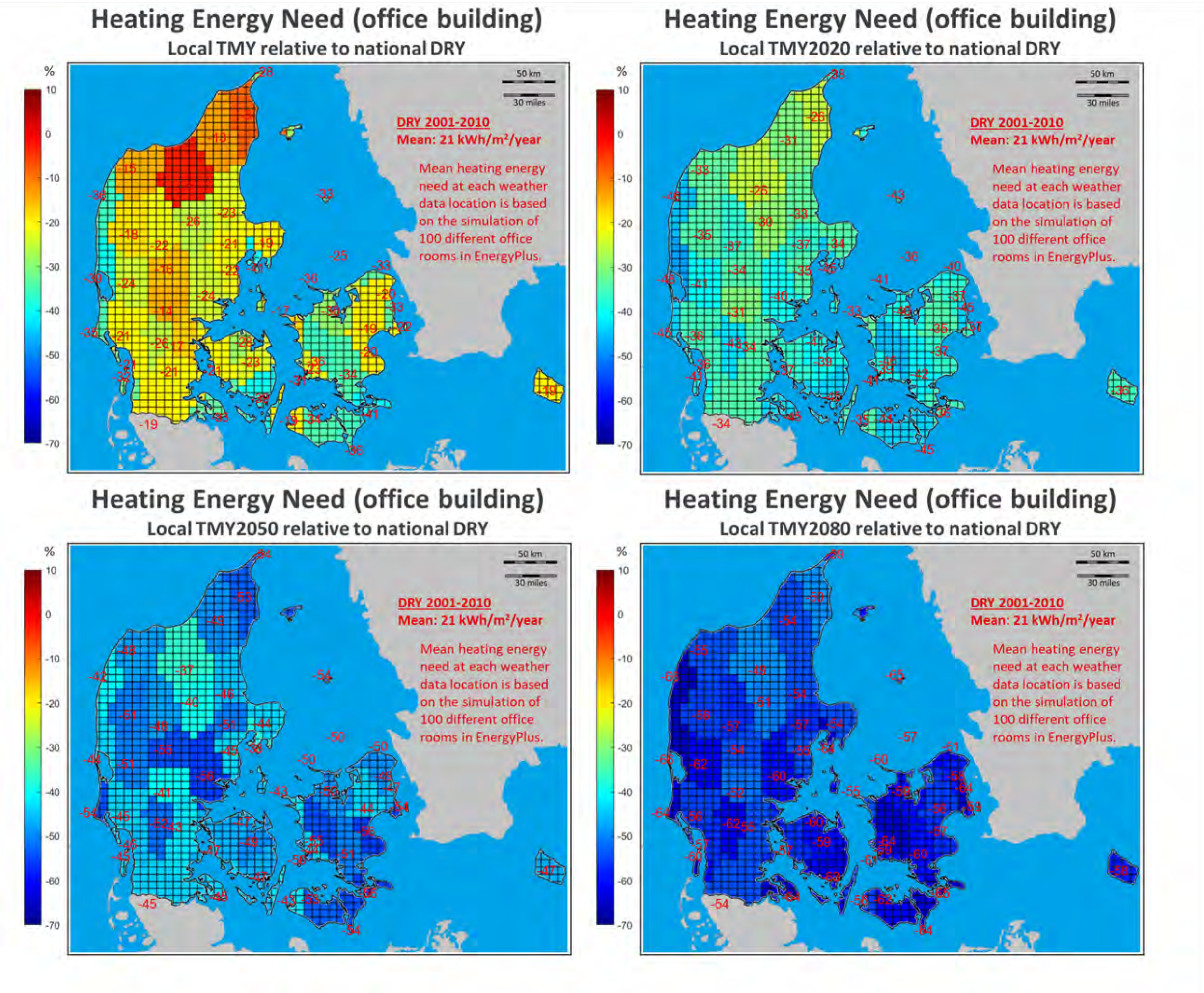

Figure 3: Local heating energy needs now and in climate change scenarios relative to DRY2013.

each TMY location relative to DRY2013. The energy need for heating and cooling for the historical TMYs is, in general, lower than for DRY; in fact, some locations do not have a cooling need according to TMY. Only a few locations have a higher cooling need.

In the 2020s scenario, the heating need is getting lower and the cooling need is getting higher for all TMy locations; more locations exceed the cooling need calculated with DRY2013. This development continues in the 2050s where it is almost only the west coast of Jutland that still has a cooling need lower than DRY2013. In the 2080 scenario, the cooling need is >200% and the heating need is <50% for the vast majority of the country.

Sensitivity analysis

Figure 5 illustrates the simulation outcome from the 1000 EP models for DRY2013 and its three morphed scenarios. The mean heating need drops and the spread is decreased as a function of the scenario time frame; the tendency is opposite for the cooling need.

The results from a sensitivity analysis on how the 24 building design parameters affect the variability of the simulation output using DRY2013 and the climate change scenarios, respectively, are shown in Figure 6. The group of most important parameters is not changed due to the climate change scenarios but a shift in priority seems to take the form: While the importance of passive means such as window area, solar heat gain coefficient (SHGC), and night ventilation drops slightly as a function of the scenario time frame, the coefficient of performance of the cooling system (COP) is getting increasingly more important. This seems reasonable as it is the outdoor temperature that is affected by climate change; this reduces the potential for night cooling and increases the importance of effectively cooling down the outdoor air before supplying it to the indoors. Consequently, the window variables get less important as they govern solar heat gain which is not affected much by the climate change scenarios.

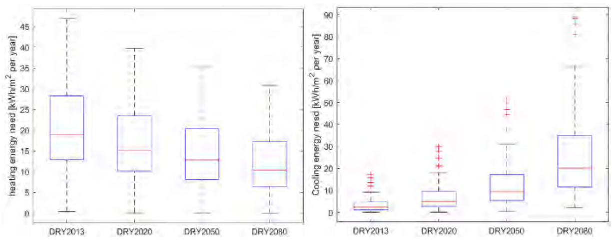

Figure 5: Simulated heating and cooling need now (DR2013) and in climate change scenarios.

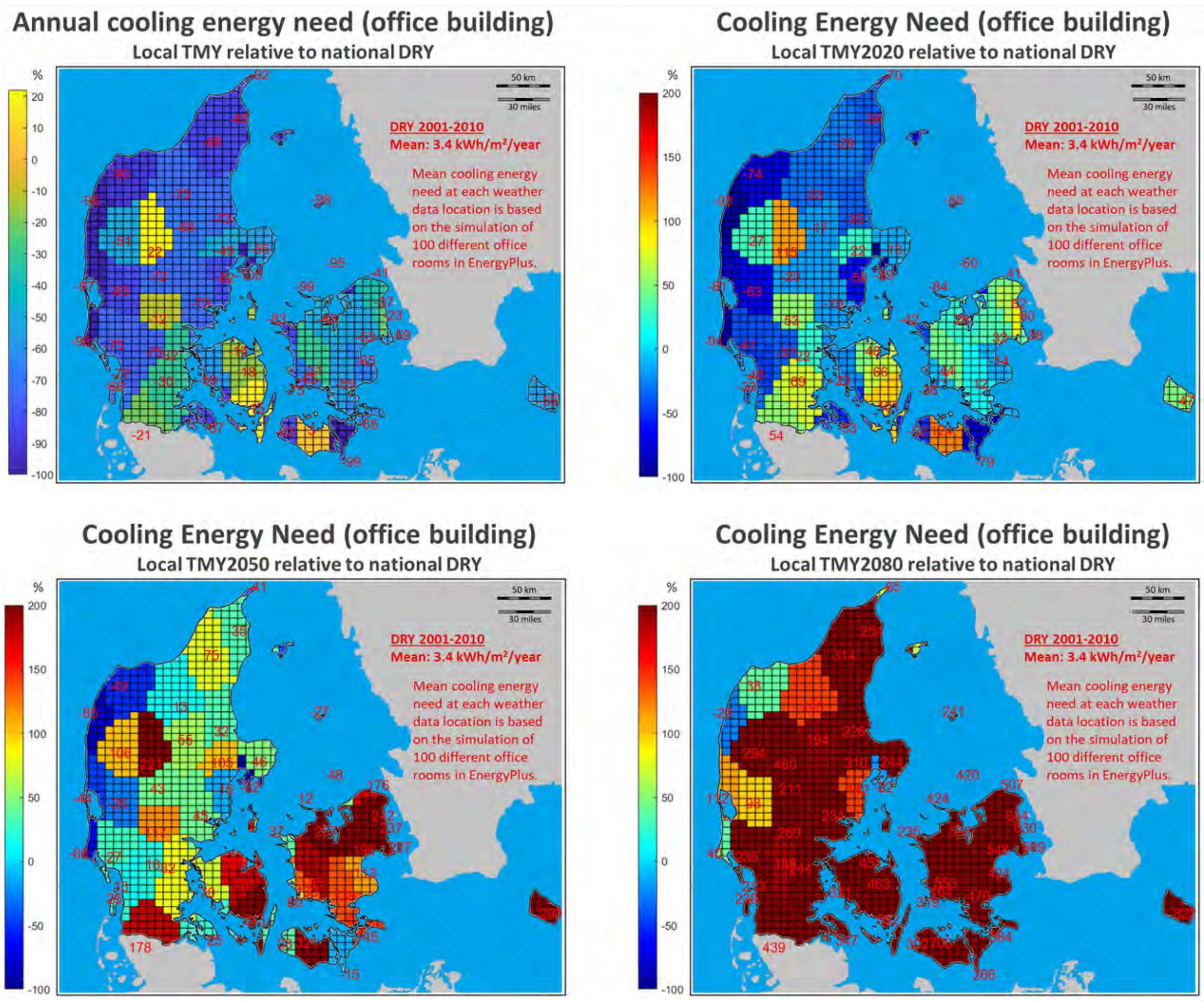

Figure 4: Local cooling energy needs now and in climate change scenarios relative to DRY2013.

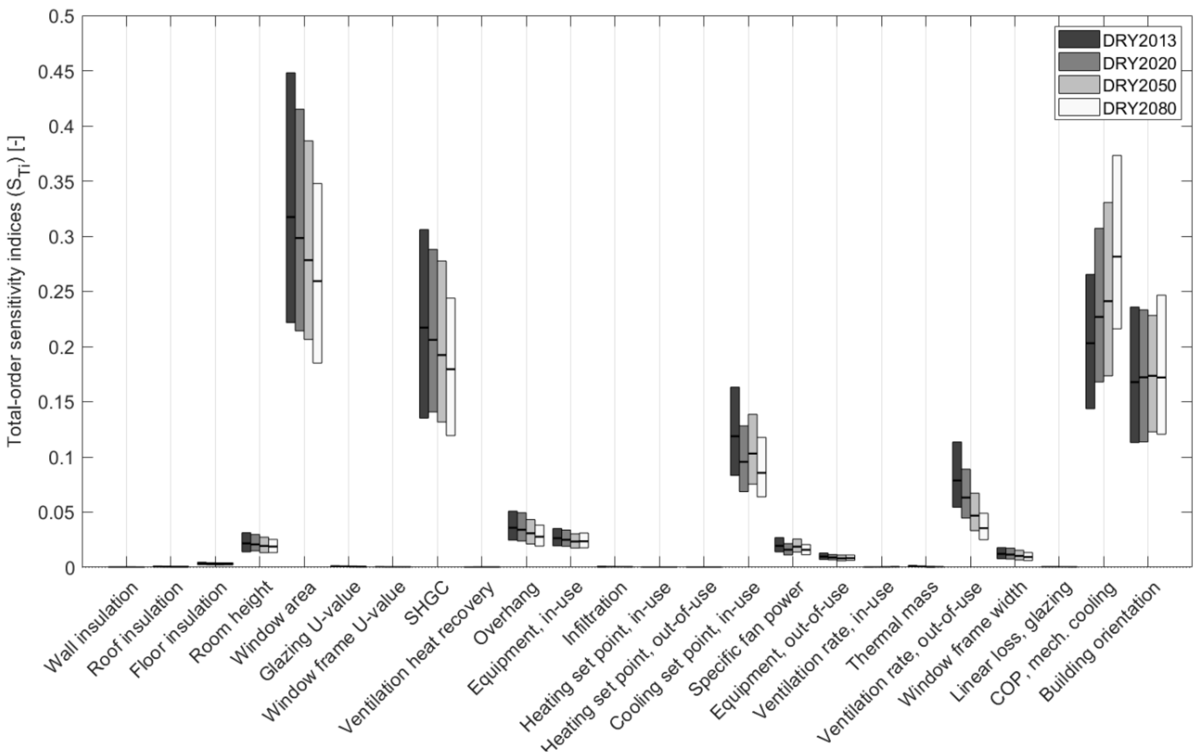

Figure 6: Results from the sensitivity analysis using DRY2013 and the climate change scenario.

Conclusion

The results of the study indicate that the current Danish practice of using mean weather data constructed from historical data for T-BPS for informing design decisions is not appropriate if building designs are to be resilient to climate change. There are several options for integrating considerations about the variability of annual weather conditions and climate change into a more climate change-resilient design practice. This paper provides a comprehensive list and discussion of these options; future research should investigate these in a Danish context carefully as an input to a discussion on changing practice regarding design weather conditions. Furthermore, sensitivity analysis indicates that variability in energy performance is becoming less sensitive to passive design; increasing outdoor temperatures due to climate change makes the energy performance more sensitive to the energy efficiency of mechanical cooling systems. This change of priorities should also be integrated into the design practice of today.

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