Indoor temperature variations in Swedish households: implications for thermal comfort

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Abstract. Everyday thermal environments affect people's comfort and wellbeing, with extreme conditions affecting human health. A strong focus on avoiding the extremes along with the introduction of tight thermal comfort criteria over the years has led to design strategies and behaviors that promote thermally stable indoor environments. However, recent research has shown that indoor temperature variation has significant health benefits, e.g. it could help tackle diabetes and obesity. These findings suggest that it is important to investigate not just the average temperature levels in households but also their distribution and variation over different periods.

In Sweden, indoor temperatures are considered to be on average high and constant due to a combination of the heating provision mechanism and the high building standards compared to other countries. This paper investigates the temperature distributions in Swedish households using detailed 15-minute indoor air temperature measurements from the 2008 BETSI-survey, provided by the Swedish National Board of Housing, Building and Planning (Boverket). Approximately two million measurements from 1306 households taken during two-week periods in winter 2007/08 are used in this investigation. Indoor temperature variation is investigated in two levels: (i) over the 2-week monitoring period and (ii) within-day. Results showed a considerable range in average dwelling temperatures of 9K, highlighting a substantial variability between homes in heating temperature and most likely in thermal comfort preferences. Regardless the different temperature levels, the majority of dwellings maintain stable thermal conditions, as demonstrated from the very low temperature variations found. Differences in daily temperature patterns were also observed.

Keywords: Thermal comfort, Indoor temperature, Housing, Indoor environment quality, Heating.

1 Introduction

People spend considerable amounts of time at home and the indoor climate they experience affects both the buildings' energy consumption and their wellbeing and health. After many years of one-sided focus on the energy performance of buildings it is becoming clear that more emphasis should be placed on the quality of buildings' indoor environment [1].

Occupants' thermal comfort is influenced by four environmental parameters: air and radiant temperature, relative humidity and air velocity. From these, temperature is considered as the most important factor for comfort [2]. Over recent years there has been an increase in data collection of indoor temperatures in households, which can help to better understand trends, preferences and patterns in populations. For example, a historic upward trend in winter indoor temperatures has been identified especially in bedrooms, with an increase in mean dwelling indoor temperature in the UK of 1.3°C per decade between 1978 and 1996 [3]. In Sweden, average indoor temperature were estimated at 21.2°C in single-family dwellings and 22.3°C in multi-family dwellings using data from 2007/08 [4, 5], whilst in 1984 the estimated averages were 20.4°C and 21.8°C respectively [6]. Whilst average values are helpful to understand general levels and historic trends, they may hide or smooth information, especially when derived from very large datasets. This work aims to investigate detailed indoor temperature measurements in Swedish homes and compare them with thermal comfort guidelines and recent findings on healthy indoor temperature variations.

1.1 Indoor climate requirements in dwellings

Standards and guides provide design criteria for the thermal environment in living spaces, including homes [7-9]. Some of them provide recommended indoor temperatures in the form of either a threshold (minimum for winter and maximum for summer) or a comfort range (Table 1). In terms of thresholds, the UK's 'Cold Weather Plan' recommends a minimum indoor temperature at home of 18°C for a sedentary person, wearing suitable clothing [10]. However, it is highlighted that temperatures up to 21°C may be beneficial for health. The World Health Organization suggests lower limits of 21°C for living rooms and 18°C for bedrooms [11, 12] while The Public Health Agency of Sweden a minimum of 18°C (21°C for sensitive persons) [13].

Table 1. Design winter indoor temperatures for residential buildings.

Study	Design minimum [°C]	Range [°C]
WHO (World Health Organization)	21.0 (living room) / 18.0 (other)	-
EN 15251 / 1.0 clo // Category I[1]	21.0	21.0-25.0
EN 15251 / 1.0 clo // Category II	20.0	20.0-25.0
EN 15251 / 1.0 clo // Category III	18.0	18.0-25.0
The Public Health Agency of Sweden	18.0 / 21.0 (sensitive persons)	20.0-23.0

[1]EN 15251 categories represent different levels of expectation.

The above recommended thresholds and ranges are mainly based on experimental research from the 1970s [14] and therefore may not reflect the variability of indoor conditions experienced in real everyday environments [15], especially in different locations around the world. The recommended ranges for heated spaces are typically rather narrow, within 3-4^{o}C, as it is assumed that this reflects the thermal preferences and needs of occupants, considered to be approximately the same. For example energy and comfort modelling are using a set-point value for the indoor temperature, i.e. 21^{o}C, with standard schedules of use. However, research in the UK has shown that these assumptions are not necessarily representative, with temperature profiles varying significantly [16], while increased exposure to thermo-neutral conditions might be a contributing factor to weight gain [3].

Similarly, it has been assumed that stable indoor temperatures are the ideal situation for most people, while recent research has shown that exposure to mildly cold or warm environments has significant health benefits, supporting dynamic and drifting temperatures for healthy indoor environments [17]. In addition to the health benefits, asymmetrical and transient thermal environments can lead to more pleasurable thermal experiences than achieved by the isotheral and static conditions, due to the effect of 'thermal alliesthesia' [18]. In a dynamic situation, a daytime variation of 8 K (e.g. 17–25°C) has been found acceptable by both young adults and elderly[19]. There is scope for further investigation of the types of indoor climates experienced in domestic buildings and their relation to comfort and health. This paper is focusing on temperature variability within the Swedish building stock using the BETSI database, as described below.

2 Methods

For the analysis presented here data from the BETSI dataset are used, which were collected in the heating season 2007/ 08. The BETSI program involved inspection of 1800 buildings, from which 1400 were residential [4]. The buildings were selected as representative of the Swedish building stock and include both single-family dwellings and apartments in multi-family buildings.

The data include air temperature and relative humidity measurements at 15 minute intervals over a period of two weeks. The corresponding outdoor dry bulb temperature and relative humidity were also included in the dataset, taken from the SMHI station (Swedish Meteorological and Hydrological Institute) closest to the dwelling. The dataset was cleaned from cases with missing or incorrect data. Values of average indoor temperature below the lowest acceptable value of 18^{o}C were also excluded, as maintaining temperatures that low for prolonged periods suggests that the homes may have been unoccupied for a big part of the monitoring period. A total of 1306 dwellings remained for analysis. The statistical analysis of the dataset was conducted in SPSS Statistics 22.

3 Results

The analysis was undertaken in two steps: the first focuses on temperature level and variation differences between dwellings over the 2-week monitoring as a representation of a short heating period. It should be noted that the two-weeks are only a snapshot of a full heating period. The second step investigates the daily temperature variations and examples of daily patterns of air temperature in the sample.

3.1 Summary statistics and 'temperature cloud'

Table 2 shows summary statistics of the dwellings' data. The average dwelling temperature ranges between 18.2°C and 26.9°C, with a mean of 22.0°C (excluding values below 18°C). The mean standard deviation is 0.7 K, with a minimum of 0.1 (negligible indoor temperature variation during the two weeks of monitoring) and a maximum of 6.5 (high indoor temperature variation).

Table 2. Summary statistics of dwellings' temperature data

	Mean	Minimum	Maximum
Dwellings' 2-week average temperature [°C]	22.0	18.2	26.9
Standard Deviation (SD)	0.7	0.1	6.5
2-week average outdoor temperature [°C]	3.8	-8.8	13.7
Standard Deviation (SD)	3.3	0.0	6.6

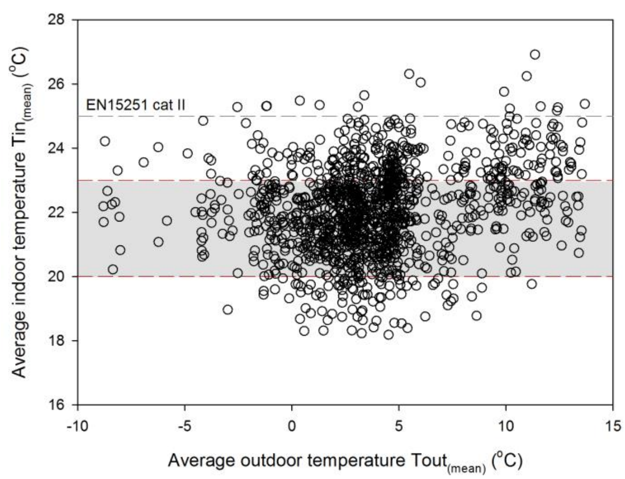

Fig. 1. Relationship between dwellings' average indoor temperature and the average outdoor temperature during the corresponding two-week monitoring period. Included is the recommended range by The Public Health Agency of Sweden (grey zone) and the EN15251 higher upper recommended value.

The range of almost 9K in average temperature between dwellings in heating mode is considerable. The scatter can be seen in Fig. 1, which shows the relationship between mean indoor and mean outdoor temperature. This result agrees with the observations of Nicol [15] of a surprisingly wide range of indoor temperatures in heated or cooled buildings. He even found that buildings with a mechanical conditioning system had a wider range of temperatures than free running buildings (non-heated/non-cooled), unlike common assumptions in standards for the opposite.

3.2 Within-'two weeks' temperature variations (monitoring period)

The dwellings' mean air temperatures and standard deviations were binned at 1^{o}C and are presented in the histograms of Fig. 2. Although the average air temperatures are nearly normally distributed, the standard deviations are clearly skewed towards very low values below 1 K, highlighting that in the vast majority of the dwellings (1100 out of 1306) there was very little variation in indoor temperature over the two-week monitoring period. It can also be seen that around 30% of the values are outside the temperature range of 20-23^{o}C recommended for comfort by The public health agency of Sweden, with the majority (25%) above 23^{o}C.

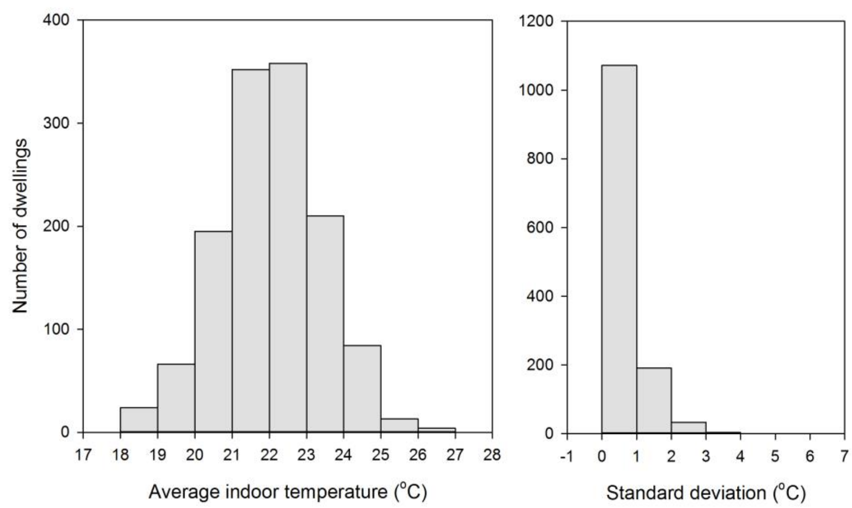

Fig. 2. Histograms of average dwelling temperature (left) and standard deviation (right) during the monitoring period.

In order to determine whether temperature variations are associated with specific levels of indoor temperature (e.g. if people maintaining on average high indoor temperatures experience high variation or vice versa), the standard deviations were plotted against the corresponding average air temperatures (Fig. 3). It can be seen that there is no correlation between the two variables, with the high standard deviations being spread across the temperature range. This suggests that temperature variation at home is not necessarily linked to a particular temperature preference and very low variations are experienced over the entire range of average dwelling temperatures (18-27^{o}C).

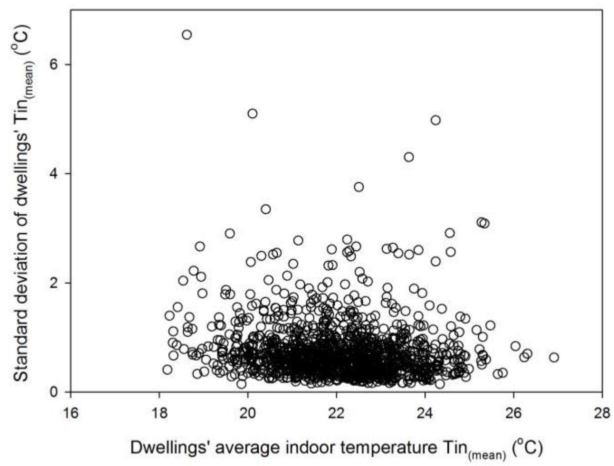

Fig. 3. Dwellings' standard deviations of measured air temperatures against the corresponding average temperatures.

Table 3 shows studies in dwellings analyzed by Nicol [15]. Whilst direct comparison cannot be made due to different measurement protocols and study durations, it is interesting to see the difference in both levels and variation in indoor temperature. Overall, the indoor temperatures in Swedish dwellings are higher and considerably more stable than in the other locations. Based on Mata et al [20], the reasons for the high and constant temperatures in Sweden are: that "the share of centrally heated buildings is much higher than in other countries; that the outdoor temperature in winter is rather stable due to low solar radiation; and that the buildings have good insulation and air-tightness (compared to other regions)". In addition to the above, it is likely that occupants have adjusted their behavior as they adapt to these indoor conditions, such as their clothing (lighter) and use of controls (less frequent or no use) [21].

Table 3. Dwelling temperatures and SD in other studies in heating season (based on [15])

Source	Location/ year	T_{in} mean	SD
[15]	Tokyo, Japan	19.6 ^{o}C	2.8 K
[16]	UK	19.0 ^{o}C	2.5 K
[22]	Harbin, China/ 2000-01	20.1 ^{o}C	2.4 K
[23]	Beijing & Shanghai/ 2012-13	21.4 ^{o}C	2.7 K
This study	Sweden/ 2007-08	22.0 ^{o}C	0.7 K

3.3 Within-day temperature variations

The data were then analyzed by day in order to see whether there are temperature drifts in the dwellings during a day. The standard deviation is used as way of expressing how much the temperature varies around the daily mean. As shown in the boxplots of Fig. 4, there is the same tendency of constant temperatures, with the standard deviation in 90% of the days being below 1K. Based on a visual inspection of the data, the higher values correspond to a number of situations: a) dwellings with individual heating where it is possible to set it lower/higher, program or switch off, b) days in the transition from heating to no-heating or vice-versa, c) false readings or readings on particularly atypical day patterns (e.g. SD=10.7K after a day with SD=0.7K) or d) particular weather conditions, e.g. solar radiation, wind etc.

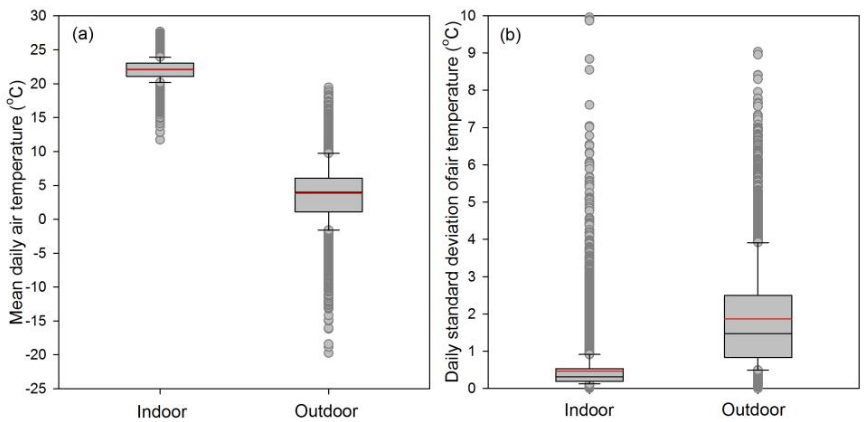

Fig. 4. (a) Daily air temperature boxplots indoors (dwelling) and outdoors (SMHI) and (b) standard deviation boxplots of daily air temperatures. Box: the 50% of the values; whiskers: the 10th and 90th percentiles; dots: outliers; black line: median; red line: mean.

For an indication of what these standard deviations mean in terms of temperature experience within a day, four examples were selected from the dataset: two for each of the main dwelling types: two apartments in multi-family buildings [(a)&(b)] and two single-family dwellings [(c)&(d)]. Typical daily variations for weekdays were created by averaging the measurements for each 15-minute time-step. Fig. 5 shows the four temperature profiles created, with the standard deviation for each time-step of the day also plotted on the graphs. As can be seen, from SD values of indoor temperature for a typical day of 0.1 to 2.0, the environments experienced are very different. The sources of variation in figures (a) and (c) are unknown but patterns can be identified, with similarities to the temperature profiles found in Huebner et al. [16]: flat temperature profile [(b) and (d)], occupancy pattern with peaks (c) and ‘steady rise’ (a). It is clear that there are differences between dwellings both in temperature levels and shapes that need to be explored further.

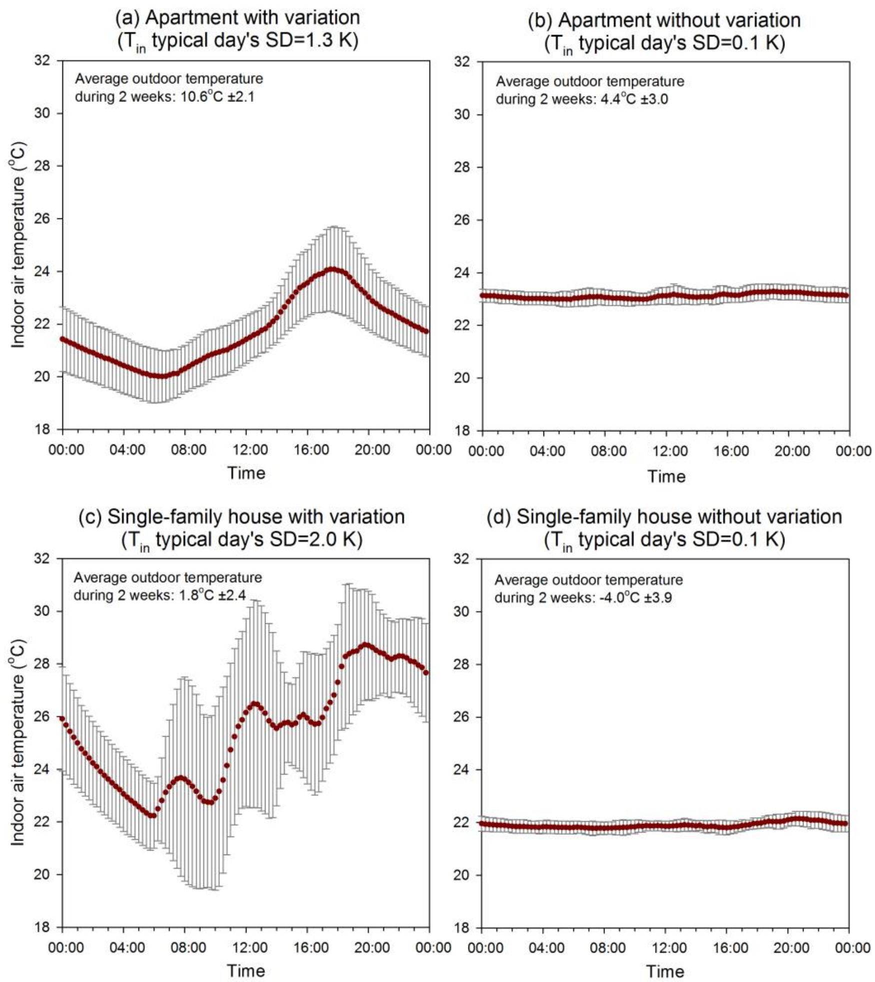

Fig. 5. Typical indoor temperature variations for (a) apartment with variation (typical day SD=1.3 K), (b) apartment without variation (typical day SD=0.1 K), (c) single-family house with variation (typical day SD=2.0 K) and (d) single-family house with variation (typical day SD=0.1 K). Standard deviation for each time-step is also included.

4 Conclusions

This exploratory paper presents results from a two-step analysis of high-resolution measurements of air temperatures in Swedish homes. A wide range of temperatures was found among dwellings, with 30% being outside the range recommended by The public health agency of Sweden. The majority of average temperatures were between

20-24^{o}C, which lies in the high end of recommended values in standards (Table 1) and higher than those found in other studies (Table 3). From the 1306 households investigated, 90% of them had standard deviations of air temperature during the monitoring period below 1K, suggesting that the majority experienced very small variations. Although such thermal stability is typically seen as positive, there may be comfort and health implications, as suggested by recent research. Future work will focus on identifying causes of temperature variation, i.e. its relationship with building type, location, climate, heating system and occupant behaviour. Furthermore, associations with perception, thermal preference, health and wellbeing will be explored, using occupants' responses to surveys from the BETSI program. Future research should also look into how healthy variations can be incorporated in indoor climate control without causing discomfort, especially to vulnerable people (e.g. elderly).

There are certain limitations in the analysis presented here: the data is almost 10 years old, the measurements correspond to a complete 24h day without distinction between occupied and non-occupied hours and the location of monitoring is not consistent in all dwellings. However, the large size of the dataset has enabled the derivation of interesting observations regarding the level and variation of indoor temperatures in Swedish dwellings.

5 Acknowledgements

The data analysed in this paper is drawn from the BETSI database, which was made available by Björn Mattsson at Boverket. D.Teli is a VINNMER Fellow supported by VINNOVA (Swedish Innovation Agency), Marie Curie Actions and the Profile 'Energy in Urban Development' within the Area of Advance 'Energy' at Chalmers University of Technology.

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