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Energy Conversion and Management 47 (2006) 671–686

ENERGY CONVERSION & MANAGEMENT

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Climate warming impact on degree-days and building energy demand in Switzerland

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Received 8 December 2004; accepted 10 June 2005
Available online 15 August 2005

Abstract

The impact of climate warming on Swiss building energy demand was investigated by means of the degree-days method. A procedure to estimate heating degree-days (HDD) and cooling degree-days (CDD) from monthly temperature data was developed, tested and applied to four representative Swiss locations. Past trends were determined from homogenized temperature data for the period 1901–2003. The range of possible future trends for the 21st century was assessed based on 41 regional climate change scenarios derived from 35 simulations with 8 global climate models. During 1901–2003, the HDD were found to have decreased by 11–18%, depending on the threshold temperature (8, 10 or 12 °C) and location. For the period 1975–2085, the scenario calculations suggested a further decrease between 13% and 87%. For CDD, accelerating positive trends were found during the 20th and 21st centuries. The HDD showed the largest absolute and the CDD the largest relative sensitivity to warming (albeit starting from relatively low levels). Weather data currently used for building design increasingly lead to an overestimation of heating and underestimation of cooling demand in buildings and, thus, require periodic adaptation. Projections were particularly sensitive to the choice of temperature scenario. Nevertheless, they suggest for the next decades significant, seasonally and regionally variable shifts in the energy consumption of Swiss buildings that

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0196-8904/$ - see front matter
doi:10.1016/j.enconman.2005.06.009

deserve further study. In particular, greater attention needs to be paid in future to the summer thermal behaviour of buildings.

Keywords: Building energy demand; Global warming; Heating degree-days; Cooling degree-days; European Alpine region; Historical temperature trends; Climate scenarios

1. Introduction

Switzerland, a small country in the European Alpine region covering 41,285 km^2 and with a population of 7,367,900 (2003), has been particularly susceptible to the impact of climate change. While the mean global temperature increased by 0.6 K in the 20th century, the temperature rise in Switzerland was much higher: 1.3 K in Eastern and Central Switzerland, 1.6 K in Western Switzerland and 1.0 K south of the Alps. The temperature rise accelerated in the last three decades of the 20th century: 0.5 K per decade in Switzerland (averaged over all regions) compared to a global average of 0.1–0.2 K per decade [1].

These trends are likely to continue. According to the Intergovernmental Panel on Climate Change (IPCC), the global average temperature will rise between 1.4 and 5.8 K in the 21st century [2,3]. Higher maximum temperatures and more hot days over virtually all land areas are very probable, along with higher minimum temperatures and fewer cold days.

Climatic parameters represent important boundary conditions for building design and the transient behaviour of the building envelope during its service life. Energy demands in buildings depend significantly on external boundary conditions, particularly on ambient temperature. Given their long lifespan—in Switzerland typically 50–100 years—buildings may, over time, be exposed to different climates.

The impact of global warming on the energy consumption of a country for space heating and cooling depends on the current and future regional climate, the required thermal comfort inside buildings and technical building features such as thermal insulation quality. Quantitative projections of future energy consumption naturally depend on the key assumptions and models used to construct future climate scenarios. In previous studies for the USA [4,5], the UK [6] and, more recently, for Greece [7], climate change was found to have significant implications for energy consumption in buildings. To our knowledge, no corresponding study has, so far, been attempted for Switzerland.

This work focuses on the impact of a gradually warming climate on heating and cooling energy demand in buildings in Switzerland. The current total energy demand of the Swiss building stock is dominated by heating. The use of cooling has, so far, been almost exclusively confined to commercial buildings. Fifty-five percent of Switzerland's fossil fuel consumption of 620 PJ (2003) occurs in households and in the trade, industrial and service sectors, with some 80% of this serving heating in buildings [8]. This study sets out to analyze building energy demand by means of the degree-days method. This is done (i) for the past, employing weather data measured between 1901 and 2003 and (ii) for the future by means of several regional temperature scenarios, as constructed from a large database of global climate model runs for the 21st century.

2. Method

2.1. Source of measured temperature data (1901–2003)

The systematic measurement of meteorological parameters started in Switzerland in 1864. Data acquisition initially took place at 80 stations three times a day only (morning, noon, evening). Improvements were made in the 20th century, particularly in the early 1980s with the launch of the automatic measurement network (ANETZ), consisting of 72 stations. ANETZ is operated by the National Weather Service (MeteoSwiss) and measures a range of meteorological parameters at 10-min intervals. Air temperatures are measured 2 m above ground level.

Begert et al. [9] used ANETZ and earlier data to produce homogenized, long term time series of monthly mean temperature for 12 stations representative of the main Swiss climate regions. These time series start in 1864 and are recommended by MeteoSwiss for the description and analysis of climate change effects. These monthly data alone were used in this study.

Unfortunately, no long time series of homogenized daily temperatures are, as yet, available for Switzerland. For this reason, a method to estimate annual heating and cooling degree-days indices from monthly temperature data is presented below.

2.2. Case study locations

Although weather conditions in Switzerland are generally temperate, large seasonal and regional differences in thermal climate do exist due to the country's complex topography and its location in the transition zone between the oceanic, Mediterranean and continental climate regimes. For brevity, analysis was restricted to the following four major locations that are represented in the data set of Begert et al. [9]: Geneva and Zurich, two large urban centres north of the Alps; Lugano, a densely populated urban area at the Alpine south side; and the small town of Davos, representative of central Alpine climate conditions (Fig. 1).

	Longitude (°E)	Latitude (°N)	Altitude (m asl)
Davos	9.85	46.82	1590
Geneva	6.13	46.25	420
Lugano	8.97	46.00	273
Zurich	8.57	47.38	556

Fig. 1. The chosen four locations represent different climatic areas in Switzerland.

2.3. Energy demand in buildings

Degree-day methods are simple, yet efficient and fairly reliable procedures for quantifying the heating and cooling energy demands in a building. Estimations are accurate if the internal temperature, thermal gains and building properties are relatively constant. The severity of a climate can be characterized concisely in terms of degree-days. Various definitions of degree-days are in use.

The definition of heating degree-days (HDD, unit: K days) used in this study is taken from a Swiss standard [10]:

$$\mathrm{HDD}(\theta_\mathrm{i}, \theta_\mathrm{th}) = m_k \sum_{k=1}^{n} (\theta_\mathrm{i} - \theta_{\mathrm{e},k}) \tag{1}$$

$$\begin{aligned} m_k &= 1 \text{ day} \quad \text{if } \theta_{\mathrm{e},k} \leqslant \theta_\mathrm{th} \\ m_k &= 0 \text{ day} \quad \text{if } \theta_{\mathrm{e},k} > \theta_\mathrm{th} \end{aligned}$$

In Eq. (1), θ_i denotes the internal temperature, $\theta_{\mathrm{e},k}$ the daily mean external temperature and θ_th the threshold temperature for heating, while k stands for the day number in the year, i.e., $k \in \{1, \ldots, 366\}$. Low θ_th values imply highly insulated buildings. With regard to internal temperature and building quality, standard values for Switzerland's current building stock of $\theta_\mathrm{i} = 20\ ^\circ\mathrm{C}$ and $\theta_\mathrm{th} \in \{8, 10, 12\ ^\circ\mathrm{C}\}$ were assumed in this study.

The annual heating demand of a building Q_h may be written as

$$Q_\mathrm{h} = K_\mathrm{tot}\mathrm{HDD} - \eta Q_\mathrm{s} \tag{2}$$

K_tot denotes the total thermal losses due to transmission and infiltration, Q_s the internal heat sources and solar gains, while η is an efficiency to factor in the share of Q_s that serves to reduce heating demand. For much of Switzerland's current building stock, ηQ_s is far smaller than $K_\mathrm{tot}\mathrm{HDD}$, and the heating demand may, therefore, be assumed to be approximately proportional to the number of heating degree-days. Where this is not the case, the relative reduction of heating energy is higher than that given by the HDD decrease.

In the absence of a European standard for computing cooling degree-days (CDD), the ASHRAE [11] definition was used.

$$\mathrm{CDD}(\theta_\mathrm{tc}) = m_k \sum_{k=1}^{n} (\theta_{\mathrm{e},k} - \theta_\mathrm{tc}) \tag{3}$$

$$\begin{aligned} m_k &= 1 \text{ day} \quad \text{if } \theta_{\mathrm{e},k} \geqslant \theta_\mathrm{tc} \\ m_k &= 0 \text{ day} \quad \text{if } \theta_{\mathrm{e},k} < \theta_\mathrm{tc} \end{aligned}$$

θ_tc denotes the threshold temperature for cooling, also referred to as the balance point temperature [11] and defined as the value of the outdoor air temperature (for a specified internal temperature) at which the total heat loss is equal to the internal and solar heat gains. The calculation of cooling energy consumption based on degree-days is subject to greater uncertainty than that for heating. If building properties are assumed to be constant, the cooling energy demand is proportional to the number of CDD.

$$Q_c = K_{\text{tot}}\text{CDD}(\theta_{\text{tc}}) \tag{4}$$

As constant building properties are assumed, this method is unable to allow for the possibility of postponing mechanical cooling by opening windows or increasing ventilation rates.

2.4. Temperature scenarios

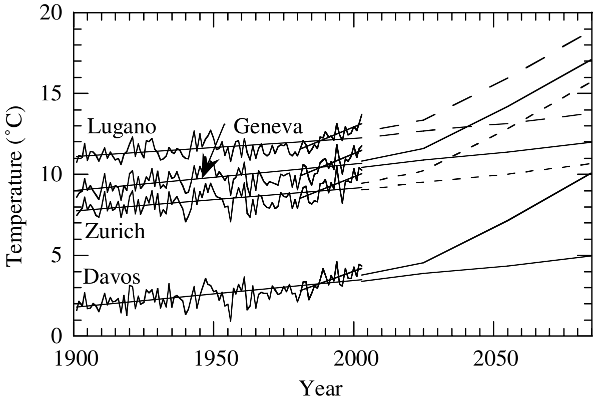
The irreducible uncertainties attached to the future global socio-economic development [12] make any projections of future climate change inherently uncertain. Accordingly, the aim of the present study was not to determine the "most likely" trajectory for future Swiss HDD and CDD but rather to mark out the range of possible futures. For this purpose, a database of 41 state of the art, quantitative regional temperature scenarios was first compiled, and a subset of the most extreme scenarios was then selected for further analysis.

All scenarios were based on simulation results from so-called coupled Atmosphere–Ocean General Circulation Models (AO-GCM). AO-GCM are the most sophisticated tools currently available to project possible changes in global climate [13]. In these models, the globe is discretized such that pressure, temperature, clouds, rainfall etc. are computed on a global grid. The horizontal grid point distance is in the order of a few degrees. This coarse resolution poses a major challenge for the production of local climate scenarios, in particular over the complex Alpine terrain. To take account of the associated uncertainty, two kinds of scenario construction methods were considered: (i) the direct use of AO-GCM grid point (GP) data and (ii) a so-called statistical "downscaling" (DS) procedure [13,14].

In a first step, two initial sets of 23 (GP) and 18 (DS) scenarios on the basis of 35 AO-GCM simulation runs for the 21st century were prepared (Table 1). All AO-GCM data used were downloaded from the Data Distribution Centre of the Intergovernmental Panel on Climate Change (IPCC-DDC) [15,16]. The set of AO-GCM and forcing scenarios (Table 1) was determined by the data availability at the time of the retrieval. Nevertheless, it represents a wide range of state of the art AO-GCM and forcing scenarios. Depending on the AO-GCM, either one or two

Table 1
The number of simulation runs considered for a given AO-GCM [3] and forcing scenario [12,28]

Forcing	IS92a		IS92aS		A1		A1F		A1T		A2		B1		B2	
AO-GCM	GP	DS	GP	DS	GP	DS	GP	DS	GP	DS	GP	DS	GP	DS	GP	DS
CGCM1	–	1	–	1	–	–	–	–	–	–	–	–	–	–	–	–
CCCma	–	–	–	–	–	–	–	–	–	–	1	1	–	–	1	1
CSIRO	–	1	–	1	1	–	–	–	–	–	1	1	1	–	1	1
DOE PCM	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–	1
ECHAM4	–	1	–	1	–	–	–	–	–	–	1	–	–	–	1	–
GFDL	–	–	–	–	–	–	–	–	–	–	1	–	–	–	1	–
HADCM3	–	1	–	1	–	–	1	–	–	–	3	1	1	–	2	1
NIES99	–	1	–	1	1	–	1	–	1	–	1	–	1	–	1	–



	1901-2003 (K/decade)	1983-2003 (K/decade)
Lugano	0.117	0.795
Geneva	0.161	0.795
Zurich	0.143	0.776
Davos	0.165	0.642

Fig. 2. Yearly mean temperatures for four locations (1901–2003) [9], tabulated past trends and range of predicted temperature increases according to GP data taken from Ref. [15].

AO-GCM grid cells covering Switzerland were considered for the GP scenarios. The analysis was based on the simulated changes in long term monthly mean temperatures for the 2020s, 2050s and 2080s relative to the 1961–1990 average (Fig. 2). The DS scenarios were derived by applying the method of Gyalistras et al. [14] to a novel 5 km gridded temperature data set [17] for Switzerland. The method estimates local climate anomalies as a function of changes in the AO-GCM simulated large scale sea level pressure and near surface temperature fields. From the derived 5 km trend maps for Swiss monthly mean temperatures in the 21st century [18,19], areas of 3 times 3 cells were chosen to represent our four case study sites. From the initial sets of 23 (GP) and 18 (DS) scenarios, annual HDD and CDD were determined, and then those marking the upper and lower limits for projections in the second half of the 21st century were identified.

2.5. Computation of past and future HDD and CDD

As stated above, the limitations imposed by the long term weather records forced us to base all our calculations on monthly temperature data. However, the associated loss in accuracy (see below) appeared tolerable given that we were more interested in assessing long term changes and trends than in precisely predicting individual monthly HDD or CDD values.

Several methods have been proposed to estimate degree-days from monthly temperature data. Thom [20] related US-HDD to the monthly average temperature and standard deviation of monthly temperature from its long term average. His equation was later modified by Ref. [21]. Other methods first construct hourly weather data from monthly temperatures and then calculate degree-days from standard degree-day equations [22–24]. A comparison of five different methods for Iasi, Romania, by Ref. [24] suggested that the most accurate results can be obtained by estimating degree-days from hourly data synthesized using site specific regression coefficients.

Unfortunately, all the above studies employed definitions of degree-days that deviate from the Swiss standard [10] (e.g., Ref. [20] used the ASHRAE definition). Moreover, the formulas were tuned to specific weather data that are not necessarily representative of Swiss climatic conditions. For these reasons, a new approximation method was developed, comprising the following two steps.

In a first step, an initial degree-days estimate, $\mathrm{HDD}_{\mathrm{m0}}$, was calculated on the basis of monthly mean temperature, as follows:

$$\mathrm{HDD}_{\mathrm{m0}}(\theta_{\mathrm{i}}, \theta_{\mathrm{th}}) = m_k \sum_{k=1}^{n} (\theta_{\mathrm{i}} - \theta_{\mathrm{e},k}) \tag{5}$$

$$m_k = \text{days in month}, \quad m_k \in \{28, \ldots, 31\} \text{ if } \theta_{\mathrm{e},k} \leqslant \theta_{\mathrm{th}}$$
$$m_k = 0 \text{ days} \quad \text{if } \theta_{\mathrm{e},k} > \theta_{\mathrm{th}}$$

In Eq. (5), θ_{i} denotes the internal temperature, $\theta_{\mathrm{e},k}$ the monthly mean external temperature and θ_{th} the threshold temperature for heating, while k stands for the month number in the year, i.e., $k \in \{1, \ldots, 12\}$. In a second step, a final estimate, $\mathrm{HDD}_{\mathrm{m}}$, was computed by adjusting $\mathrm{HDD}_{\mathrm{m0}}$ according to:

$$\mathrm{HDD}_{\mathrm{m}}(\theta_{\mathrm{i}}, \theta_{\mathrm{th}}) = \mathrm{HDD}_{\mathrm{m0}}(\theta_{\mathrm{i}}, \theta_{\mathrm{th}}) + F_{\mathrm{corr}}(\theta_{\mathrm{i}}, \theta_{\mathrm{th}}) \tag{6}$$

The correction function F_{corr} was estimated by regressing the differences between the results obtained from Eq. (5) and those from the much more precise Eq. (1) on the associated monthly mean temperatures. This analysis was conducted for the years 1981–2003. Eq. (1) was evaluated using daily average ANETZ temperatures, since these were considered to be the most accurate available. The same method was applied for cooling. HDD threshold temperatures of 8, 10 and 12 °C and CDD threshold temperatures of 18.3, 20 and 22 °C were considered. A threshold temperature for cooling of 18.3 °C represents an ASHRAE [11] standard numerical value.

Fig. 3 shows an example of such a correction function based on weather data for the locations Davos, Geneva, Lugano and Zurich. The averages and standard deviations of the differences

	HDD_8	HDD_{10}	HDD_{12}	$\mathrm{CDD}_{18.3}$*	CDD_{20}*	CDD_{22}*
Average relative error (%)	0.4	-0.7	0.5	-6.7	17.5	463
Standard deviation of relative error (%)	3.1	2.7	2.1	17.3	22.6	541

*excluding Davos

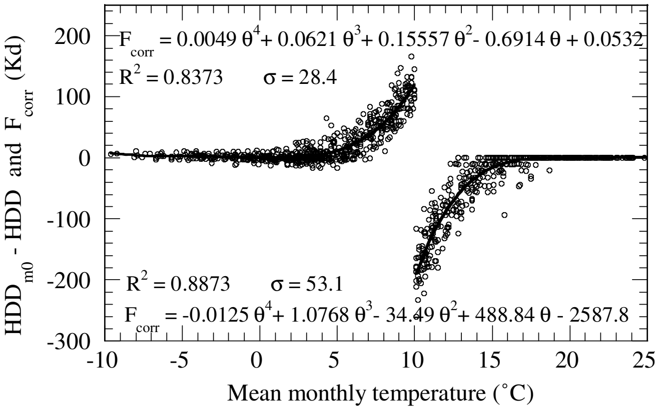


Fig. 3. Example of correction function F_{corr} using $\theta_{\mathrm{th}} = 10$ °C, determined by means of data measured between 1981 and 2003, and average errors occurring when applying correction functions.

between actual (Eq. (1)) and predicted (Eqs. (5) and (6)) annual HDD and CDD are additionally displayed for the different threshold temperatures. Since CDD showed increasing estimation errors with rising threshold temperature, this study focused on $CDD_{18.3}$.

3. Results

3.1. HDD

For all threshold values of 8, 10 and 12 °C, the HDD decreased significantly in Davos, Geneva, Lugano and Zurich over the 20th century (Fig. 4). Fig. 4 also includes the two most extreme HDD projections found using the GP temperature scenarios. These HDD projections were obtained for two simulation runs with the CCSR/NIES-GCM [25] under the IPCC forcing scenario A1F [12] ("warm" temperature projection) and the CCCma-GCM [26] under the forcing scenario B2 [12] ("cool" temperature projection). It can be seen that a further decrease in HDD must be expected in the course of the 21st century, and that the rate of HDD decrease in the last 20 years is of the same order as, or even larger than, the rate projected under the extreme "warm" temperature scenario.

Fig. 5 shows that for all locations and threshold temperatures considered, the rate of HDD decrease in the period 1983–2003 was at least four times higher than the rate over the whole century. For the period 1983–2003, calculations indicate a decrease in HDD between 10% for a poorly insulated building ($\theta_{th} = 12$ °C) in Davos to 25% for a highly insulated building ($\theta_{th} = 8$ °C) in Lugano.

Today, Swiss building designers use either monthly meteorological data provided by the Swiss Association of Engineers and Architects (SIA) [10] or semi-synthetic hourly data generated at EMPA using the Design Reference Year (DRY) method [27]. A comparison between observed HDD in the period 1983–2003 and SIA and DRY HDD is presented in Fig. 6. It can be seen that the SIA and DRY data, which are based on measurements in the periods 1961–1970 (SIA) and 1981–1990 (DRY), increasingly overestimated the HDD during the last 20 years. A linear trend

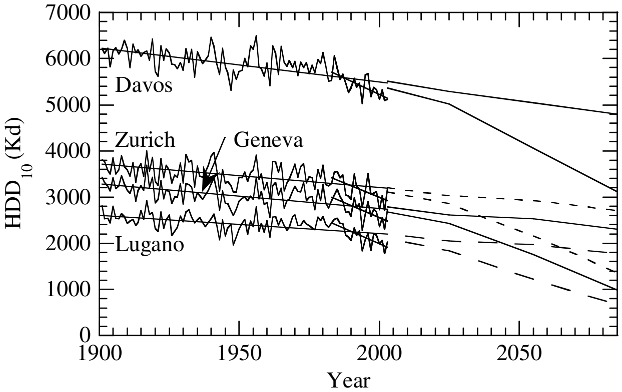


Fig. 4. HDD_{10} at four locations computed using homogenized monthly data [9], the correction function for $\theta_{th} = 10$ °C and GP temperature predictions taken from Ref. [15].

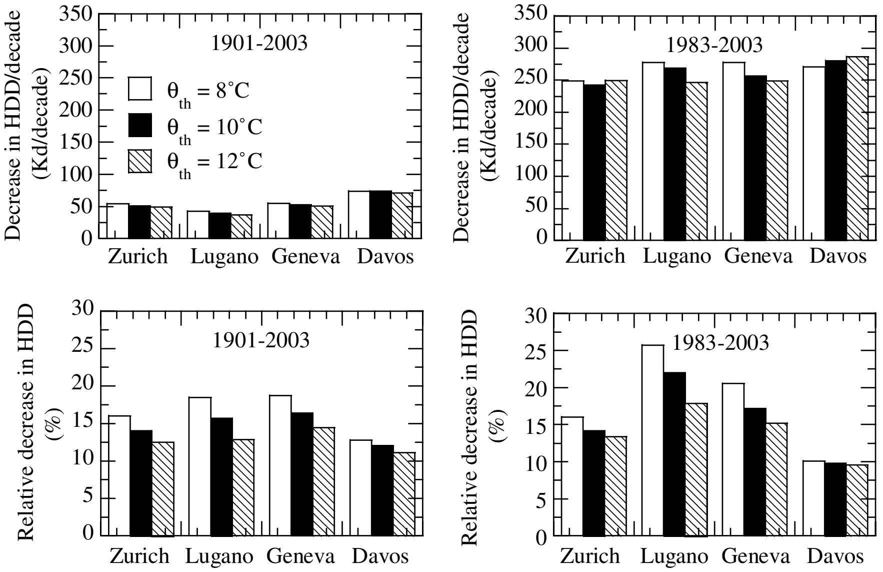
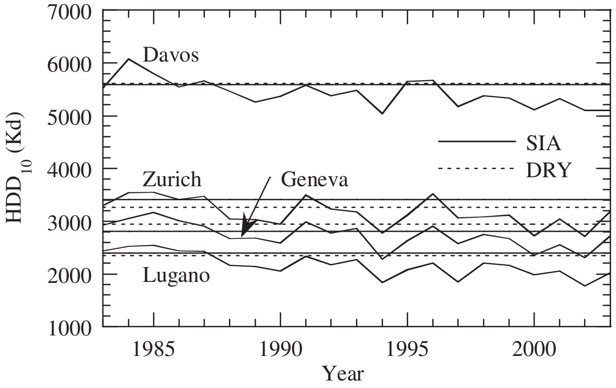


Fig. 5. Decrease of HDDs in the periods 1901–2003 and 1983–2003, based on linear trend lines.



	SIA overestimation of HDD_{10} 1983-2003 (% / year)	DRY overestimation of HDD_{10} 1983-2003 (% / year)
Zurich	0.84	0.80
Lugano	1.36	1.33
Geneva	0.98	1.02
Davos	0.53	0.53

Fig. 6. Comparison between computed HDD based on data measured between 1983 and 2003 [9] and SIA [10] and DRY data, respectively.

line fit suggests that since 1983, and on average over all four locations, both the SIA and DRY tend to overestimate the HDD_{10} by around 0.93% per year.

In order to explore the sensitivity of HDD to possible future warming, a sensitivity analysis was performed by adding yearly uniform temperature changes to daily DRY data. The results (Fig. 7) suggest that the largest absolute HDD decrease due to future warming can be expected to occur in Davos ($\theta_{th} = 12$ °C), whereas buildings in Lugano ($\theta_{th} = 8$ °C) will probably experience the greatest relative change.

Fig. 8 depicts the range of estimated relative HDD decreases for threshold values of 8, 10 and 12 °C at the four case study locations under the GP and DS scenarios. The responses obtained

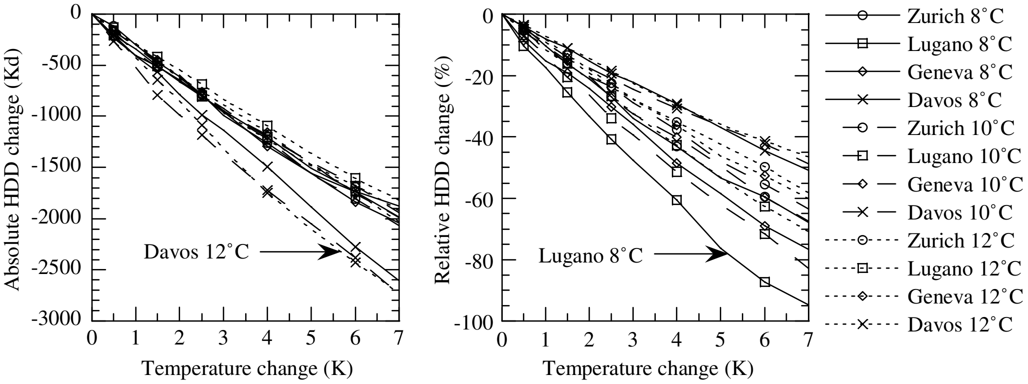


Fig. 7. Sensitivity of HDD to temperature changes at four locations.

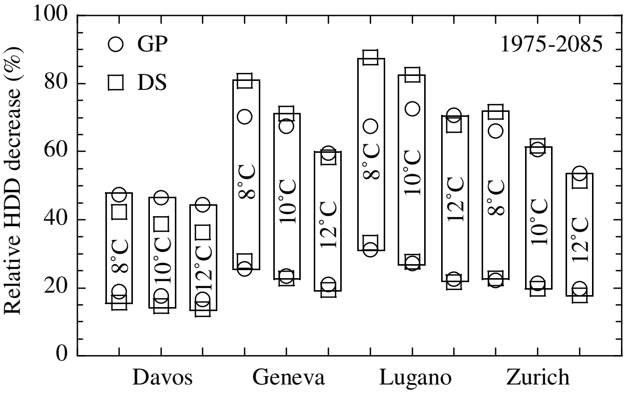


Fig. 8. Relative HDD decreases for three threshold values and at four locations in the period 1975–2085.

range very widely, between 13% and 87%, depending on location, building quality and the temperature scenario used. The choice of scenario generally showed the greatest impact. The extreme HDD projections found for the DS temperature scenarios were given by the NIES99 [25] AO-GCM under the forcing scenario IS92a [28] and the DOE-PCM AO-GCM [29] under the forcing scenario B2 [12]. In Fig. 8, it can be seen that the HDD projections resulting from the "cool" GP and DS scenarios yielded comparable results, while some major differences occurred in the HDD projections based on the "warm" GP and DS scenarios at all sites except Zurich. The largest relative decreases were found for well insulated buildings in Lugano, and the largest absolute decreases (not shown, but cf. Fig. 7) occurred for poorly insulated buildings (θ_{th} = 12 °C) in Davos.

3.2. CDD

The estimated trends in $CDD_{18.3}$ between 1901 and 2003 are shown in Fig. 9. It can be seen that the cooling degree-days rose at all locations, with the largest rates of increase occurring in Lugano and Geneva. There were almost no $CDD_{18.3}$ in Davos between 1901 and 2003. As the summer

$CDD_{18.3}$ (Kd/decade)	1901-2003	1901-2002	1983-2003	1983-2002
Zurich	5.11	3.64	42.11	11.07
Lugano	9.85	7.77	65.92	23.91
Geneva	9.94	8.02	57.63	17.51
Davos	0.11	0.05	1.13	-0.20

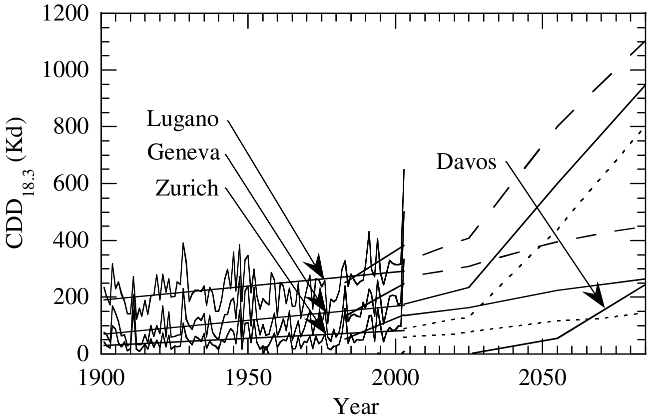


Fig. 9. Past $CDD_{18.3}$ values (1901–2003) with linear trend lines (1901–2003 and 1983–2003) and predicted future $CDD_{18.3}$ (2004–2085) based on GP temperature predictions taken from Ref. [15].

of 2003 was exceptionally hot, trends were also computed without the year 2003. Between 1983 and 2003, the rate of increase at all locations was 5–10 times the rate over the 20th century. Again, the 1983–2003 trends were found to be at least of the same magnitude as the 21st century trends calculated using the extreme "warm" GP temperature scenarios. The range of CDD projections based on GP scenarios was given by the same AO-GCM runs as for HDD.

The calculation of CDD using DRY data (not shown) suggests that between 1983 and 2003, the DRY data underestimate the $CDD_{18.3}$ by 4% per year. This figure drops to 1.2% per year if the 2003 data are excluded.

The temperature sensitivity of CDD, as assessed by adding yearly uniform temperature increases to daily DRY data, is shown in Fig. 10. It can be seen that the largest absolute sensitivities occurred for low temperature threshold values (left), whereas relative changes in CDD were found to rise dramatically with increasing temperature threshold (right).

Fig. 11 depicts the obtained ranges for the absolute and relative $CDD_{18.3}$ increases in the period 1975–2085 based on the GP and DS temperature scenarios. The range of CDD projections based on DS data was marked by simulations with the HadCM3 AO-GCM [30] model under the forcing scenario A2 [12] ("warm" temperature projection) and with the DOE-PCM AO-GCM [29] model under the forcing scenario B2 [12] ("cool" temperature projection). Of the four locations, Lugano shows the greatest absolute change in $CDD_{18.3}$. However, as a percentage, this change is smallest (cf. Fig. 10). As $CDD_{18.3}$ remained very close to zero in Davos in the 20th century, no percentage values were computed for this location. Again, the projected changes were highly dependent on the choice of temperature scenario. Large differences were obtained between the CDD projections for the "warm" GP and DS scenarios.

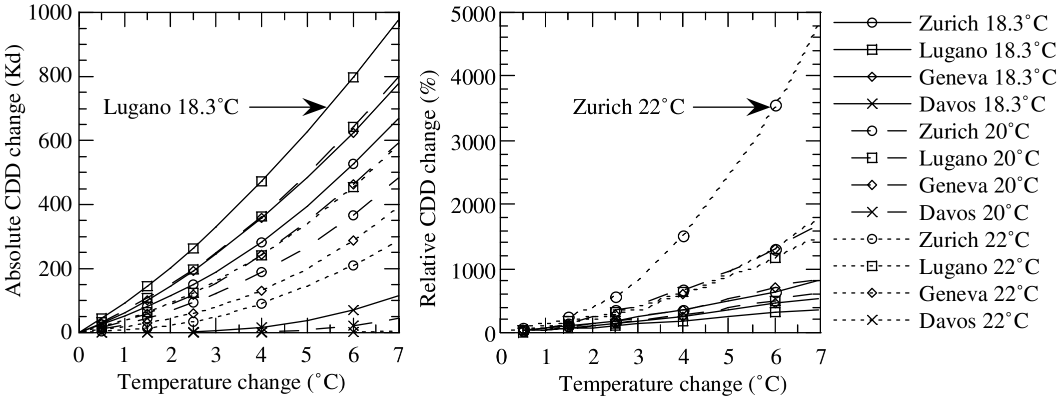


Fig. 10. Sensitivity of CDD to temperature changes at four locations.

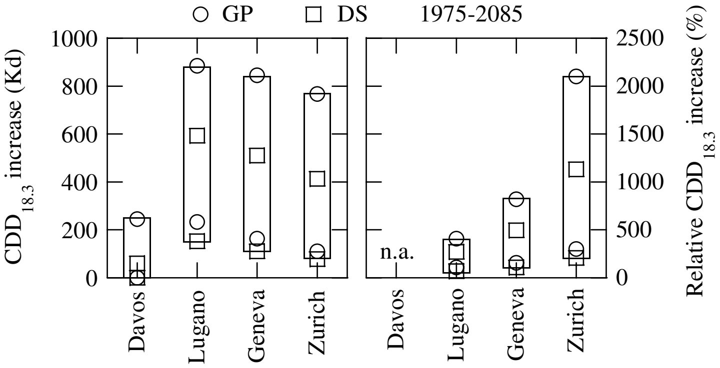


Fig. 11. $CDD_{18.3}$ increases at four locations predicted for the period 1975–2085.

4. Discussion and conclusions

The impact of climate change on building design parameters for computing energy demand for heating and cooling was investigated in this study. Application of the degree-days method with typical temperature threshold values for heating of 8, 10 and 12 °C assumed for Switzerland's current building stock revealed a significant relative HDD decrease, between 11% and 18% depending on building quality and location, over the period 1901–2003. This relative decrease was most pronounced in highly insulated buildings in Lugano and Geneva. On the other hand, the absolute decrease in HDD was highest at the coolest site, Davos. With regard to the future heating demand in buildings in Switzerland (1975–2085), further significant reductions of 13–87% are expected, equally depending on building quality, location and, most importantly, the magnitude of future warming. Relative reductions are likely to be most pronounced in highly insulated buildings south of the Alps, whereas absolute reductions will probably be greatest in poorly insulated buildings in presently relatively cool locations such as Davos. In buildings with high solar and internal gains, the future relative reduction of heating energy consumption will even exceed the decrease in HDD.

As regards cooling energy demand, a significant increase in cooling potential was found to have occurred between 1901 and 2003 (between 50% and 170% based on $CDD_{18.3}$). In the period 1975–2085, the $CDD_{18.3}$ are projected to increase by up to 2100%. This high value was computed for Zurich, where the initial value was low. 18.3 °C is sometimes considered a relatively low threshold value for cooling and may apply only to buildings with higher thermal gains. The impact of possible future warming on cooling demand certainly needs to be investigated in more detail in further studies. The fact that the 1983–2003 trends were of the same magnitude as the estimated trends under the most extreme temperature scenarios is of particular concern.

This study has also shown that the SIA [10] and DRY [27] weather data currently in use by building designers and HVAC engineers in Switzerland will lead increasingly to an overestimation of heating energy demand. Similarly, the use of DRY data to compute cooling power and cooling energy consumption is likely to result in a progressive underestimation of the future demand. It, therefore, seems obvious that continuous updating of weather data for building design is needed. These findings concur with those of a UK study performed by Pretlove and Oreszczyn [6].

The generally significant trends towards less heating and more cooling found in this study confirm the results of previous studies [4–7]. However, to our knowledge, this is the first survey to have included a long term historical analysis based on homogenized temperature time series and to have investigated the possible evolution of building energy demand far into the 21st century.

The remaining uncertainties in this study stem mainly from the simple degree-days model for computing cooling demand and, to an even larger extent, the uncertainties related to the future radiative forcing of the climate system and to the global and regional models used to estimate the associated changes in regional temperatures.

Except in the case of CDD_{20} and CDD_{22}, the errors resulting from our HDD/CDD estimation procedure are similar to those obtained by Belzer et al. [5] using the Thom method in the USA. The use of a relatively simple algorithm based on monthly input data is believed to have generally enhanced the robustness of our results. This is because our approach matched the limited precision of global climate models, whose performance tends to decrease with increasing spatial and temporal resolution. In addition, more complicated algorithms that would have used daily data and/or additional weather variables might have depended to an even larger degree on the details and assumptions of the used climatic scenarios and might, thus, have led to less robust projections as compared to the present results.

Our analysis indicates that the uncertainty related to the future radiative forcing of the global climate system and the associated global temperature response is probably the most important factor for quantitative projections of future Swiss HDD and CDD. However, the differences between GCM grid point based and statistically downscaled temperature scenarios were also significant, in particular for the CDD. This result was at least partially caused by the different global simulations available for the GP and DS scenarios (Table 1). However, it probably also reflects the particularly large uncertainty associated with the estimation of possible changes in regional summer time temperatures for the European Alps, as discussed in Refs. [31–33].

This study points to the significant impact that climate warming is likely to have on building energy features and operation costs. An annual 300 PJ provided by fossil fuels, roughly equivalent to 3 billion euros per year, is currently needed to heat Swiss buildings. Because cooling has been of minor importance in Switzerland to date, there is a lack of good equivalent data.

Our regionalized analysis also suggests widely varying shifts in future energy demand depending on location and season. Winter time heating costs will significantly decrease, the main fuels being heating oil and natural gas, whereas more expensive electrical energy will be needed for air conditioning during the summer. Future studies will need to show whether the total energy costs for building operation in Switzerland will actually decrease or increase, given the different costs of energy carriers, building stock features and the uncertainties in the spatio-temporal pattern of future climate change.

It has to be stressed that despite the expected higher ambient temperatures, high level building insulation is still necessary in order to reduce greenhouse gas emissions. Particularly in commercial buildings, a significant increase in investment costs for the installation of air conditioning equipment is very likely in the next couple of decades. As the typical service life of a building in Switzerland stands at 50–100 years, today's building design needs to take account of future climatic boundary conditions, in particular with the aim of reducing the future cooling energy demand. However, more detailed work on the future thermal behaviour of buildings in the summer is needed.

Acknowledgement

We gratefully acknowledge our debt to Switzerland's National Weather Service (MeteoSwiss) for all measured data (1901–2003), to M. Jakob (ETH-CEPE) for the energy economic data and to T. Frank (EMPA) for valuable discussions. Construction of the DS climate scenarios was financed by the Swiss Federal Research Station for Agroecology and Agriculture (FAL, project CS-MAPS) and the Swiss Agency for the Environment, Forests and Landscape (BUWAL, project No. 2001.L.03/TREWALP).

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