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Simple future weather files for estimating heating and cooling demand

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ABSTRACT

Estimations of the future energy consumption of buildings are becoming increasingly important as a basis for energy management, energy renovation, investment planning, and for determining the feasibility of technologies and designs. Future weather scenarios, where the outdoor climate is usually represented by future weather files, are needed for estimating the future energy consumption. In many cases, however, the practitioner's ability to conveniently provide an estimate of the future energy consumption is hindered by the lack of easily available future weather files. This is, in part, due to the difficulties associated with generating high temporal resolution (hourly) estimates of future changes in air temperature. To address this issue, we investigate if, in the absence of high-resolution data, a weather file constructed from a coarse (annual) estimate of future air temperature change can provide useful estimates of future energy demand of a building. Experimental results based on both the degree-day method and dynamic simulations suggest that this is indeed the case. Specifically, heating demand estimates were found to be within a few per cent of one another, while estimates of cooling demand were slightly more varied. This variation was primarily due to the very few hours of cooling that were required in the region examined. Errors were found to be most likely when the air temperatures were close to the heating or cooling balance points, where the energy demand was modest and even relatively large errors might thus result in only modest absolute errors in energy demand.

1. Introduction

Global warming is apparent and there is general consensus that even by dramatic reductions in the global anthropogenic emissions of greenhouse gasses, adaptation action will be necessary to address those impacts that are already unavoidable. While substantial reductions in CO_2 emissions can be achieved from optimized energy use in buildings, present and future constructions require to be taken into account the changing climate conditions, including increased risk and intensity of extreme events such as floods, strong winds and heat waves. Unsurprisingly, there is a strong interest in predicting the effects of the expected future climate warming on the built environment in terms of developing appropriate adaption and mitigation strategies [1–3]. In this context, there is a particular need from property owners and facilities managers for estimates of the future energy demand for heating and cooling [4].

The energy demand of buildings, both now and in the future, can be quantified in a variety of ways. Common methods utilize (i) Heating Degree Days (HDD) and Cooling Degree Days (CDD) from which fuel consumption is directly inferred [5–7], (ii) total energy consumption or heating and cooling demand [8,9], (iii) relative changes in energy demand [10,6], or (iv) CO_2 emissions, which are a function of energy consumption and supply source [10]. Other factors directly related to buildings' thermal performance can be quantified by metrics as suggested by de Wilde [11], i.e. (i) peak demand of a building [12] (ii) peak demand on the grid [13] (iii) and the overheating risk in different types of buildings [14–16]. In this article we consider the relative change of the energy demand using both a degree day method and a dynamic simulation tool.

To determine the annual energy demand of a building, we require a weather file that describes the typical weather

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conditions at the building's location, as well as information on the structure and usage of the building. A typical weather file is usually constructed from real, measured data, the details of which are discussed in Section 2.1. To determine the *future* annual energy of a building requires a future weather file, i.e. a projection of the weather at some time of interest in the future. Research in constructing future weather files has received significant interest recently, and this work is summarized in Section 2.2.

Despite the significant interest, there is evidence that future weather files are often not readily available in many regions. For example, Jentsch et al. note the lack of availability of approved climate change weather files for simulation programmes [15]. This is supported by Jones and Thornton who also comment that the lack of availability of weather data is a serious impediment to undertaking climatic modelling to assess the impact on agriculture [17].

The lack of available future weather files is, in part, due to the difficulty in acquiring future weather projections within a sufficiently localized region and at the hourly temporal resolution required by standard weather file formats. To produce such data typically requires downscaling global circulation models to regional levels, e.g. using regional climate models, followed by detailed analyses to assert the quality of the projections. This work requires expert knowledge of climatology and is typically conducted at dedicated research centres and national meteorological institutes. A wide range of global and regional climate projections provided by different climate modelling groups may be extracted from international multi-model inventories like the CMIP5 (Coupled Model Intercomparison Project) and CORDEX (Coordinated Regional Climate Downscaling Experiment) data centres, however, typically at coarse temporal (daily) and spatial resolutions (25–50 km).

In this study we investigated the implications of temporal resolution on future simulations of buildings' energy demand. To address this issue we used a simple "change-based" method for constructing future weather files, e.g., adding an estimated annual increase in air temperature to an existing weather file, and we then considered whether the results provide useful estimates of a building's future energy demand. We investigated how estimates of a building's energy demand differ based on different future weather files constructed using coarse (annual), medium (monthly) and fine (hourly) temporal resolution data of air temperature change. In this study we only considered a single parameter, outside dry bulb temperature, of a future weather file, i.e. other parameters such as humidity, solar irradiation, precipitation and wind speed were not considered. However, we note that the work of [18] suggested that "… with a +10% change in proposed future values for solar radiation, air humidity or wind characteristics, the corresponding change in the cooling load of the modelled sample building is predicted to be less than 6% for solar radiation, 4% for RH and 1.5% for wind speed, respectively". Similarly, as noted in Ref. [19] even though the thermal comfort of a building depends on many different weather parameters such as outdoor dry bulb temperature, relative humidity, wind speed and solar irradiation the most significant weather parameter that has the strongest correlation with the internal thermal comfort is the outside air temperature during warm periods. Also, Kershaw et al., who investigated internal temperatures and energy usage in buildings, pointed out that the external air temperature is a major driver of the internal temperature [16].

The emphasis of the present work was to investigate how well a future weather file was able to predict future energy demand, whereas broadly speaking, previous work has been concerned with how "realistically" a future weather file models the expected weather. Thus, our focus in this paper was on the application of future weather files rather than on climate modelling. Of course, we expect more "realistic" future weather files to provide accurate estimates of energy demand. However, as we previously discussed, the creation of these files can be difficult or at least impeded by the lack of available data. If simpler future weather files can produce very similar estimates of a building's energy demand, this will facilitate the modelling of future energy demand by practitioners.

In the following we first briefly review how historical weather files are created (Section 2.1) and categorize different methods to construct future weather files. Three common ways are discussed for constructing future weather files with annual, monthly and hourly temporal resolution (Section 2.2). In Section 2.3 we describe the commonly used methods to estimate the energy demand of a building, such as the degree-day method and dynamic building simulations. In Section 3 we investigated the sensitivity of a building's energy demand to three different methods of calculating a future weather file, where the calculations were based on the abovementioned coarse (annual), medium (monthly) and fine (hourly) estimates of future air temperature changes obtained from a regional climate model. We used the degree-day [20] analysis, which is independent of any specific building model, and the sensitivity is measured based on the change in the number of heating and cooling degree-days resulting from the analyses. For comparison we also investigated the sensitivity of three dynamic simulation models to the differently constructed future weather files. These three building models were (i) an existing naturally ventilated historical building, (ii) the same building renovated to have an air tight envelope, windows with improved thermal properties and naturally ventilated and (iii) the same building renovated as (ii), where the ventilation is provided by mechanical ventilation, and the heat-losses due to ventilation are recovered. Section 4 discusses the experimental results. Finally, Section 5 summarizes our findings and discusses some possible lines of future research.

2. Construction of weather files

This section outlines how current weather files are constructed based on historical observations of weather parameters as well as how future weather files are constructed and used to provide estimates of the energy demand of buildings.

2.1. Historical weather files

A weather file consists of a variety of parameters that vary with the type of weather file. The most common weather files are (i) the Example Weather Year (EWY) developed by Chartered Institution of Building Services Engineers (CIBSE) [21] and mostly used in UK. (ii) the Typical Meteorological Year (TMY) developed in 1978, which is mostly used in the USA, (iii) the International Weather Year for Energy Calculation (IWYEC) developed and used by ASHRAE in the USA and other global locations, (iv) the Test Reference Year (TRY) and Design Summer Year (DYS) developed by the CIBSE and used in Europe, and (v) the Design Reference Year (DRY) developed by Ref. [22] and used in Denmark and 20 other countries.

In this paper we used data from a Design Reference Year (DRY), which comprises 25 parameters. The DRY was chosen as the base line for our experiment mainly because of our knowledge of how the files were created as well as availability. Each parameter is assigned hourly values for a period of one year, i.e. the temporal resolution is hourly, and thus a DRY file contains 8760 values for each parameter. The construction of data in a DRY file is similar to

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the construction of data for other weather files. The basic steps in constructing a weather file are:

(i) Collect real weather data over a period of years. The DRY file is constructed using weather data for the 15 year period of 1975–1989.
(ii) Compute the average year, i.e. determine the average value of each parameter over the 15 year period.
(iii) For a given interval, e.g. 1 month, compare the monthly means with each of the 15 actual months and select the actual month that is closest to the average. The selected month then becomes part of the weather file. Repeat this process for all intervals in the year [22].

Thus, a weather file is not the average of weather parameters over some period. Rather, it consists of samples of real weather files taken from this period, where the samples are chosen for their similarity to the average of the weather parameters. The measure of similarity can change across methods, but typically considers various factors, including both monthly and seasonal mean values and occurrence of cold, warm, sunny and overcast days. The true correlation between different parameters such as air temperature, solar irradiance, cloud cover and wind is preserved. Note that the sampling of real weather files ensures that the variance or standard deviation of values in the weather file is approximately the same as for an actual year. In contrast, the variance of the average year is much lower, being reduced by the square root of the number of years.

2.2. Constructing future test reference years

The Special Report on Emission Scenarios (SRES) [23] developed by the International Panel on Climate Change (IPCC) defines a family of possible emission scenarios for the next 100 years, based on economic, social, technological and environmental assumptions. Specifically, this paper considers scenario A1B [24], which represents an intermediate scenario, and which has been used in a number of different climate model experiments. Climate data from coupled atmosphere-ocean Global Circulation Models (GCM) are typically available at a temporal resolution of a month and a coarse spatial grid resolution of 150–300 km. These projections may be further refined using Regional Climate Models (RCM) to provide climate projections at a grid resolution of typically 10–50 km. The temporal resolution of the regional projections is generally available from data centres at a temporal resolution of days or hours.

As noted earlier, climate projections vary in both spatial and temporal resolution. Here we will not consider the variability of spatial resolution. Rather, given an existing weather file and corresponding projections of future changes in these weather parameters, we investigate whether the temporal resolution has a significant effect on estimates of a building's energy consumption.

Projections of future weather conditions can be broadly categorized as (i) absolute or (ii) relative. In the former case, projections of weather parameters from climate simulations are used directly, while in the latter case projections of expected *changes* in weather parameters are used. The projected changes are then added either to a synthetic weather series derived from a weather generator, or to an existing (observational) weather series, in order to produce the final future weather file. Both methods will be described below.

2.2.1. Category 1 – absolute

One general method used to construct future weather files is to obtain the absolute values directly from regional climate models. This method has been used by Refs. [8,9]. As mentioned above, regional climate model simulations are governed by Global atmosphere-ocean Circulation Models (GCM), typically at spatial resolutions of ~200 km, and produce finer scale projections at a spatial resolution of 10–50 km. The advantages of using direct input from climate models are that the physical correlations between the weather parameters are preserved (as well as they are captured by the models) and that data is, in principle, available at hourly resolution, as required by dynamic building simulation models. Unfortunately, for practical purposes only 6-hourly time series data are generally stored by international data centres, and since 1-hourly data is not stored locally by all modelling groups, the availability of such data may be sparse. Moreover, the complexity of the models usually requires collaboration with climate modelling experts to ensure proper use of such data.

Recently, the "absolute" approach has been extended to create future weather files that are based on a probabilistic weighting over a number (ensemble) of climate model realizations. For example [15,14,25,26] use a set of stochastically generated climate change weather files produced by experts in climatology as part of the UKCIP climate change scenarios for the UK (UKCP02 and UKCP09). A stochastic weather generator was used to generate statistically plausible weather data, based on actual observations and a Regional Climate Model (RCM) with a spatial grid resolution of 25 km. The weather generator yields daily and hourly data at a 5 km spatial resolution. In Ref. [25] this method was compared to a relative method, described below, in which predicted *changes* are added to an existing reference year weather file. The weather generator method was found to produce more realistic projections[1] of the future weather than the relative method. However, national weather generators are not available in all countries, which limits their application.

2.2.2. Category 2 – relative

Relative methods are provided with projections of *changes* in weather parameters rather than the absolute values from climate models, typically calculated as the difference between a future (scenario) time period and a control period. These relative changes are then incorporated into a current reference year weather file based on observations in order to produce the future weather file. When used to analyse historical time series data, climate models generally exhibit systematic biases, which carry over and may even be more emphasized in future projections. Systematic biases can be attributed to errors in the model formulation, such as shortcomings in the parameterization of sub-grid processes, and more fundamentally to the deficiencies in accurately representing the climate system, e.g. the climate sensitivity, due to our lack of knowledge. As noted in Ref. [6]"… this means that even the present day climate [predictions] may be biased, for example warmer than measured. It is generally assumed that any changes to the climate caused by anthropogenic forcing are then biased by the same amount so that the changes in climate are correct. It is for this reason that climate change scenarios generally quote changes rather than absolute values".

Projected changes can be incorporated into a present-day weather file in a variety of ways, depending on the climate parameter in questions (e.g. air temperature), as discussed in Ref. [6] and include (i) directly adding the change (shift), (ii) multiplying the present-day data by a scaling factor (stretch) that controls the variance of the parameter and (iii) a combination of (i) and (ii).

[1] There are a variety of ways researchers have quantified whether projections are realistic. For example, Eames [25] considers (i) intervariable relationships, (ii) statistical plausibility as measured by mean and variance, and (iii) minimum and maximum air temperatures.

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The predicted changes may have different temporal resolutions. For example [7,15,6] used monthly predictions [27], used seasonal mean changes, and [28] discussed annual changes.

The work of [6,28] are particularly relevant to the work described here. The focus of [6] was to produce design weather data for buildings thermal simulations that account for future change to climate. Their main aim was to develop a practical method by adjusting present-day weather data based on predicted changes in climatic parameters that produced meteorologically consistent data at a fine spatial resolution of 25 km (RCM). The authors compare their "morphing" method with data derived directly from a regional climate model. To do so, they looked at the change in the number of heating degree-days, observing that this provides a means of comparing the present morphing method with the changes to the degree day computed directly from the regional climate model. While this is similar to what we describe here, there is an important distinction. While Belcher et al. used the degree-day method to partially validate the quality of their constructed future weather file, in contrast, we used the degree-day method to assess the ability of different future weather files to estimate future energy demand.

The work of [28] focuses on developing a framework for producing future weather files that is able to deal with different levels of available climate change information, while retaining the key characters of a "typical" year weather data for a desired period. The different levels of available information included predicted changes at different temporal resolutions. However, once again, the focus was on constructing realistic weather files, not on their application, and there was no investigation of the effect that different resolution has on estimates of a building's future energy demand.

2.3. Methods to estimate energy demand

Here we briefly discuss two common methods for estimating energy demand for a building: (i) degree day method and (ii) dynamic simulations of a building.

2.3.1. Degree-day method

Heating and cooling demand are generally functions of various weather parameters, including outside dry bulb temperature, humidity, solar irradiation, wind speed and direction. The degree-day method on the other hand only considers the outside dry-bulb temperature. Nevertheless, it is commonly used as a convenient method for estimating heating and cooling demand in a building.

The principle behind the degree-day method is that heating and cooling demand are proportional to the area below or above a balance point temperature. For a particular building a heating balance point temperature is defined as the temperature below which heating is required to maintain a comfortable temperature. Similarly, for a particular building, a cooling balance point is defined as the temperature above which cooling is required to maintain a comfortable temperature. These two balance points are usually different.

The degree-day method assumes a linear relationship between energy demand and the degrees above (below) the cooling (heating) balance point temperature. If t_{bh} is the heating balance point, then the energy demand for heating, Q, is

$$Q_{\mathrm{net},h} \propto \frac{\sum_i^{8760} \max(0; t_{bh} - t_i)}{24} \tag{1}$$

where t_i is the hourly outside temperature at hour i provided by a weather file.

Similarly, we can calculate the energy for cooling. If t_{bc} is cooling balance point, then the energy demand for cooling, Q, is

$$Q_{\mathrm{net},c} \propto \frac{\sum_i^{8760} \max(0; t_i - t_{bc})}{24} \tag{2}$$

where t_{bc} *is* the cooling balance point.

The degree-day method is a convenient way to examine the effect of different weather files on estimates of the energy demand of buildings [20]. As noted earlier, the number of degree-days above a balance point temperature is independent of the specifics of a building – it is the constant of proportionality needed in Equations (1) and (2) that is building specific and which converts degree-days into energy demand. Despite this advantage, the degree-day method has a number of disadvantages as noted in, for example [29,28]. Guan argues that some of the limitations of the degree-day method are (i) that it requires that building use and heating and cooling systems are constant, and (ii) that it is only appropriate in climates where humidity is not an issue. To address these concerns regarding the degree-day method, we also provide experiments using dynamic building simulations, which do not have these limitations.

2.3.2. Dynamic building simulation

A dynamic building simulation can also be used to estimate a building's energy demand. Using a dynamic simulation, the energy performance of a building is calculated based on the building's location, construction type, form of ventilation, occupancy and weather parameters at the location of the building. Dynamic simulations address some of the limitations of the degree-day method as the heat losses and heat gains are calculated (i) based on the particular building's thermal properties and internal gains on an hourly base, (ii) and take into account other weather parameters, which could affect the annual energy demand, such as solar gains, wind, humidity etc. Based on outputs from the dynamic simulation programmes the heating and cooling balance point can be calculated for the specific building.

Dynamic building simulations are becoming commonly used to analyse the performance of the envelope of new buildings, and the performance of different passive and active heating and cooling systems [15,25,10,30]. Examples of dynamic building simulation programs include TAS,[2] BSim,[3] IES,[4] IDAICE[5] or Energy Plus.[6]

A dynamic building simulation requires both (i) a detailed model of the building and its heating and cooling elements, and (ii) a weather file that represents the typical weather conditions in the location of the building. To investigate the impact of climate change on buildings, a dynamic building simulation must be carried out using a future weather file incorporating climate change projections. Dynamic simulation programmes typically require weather files to have an hourly temporal resolution.

3. Methodology

To determine whether the temporal resolution of future weather files affects estimates of a building's energy demand, we

[2] TAS (Thermal analysis simulation) software developed by a company Environmental Design Solution Limited (EDSL), UK mostly used in UK.

[3] BSim (Building Simulation) is an integrated PC tool for analysing buildings and installations developed by the Danish Building Research Institute SBI, now part of Aalborg University, that is mostly used in Denmark.

[4] IES (Integrated Environmental Solutions), mostly used in the UK, USA, France, Germany.

[5] IDAICE – IDA Indoor Climate and Energy is a building simulation tool developed by EQUA Solutions that is mostly used in Sweden, Finland, Germany, Switzerland and UK.

[6] Energy Plus –is a whole building simulation program developed by the US Department of Energy.

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constructed three future weather files based on the relative methods described in Section 2.2.2. In the following we refer to the three weather files as Annual, Monthly and Hourly offset methods:

1. Annual offset method – adding the expected annual increase in air temperature to a past design reference year
2. Monthly offset method – adding the expected monthly increases in air temperature to a design reference year
3. Hourly offset method – adding the expected hourly increases in air temperature to a design reference year

Note that in all three cases, only the air temperature parameter of the design reference year was changed. All other parameters were unaltered.

3.1. Weather data

To construct the three future weather files we considered an existing weather file consisting of n parameters, p_1, p_2 … p_n. Each parameter, p_i, is a vector of 8760 hourly values. We also considered a projection of changes to each of these parameters, denoted Δ_1, Δ_2 … Δ_n. Each parameter, Δ_i, is a vector. The dimensionality of the vector may be different from that of the corresponding parameter p_i. For example, in the case of dry bulb temperature, the predicted change might be (i) a single 1-dimensional projection of the average annual change in air temperature, (ii) a 12-dimensional projection of the average monthly change in air temperature, or (iii) a 8760-dimensional projection of the hourly change in air temperature. Each parameter, p'_i, of a future weather file is constructed by adding the projected changes, Δi, to the corresponding parameter values, p_i, in the existing weather file. In this paper, we only considered the parameter of air temperature. All other parameters were left unchanged.

Mathematically, for case (i) we have:

$$p'_i = p_i + \Delta i_a \tag{3}$$

where Δi_a is a scalar constant predicting the average annual change in air temperature. This value is added to each of the 8760 values of p_i to produce the final hourly projections, p'_i.

For case (ii) we need to convert the 12-dimensional vector of monthly average changes to a 8760-dimensional vector of hourly projections. To do so, we simply add each of the 12 values by the number of hours in the corresponding month. Given the resulting vector, Δi_m, we then have:

$$p'_i = p_i + \Delta i_m \tag{4}$$

For case (iii) we have:

$$p'_i = p_i + \Delta i_h \tag{5}$$

where Δi_h is a 8760-dimensional vector predicting the expected hourly changes in air temperature. These values are added to each of the corresponding 8760 values of p_i to produce the final hourly projections, p'_i.

The DRY weather file used in this study is based on actual rather than interpolated weather data for our region of interest, and the fact that it covers the period from 1975 to 1989, which falls within the normal period of 1961–1990 commonly used by the meteorological community.[7]

Table 1
Monthly changes calculated from HIRHAM5-BCM.

Monthly change	
Month	Monthly change T °C
January	1.35
February	1.42
March	1.93
April	1.60
May	0.95
June	1.18
July	1.06
August	1.02
September	1.07
October	1.13
November	1.30
December	1.87

Annual, monthly and hourly climate projections were investigated for Gentofte, a suburb of Copenhagen, Denmark. Hourly data from a transient regional climate simulation at a spatial resolution of 25 km was provided by the Danish Meteorological Institute (DMI). The obtained data covers the control period of 1961–1990 and a future scenario period of 2021–2050 using the IPCC A1B scenario. The climate simulation was carried out using DMI's HIRHAM5 regional climate model, forced by the BCM GCM (Bergen Climate Model) and was part of the EU-ENSEMBLES project [31]. The choice of the scenario period 2021–2050 is somewhat arbitrary, and was chosen based on the fact that the components such as HVAC systems of new and refurbished buildings are currently expected to have a lifetime of 20–30 years.

To extract the weather data (in this case only air temperature) for the Gentofte region, the Climate Data Operator (CDO) [32] software was used, specifically the REMAP operator.[8]

To generate the projected hourly changes in air temperature, a 8760-dimensional hourly offset Δ_h was computed by taking the difference between the average regional climate model projections for the period 2021–2050[9] and subtracting the corresponding average regional climate model projections for the control period 1961–1990.

Picking out individual years in a climate simulation is not meaningful, since climate models provide both a projection of the statistical properties of the weather based on the prescribed concentrations of greenhouse gasses and atmospheric aerosols overlaid with natural climate variability. Due to natural variability, the usual best practice in climate science, which we adopt here, is to consider averages of typically 20 or 30 years rather than individual years (30-year averages has been the de facto best practice for many years, corresponding to the iconic meteorological normal period 1961–1990, whereas 20-year averages have been the norm in the last two IPCC reports).

The projected hourly changes in air temperature, a 8760-dimensional hourly offset, Δ_h is given by

$$\Delta_h = \widehat{y}_{2021-2050} - \widehat{y}_{1961-1990} \tag{6}$$

where Δ_h is a 8760-dimensional vector of hourly differences and $\widehat{y}_{2021-2050}$ is given by

$$\widehat{y}_{2021-2050} = \frac{1}{30}\sum_{i=2021}^{2050} y_i, \tag{7}$$

[7] Note, that the DRY format is not compatible with some dynamic simulation programs, such as TAS. We therefore converted the DRY formatted data to an Energy Plus format (EPW).

[8] The input parameters to CDO are the longitude and latitude for Gentofte, i.e. lon = 12.67/lat = 55.63 (bicubic interpolation between grid cells i.e. REMAPBIC).

[9] in the obtained model data year 2047 is missing.

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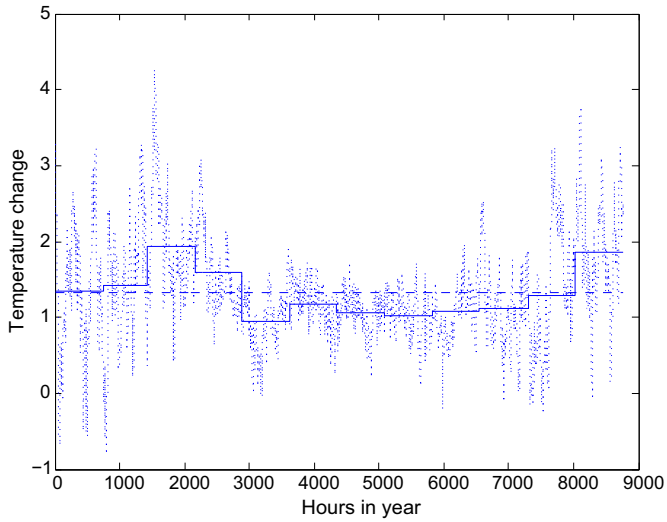

Fig. 1. Annual (dashed), monthly (solid) and hourly (dotted) projections of air temperature changes for the period 2021–2050.

and

$$\hat{y}_{2021-2050} = \frac{1}{30}\sum_{i=2021}^{2050} y_i, \tag{8}$$

and y_i is a 8760-dimensional vector of hourly air temperatures for year i.

In order to assess the quality of the regional climate model simulation, we note that the expected annual and seasonal changes in Denmark for different weather parameters based on 13 simulations from the ENSEMBLES multi-model experiment are summarised in Ref. [33]. Assuming the IPCC A1B scenario, the mean annual air temperature change in Denmark based on this ensemble of model projections is estimated at approx.1.2 °C for the period 2021–2050 as compared to the control period (1961–1990). Conversely, the annual change in air temperature for the same period in Gentofte, Copenhagen area, based solely on the hourly HIRHAM5-BCM data set is approximately 1.32 °C. This seems to be consistent with the more robust ensemble estimate, bearing in mind that we are comparing one model to many and many grid points to a single grid point. In the following experiments all quantities (annual, monthly, hourly changes) were calculated using HIRHAM5-BCM data, ensuring that the only observed difference were due to differences in temporal resolution. The monthly changes are enumerated in Table 1 below.

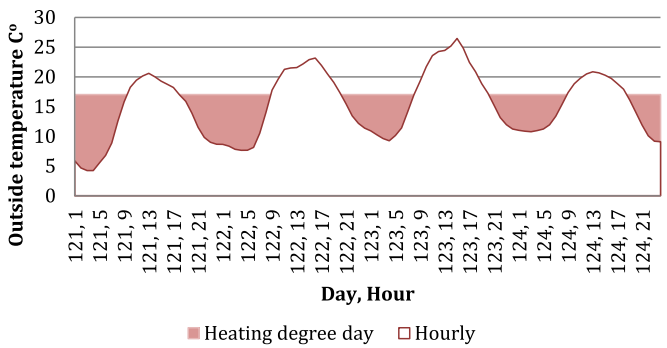

Fig. 2. Temperature profile for a 4-day period in May (day numbers 121–124) for the hourly weather file. The x-axis label, d, h refers to day d and hour h in that day. The shaded area represents the days when energy is needed for heating.

Table 2a
Number of hours when outside temperature is above or below heating and cooling base line in 3 different weather files.

Number of hours above (below) cooling (heating) balance points					
	Hourly	Monthly		Annual	
		Number of hours	Percentage of hourly	Number of hours	Percentage of hourly
Above 25	92	87	94.6%	98	106.5%
Above 26	60	55	91.7%	62	103.3%
Above 27	37	33	89.2%	37	100.0%
Below 17	7706	7713	100.1%	7630	99.0%

Percentages are relative to the hourly data.

The annual and monthly future weather files were constructed based on Equations (3)–(5), respectively. Fig. 1 illustrates the corresponding annual (horizontal line dashed), monthly (solid) and hourly (dotted) changes.

3.2. Degree day method balance points

We assume that the balance point for heating is 17 °C, which is typically used for estimating the heating degree days in Denmark and the balance point for cooling is 25 °C, above which "active" cooling is required. We assume that natural cooling can be obtained between 17 and 25 °C.

3.3. Building simulations

For comparison and to address the limitations of the degree-day method a dynamic thermal simulation model in TAS was constructed for an arbitrary existing, historic, naturally ventilated building in the Gentofte municipality near Copenhagen. In addition to exploring its present-day appearance, we consider two types of modifications, which have different energy efficiency consequences and different types of ventilation systems, to assert the dependency of our results on the particular choice of building. A detailed setup of the three models may be found as Supplementary Information and outlined below.

The reference building is an old residential building from 1920, which is now used as a day-care centre for children between 6 months and 3 years of age. The building is a 2-story building with unheated basement and unheated attic space. The building is heated by district heating with a heated area of 279 m^2 and a total area of 571 m^2. The building is naturally ventilated, except for the bathrooms, which have mechanical extracts. The building has recently been upgraded by adding 300 mm of insulation between the 1st floor and the unheated attic. The U-value of such a construction is typically 0.13 W/m^2K. The cavities of the external facades on the ground floor and 1st floor were recently (2009) insulated with 170 mm and 130 mm of cavity insulation

Table 2b
Area represents the heating degree days, that can be expressed as the energy demand required for cooling or heating, when outside temperature is above or below cooling or heating base line in 3 different weather files.

Area representing the energy required for heating or cooling					
	Hourly	Monthly		Annual	
		Area	Percentage of hourly	Area	Percentage of hourly
Above 25 (Cooling)	191	167.51	87.7%	189.71	99.3%
Below 17 (Heating)	7706	7713	100.1%	7630	99.0%

Percentages are relative to the hourly data.

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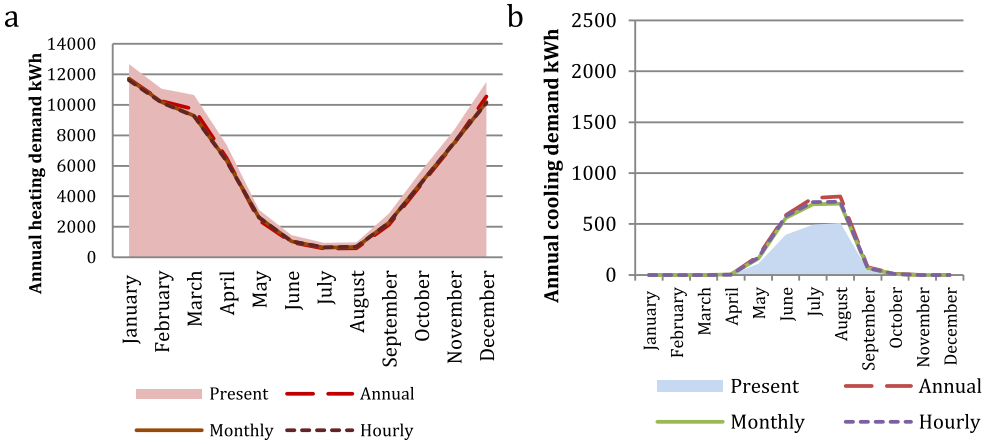

Fig. 3. a. Annual heating demand for the "existing" building for weather files based on present (shaded), annual (dashed), monthly (solid) and hourly (dotted) changes. b. Annual cooling demand for the "existing" building for weather files based on present (shaded), annual (dashed), monthly (solid) and hourly (dotted) changes.

respectively. The U-values of such constructions are typically 0.16 W/m^{2}K and 0.21 W/m^{2}K respectively. The original wood framed windows now have secondary glazing placed 120 mm from the external window frames. The U-value of such a construction is typically 2.8 W/m^{2}K.

Comparison of the simulation results with the actual energy usage and measured temperature of the building was used to validate the accuracy of the model.

Two other models, which are variations of the existing building, were also created with different types of ventilation. Thus we have three building models:

1. "Existing",
2. "Improved-NV", where the building's leakage was reduced by tightening the windows and doors, and the thermal performance of the windows in all occupied spaces was improved by adding a 3rd layer of K-coated glazing on the inner frame and improve the U-value to 0.8 W/m^{2}K. Natural ventilation was also established through carefully chosen top windows for the air supply using existing chimneys to extract the air.
3. "Improved-MV", is the same as 2, except that the passive ventilation system was replaced with a mechanical ventilation system, in which heat-recovery could be applied. However, we did not include heat-recovery in the present comparison. A more detailed description of the three building models is provided in Appendix 1.

4. Results

We considered the number of hours each of the three weather files is above or below a balance point temperature. For a particular weather file, we plotted the outside temperature as a function of time, and examined the area between the curve and the balance point, as shown in Fig. 2.

By assuming that this area is directly proportional to the energy demand, noting that in all weather files we have only changed the air temperature, whereas other weather parameters were kept the same. This means that other parameters such as solar gains, which may influence the energy demand, were not considered here.[10]

Consequently, if this area is approximately the same for all three weather files, then all three weather files result in very similar estimates of energy demand.

Table 2 enumerates both the number of hours and the area under the curve for a range of heating and cooling balance points. We observe that for the heating balance point, the differences across weather files are very small, typically less than 1%. This result is in line with the heating estimates made for all three building models below. In contrast, we observe greater percentage differences across the weather files for the cooling balance points. This can be explained by the fact that the number of hours above these thresholds is actually quite small, e.g. there are only 92 h out of 8760 in the weather file where the air temperature exceeds 25 °C based on the hourly-change weather file, and only 37 h where the air temperature is expected to exceed 27 °C. Thus, even a small change, i.e. a single hour difference, results in a 1% or 3% (1 in 37) change respectively.

Fig. 3 (a) and (b) shows the estimated annual heating and cooling demand for the "existing" building based on a TAS simulation using the three different weather files (annual, monthly, hourly) where again the weather files differ only in their air temperature parameter, i.e. all other parameters, e.g. humidity, wind speed etc. are identical. Figs. 4a and b and 5a and b show the same for the "Improved-NV" and the "Improved-MV building models respectively. Note that the vertical scales are different for heating and cooling. Table 3 summarises the results.

We observed that there is almost no difference in the predicted heating demand when using the three different future weather files. In particular, for the "existing" building the heating demand estimated using the future weather files based on annual and monthly changes differ by no more than 1% with respect to the hourly-change weather file. The same is true for the "Improved-NV" building model, despite the very different thermal properties of the building, which drop total heating demand from approximately 67 MWhours to 19 MWhours. For the "Improved-MV" model, the differences in the estimated heating demand across weather files is only slightly larger, 3% (annual) and 1% (monthly) with respect to the hourly-based weather file. Once again, there is a very significant difference in the thermal properties of the "Improved-MV" model, with the total heating demand dropping to about 10 MWhours.

The differences in the predicted cooling demand, when using the three different future weather files, is slightly larger. We observe that the cooling demand estimated based on the annual change is between 2% and 5% greater than for the hourly estimated.

[10] We note that the work of [18] suggests that "… *with a +10% change in proposed future values for solar radiation, air humidity or wind characteristics, the corresponding change in the cooling load of the modelled sample building is predicted to be less than 6% for solar radiation, 4% for RH and 1.5% for wind speed, respectively*".

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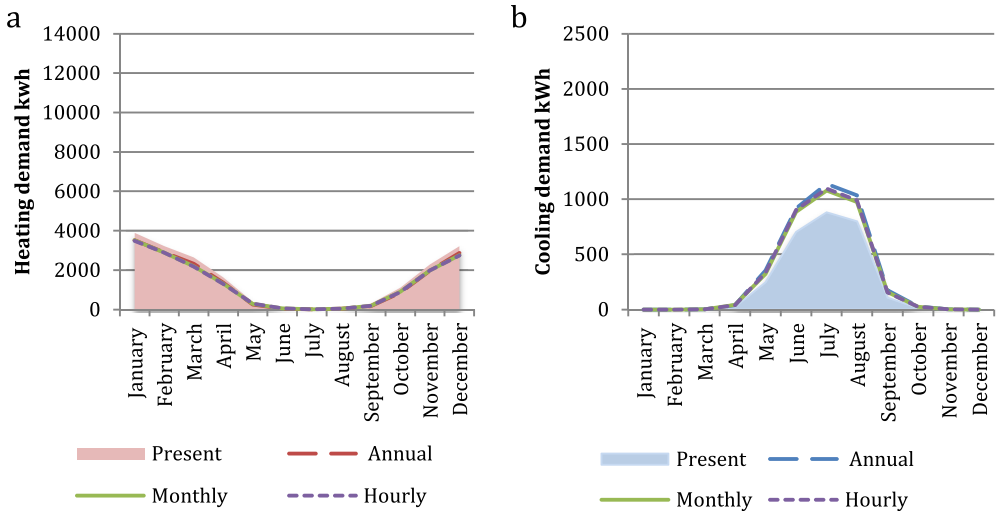

Fig. 4. a) Annual heating demand for the "improved NV" building for weather files based on present (shaded), annual (dashed), monthly (solid) and hourly (dotted) changes. b) Annual cooling demand for the "improved NV" building for weather files based on present (shaded), annual (dashed), monthly (solid) and hourly (dotted) changes.

Conversely, we observe that the cooling demand estimated based on the monthly change is between 0 and 3% less than for the hourly estimated.

5. Discussion

Experimental results using both the degree-day method and dynamic simulations of three buildings with very different thermal properties seem to indicate that even coarse annual estimates of air temperature change produce useful estimates of energy demand. This result is not obvious as it is easy to construct examples of hourly air temperature changes and corresponding annual air temperature change that would give very different results. For example, consider Example 1 in Fig. 6 in which the hourly differences are all zero except during the summer period where the differences are large, say 10 °C (dotted). The average annual change is then estimated to be 2.5 °C (dashed). Now consider a hypothetical real weather file, describing a location where heating is required throughout the year, as even during the summer period, the measured air temperature is usually about 1 °C below the heating balance point. When we add the two temperature difference curves of Fig. 6 to baseline temperature curve (solid), we obtain two future weather curves, depicted in Fig. 6 (dotted and dashed). The curve based on a single annual change remains below the heating balance point. However, the curve based on hourly changes now requires almost no heating during the summer period. We believe that such a pathological example is very unlikely in practise.

Conversely, it is also easy to construct an example where the hourly and annual air temperature differences will give the same result. Consider an arbitrary hourly air temperature difference curve, as illustrated in Fig. 7. The horizontal line is the average annual air temperature change calculated from this hourly data. Thus, by definition, the area under the horizontal line is equal to the area under the hourly curve. We refer to this area as A.

Now, consider a weather data curve of Fig. 8, where all air temperatures are below the heating balance point, i.e. heating is

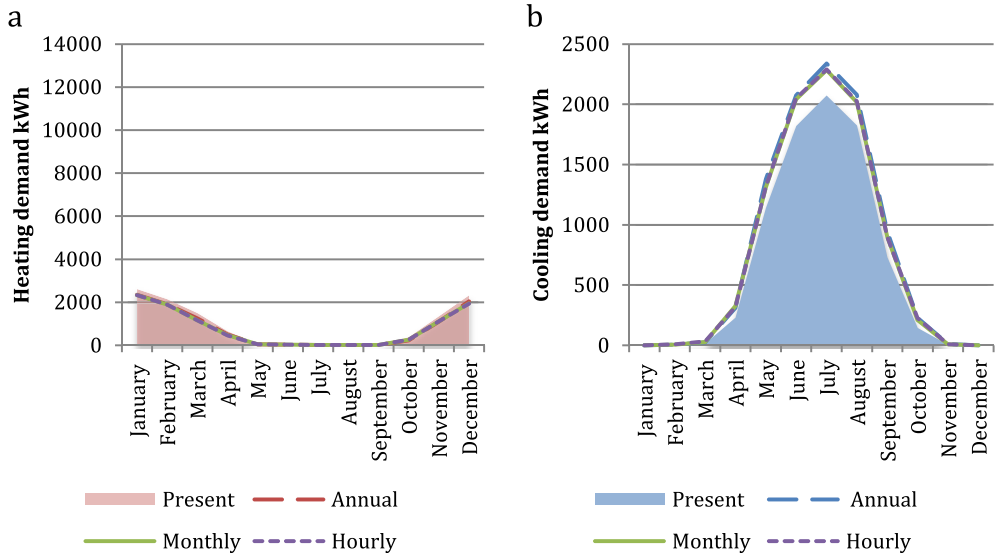

Fig. 5. a) Annual heating demand for the "improved MV" building for weather files based on present (shaded) annual (dashed), monthly (solid) and hourly (dotted) changes. b) Annual cooling demand for the "improved MV" building for weather files based on present (shaded) annual (dashed), monthly (solid) and hourly (dotted) changes.

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Table 3a
Annual heating demand for the three buildings with three future weather files in comparison to the fine temporal resolution (hourly). Shaded columns present the present heating demand for the buildings, which will decrease in the future.

Annual heating demand					
Present	Hourly	Monthly		Annual	
kWh	**kWh**	**kWh**	**Percentage of hourly**	**kWh**	**Percentage of hourly**
Existing building					
76547	67128	67331	100.3%	67641	100.8%
Improved NV					
18877	16056	16145	100.6%	16321	101.7%
Improved MV					
11126	9256	9311	100.6%	9502	102.7%

required at all time. Thus, based on the degree-day method, the heating energy is proportional to the area between the air temperature curve and the horizontal line representing the balance point. We refer to this area as area B. When we add a temperature difference curve to the weather data, we obtain a new curve and the future heating demand is given by the area, C=B−A, i.e. we obtain exactly the same degree-days whether hourly changes or an annual change are used.

A discrepancy between hourly and annual air temperature changes only manifests itself when the future weather air temperature curve intersects the heating balance point, as depicted in Fig. 9. In this illustrative example, both the hourly and annual future weather files do not contribute to heating degree-days for points above the heating balance point temperature. The hourly estimate of the heating demand is proportional to the area between the hourly curve and the horizontal balance point line and similarly for the annual estimate of heating demand. Thus, the error is the difference in these two areas. In practice, an air temperature curve may cross the balance point multiple times, which complicates any more general analysis.

We observe from Fig. 1 that the actual hourly air temperature changes predicted for the Copenhagen region are generally smaller during the summer period and largest during the winter period. However, Fig. 10, which shows the DRY file used in Section 3.1 reveals that when the predicted air temperature changes are largest, the temperature curve is usually very far from the heating balance point and thus the hourly or annual predicted air temperatures seldom exceed the heating balance point temperature. Thus the annual and hourly heating energy estimates are close. Conversely, for cooling demand, we observe that (i) there are very few hours in the DRY file that exceed the cooling balance point, and (ii) these point are close to the threshold. Thus we would expect the error to be larger between the hourly and annual

Table 3b
Annual cooling demand for the three buildings with three future weather files in comparison to the fine temporal resolution (hourly). Shaded columns present the present cooling demand for the buildings, which will increase in the future.

Annual cooling demand					
Present	Hourly	Monthly		Annual	
kWh	**kWh**	**kWh**	**Percentage of hourly**	**kWh**	**Percentage of hourly**
Existing building					
1556	2265	2197	97.0%	2387	105.4%
Improved NV					
2776	3540	3485	98.4%	3684	104.1%
Improved MV					
7981	9174	9130	100.5%	9398	102.4%

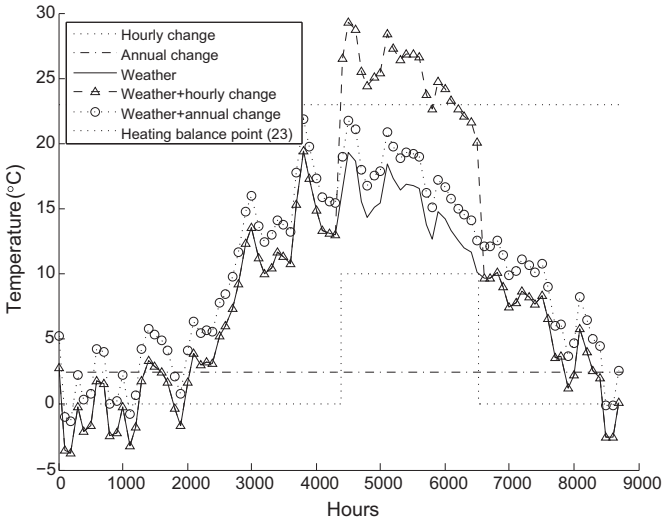

Fig. 6. Weather data smoothed using a moving 1-week average for illustrative purposes (solid), annual change (dashed), hourly change (dotted), Weather + annual change (circle + dotted), Weather + hourly change (triangle + dashed), balance point for heating degree day (dotted).

predictions, and this is supported by experiments. In general, we would expect the relative error between coarse (annual) and fine (hourly) temporal predictions of air temperature changes to be large when the actual weather file data is close to a balance point. However, while the relative error may be large, the absolute error in energy may still be small, since, when the air temperature is near a balance point, much less energy is needed to heat or cool a building.

Clearly, the energy demand of buildings is also sensitive to other weather parameters than air temperature such as wind, solar gain or precipitation, as well as cross-correlations between parameters. None of these have been investigated here and should be addressed in a future study. However, once again, we note that previous work by Ref. [18] suggests that the effect of these parameters could be relatively small (less than 10%).

The practical implication of our results is to recommend that in cases with limited access to high temporal resolution weather data,

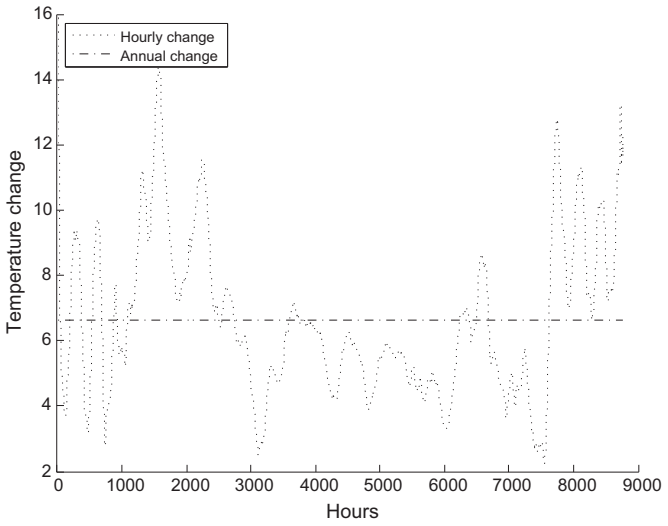

Fig. 7. Hourly air temperature change smoothed using a moving 1-week average for illustrative purposes (dotted) and average annual change (dashed).

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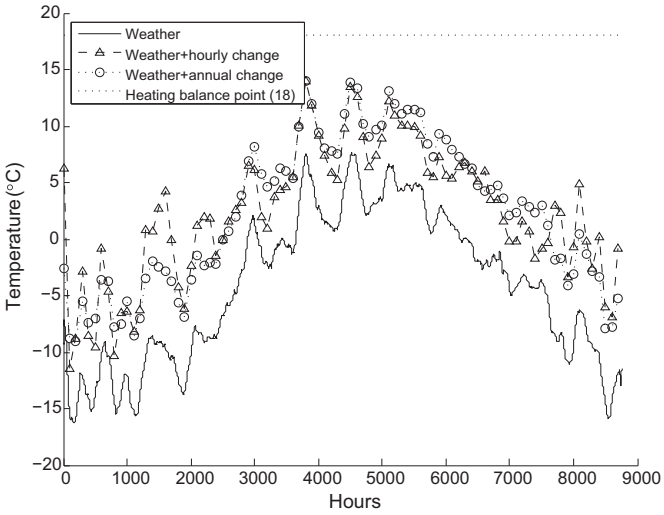

Fig. 8. Weather data smoothed using a moving 1-week average for illustrative purposes curve (solid), added hourly change curve (triangle + dashed), added annual change curve (circle + dotted) and heating balance point temperature at 18 °C (dotted).

using the annual change in air temperature may produce close estimates. Moreover, the coarse resolution weather file is, from an energy simulation point of view, simple to construct.

6. Conclusion

This paper examined whether future weather files constructed with coarse temporal resolution data of expected changes in air temperature could provide useful estimates of heating and cooling demand. Experimental results using both the degree-day method and dynamic simulations indicated the even a single estimate of expected annual change in air temperature can provide very similar estimates of energy consumption to those obtained using fine, hourly temperature change estimates. In particular, heating demand estimates were within 3% and cooling demand estimates were within 4% of one another.

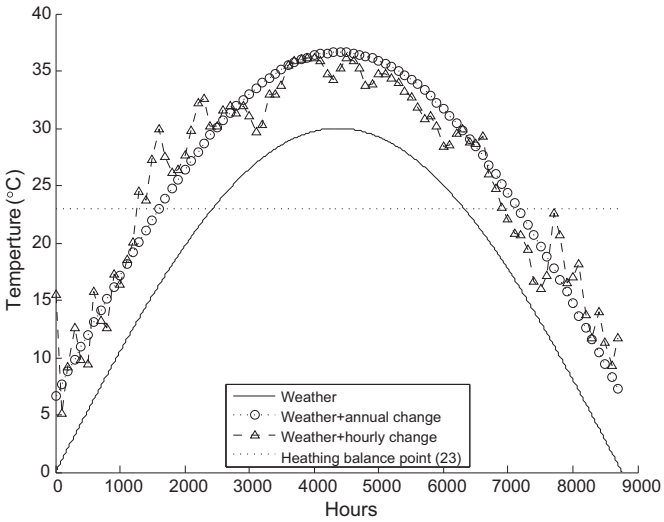

Fig. 9. Synthetic weather data (a sinusoid curve) (solid), added annual change (circle + dotted), the hourly change added (triangle + dashed), heating balance point (23 °C) (dotted).

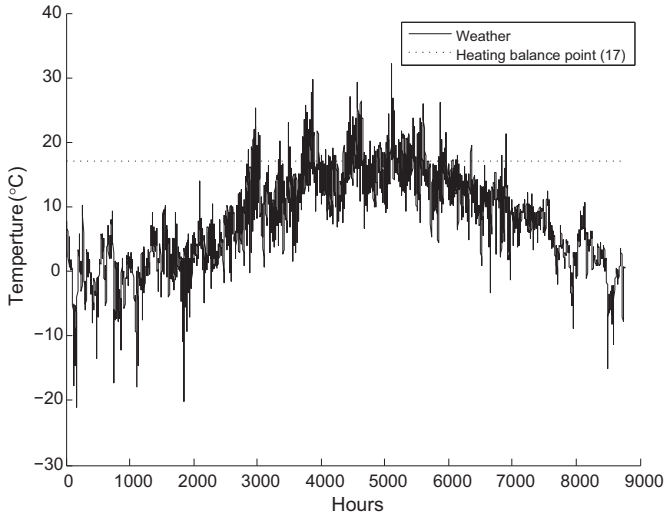

Fig. 10. DRY temperature (solid) and heating balance point at 17 °C (dotted).

Arguably, large relative errors are most likely when the air temperatures are close to the heating or cooling balance points. However, energy demand in these regions is modest and even relatively large errors may only result in modest absolute errors in energy demand.

A limitation of our investigation is that it only considers the change in the dry bulb temperature. Further work is needed in order to confirm whether other parameters, such as wind, precipitation, cloud cover or humidity can be treated similarly. Likewise, further work is needed to determine the sensitivity of energy demand estimates to the correlations between parameters and to take into account the inherent uncertainties of climate model projections.

In this paper we only present results for one location, i.e. Gentofte, which is used here to illustrate some of the technical challenges, practitioners face. In that context our findings are significant, since there is evidence [15,17] that many practitioners have difficulty obtaining future weather file data. While better data is always preferable, our study reveals that the in the absence of high temporal resolution data, a coarse annual estimate of the expected change in annual air temperature may be a pragmatic and more accessible way when estimates of future energy demand is requested. Clearly, more research is needed in order to test strengths and weaknesses of the methodology comprehensively, e.g. under different climate conditions and for different building types. This was however beyond the scope of this study, e.g. in terms of data availability. In the future, we intend to extend our work to assess the methodology for other climatic regions as well.

This paper has examined whether future weather files constructed using coarse temporal resolution data could provide useful estimates of future energy demand. Future weather files can and are used to estimate other factors and future work is needed to evaluate whether the methodology proposed here is useful for other factors such as estimating future thermal comfort.

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Appendix 1. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2014.04.006.

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