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Thermal monitoring and indoor temperature predictions in a passive solar building in an arid environment

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Abstract

In this paper, results of a long-term temperature monitoring in a passive solar house, located at the Sede-Boqer Campus of the Ben-Gurion University, in the Negev region of Israel are presented. Local latitude is 30.8°N and the elevation is approximately 480 m above sea level. The climate of the region is characterized by strong daily and seasonal thermal fluctuations, dry air and clear skies with intense solar radiation. The monitored building consists of a two storey, passive solar house and belongs to a student dormitory complex located at the Sede-Boqer Campus. Formulae were developed, based on part of the whole monitoring period, representing the measured daily indoor maximum, average and minimum temperatures. The formulae were then validated against measurements taken independently in different time periods. In managing the building, the main objective in the winter was to bring up the indoor temperature by direct and indirect solar gains while in the summer it was to keep the temperature down. Therefore, analysis of the data and development of predictive formulas of the indoor temperatures were done separately for the winter and for the summer. Measured data of each season were then divided into two sub-periods, the first one used to generate formulas based on measured data (generation) and the second for testing the predictability of the formulas by independent data (validation). In general, a fairly good agreement was verified between onsite measurements and results of the formulae, with regard to daily indoor maximum, average and minimum temperatures. The issue of using outdoor temperatures measured in the adjacent street canyon instead of those registered at the local meteorological site for evaluating the building's cooling demand is also addressed in the paper. The developed formulae were here used for estimating the building's thermal and energy performance in summer, taking into account: (1) solely climatic data from the meteorological station; (2) climatic data from the meteorological station, except for outdoor ambient temperature, which was monitored adjacent to building. Results indicated that the calculation of the building's energy demand for air-conditioning based on temperature data collected at the meteorological station would yield half of the cooling degree-days externally and about two-thirds of that internally, as compared to adopting measured canyon temperatures for such calculations.
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1. Introduction

According to climatic design, for arid locations, it is advised to build with a great amount of thermal mass, taking advantage of solar gains in winter, so that daytime heat is stored within the building and its fabric for the nighttime period, when temperatures drop. Thermal mass is also of great benefit in summer, allowing daily fluctuations of outdoor temperatures to be smoothened, so that a more stable pattern of the indoor conditions is created. Givoni [1] suggests for hot-dry regions buildings with high-mass walls and roof and the use of openable glazing, combined with insulated shutters, in order to promote ventilation in the hours when outdoor temperature drops down. In regions with cold winters, both the minimization of solar gains in summer and maximal solar

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utilization in winter should be regarded as main objectives and openings should be designed accordingly.

In this paper, we present the results of a long-term monitoring of a passive solar house, located at Sede Boqer, Negev Desert, in Israel. Considering that a "passive house requires active users", the house was operated in a climate-responsible manner throughout the seasons. This paper shows summarized results of such measurements, also presenting formulae, which were developed for predicting indoor air temperatures in the monitored building. As these formulae are based on climatic data, commonly registered at meteorological stations, the issue of adopting site-specific outdoor temperatures instead of those gathered at the meteorological station for evaluating comfort and cooling demand is also addressed in this paper. Evaluations of a given building's energy demand for air conditioning tend to consider climatic data from the local meteorological station, not necessarily close to the spot where the building will be sited. Oke [2] discusses the importance of locating meteorological locations within the city and the difficulties that sometimes arise when selecting reliable climatic data, which actually represent the urban micro-climate. The formulae were here used for estimating the building's thermal and energy performance in summer, taking into account: (1) solely climatic data from the meteorological station; (2) climatic data from the meteorological station, except for outdoor ambient temperature, which was recorded outside the building.

2. Local climate

The monitored building is located at the Sede-Boqer Campus of the Ben-Gurion University, in the Negev region of Israel. Local latitude is 30.8°N and the elevation is approximately 480 m above sea level. The climate of the region is characterized by strong daily and seasonal thermal fluctuations, dry air and clear skies with intense solar radiation. In summer, average daily maximum temperature is 32 °C and average daily minimum is 17 °C. Global radiation averages 7.7 kW h/m²/day during June and July. In winter, days are typically sunny and have an average daily maximum temperature of 14.9 °C and a minimum of 3.8 °C. Prevailing winds blow in summer from the northwest and are consistently strong in the late afternoon and in the evening, according to Bitan and Rubin [3] and Etzion et al. [4].

2.1. Thermal comfort conditions for Sede boqer

In this study, the adaptive approach originally proposed by Nicol and Humphreys [5] was used for establishing ideal operative temperatures in the building. The adaptive approach goes under the assumption that "if a change occurs such as produce discomfort, people reach in ways which tend to restore their comfort". Brager and De Dear [6] showed that the adaptive comfort standard (ACS), proposed to ASHRAE Standard 55 has a great energy-

Table 1
Adaptive comfort ambient temperature range for Sede Boqer—2006

Month	$T_{a,out}$	T_{comf}	Lower limit (90% acceptability)	Upper limit (90% acceptability)
Jan	10.1	20.9	18.4	23.4
Feb	12.0	21.5	19.0	24.0
Mar	14.5	22.3	19.8	24.8
Apr	17.5	23.2	20.7	25.7
May	20.4	24.1	21.6	26.6
Jun	23.9	25.2	22.7	27.7
Jul	24.58	25.4	22.9	27.9
Aug	26.0	25.9	23.4	28.4

saving potential. Conventional standards define thermal comfort within narrow limits, therefore making it difficult for non-residential buildings to function without any mechanical assistance, even in relatively mild climatic conditions. Since the present project is related to the need of energy conservation in buildings, the adaptive approach was adopted.

For naturally ventilated buildings, ASHRAE Standard 55 suggests an alternative for the PMV-based method for establishing a comfort zone. Optimum comfort temperature T_{comf} is therefore calculated based on the monthly mean ambient temperature $T_{a,out}$ [7]:

$$T_{comf} = 0.31 T_{a,out} + 17.8. \tag{1}$$

The comfort range for 90% acceptability is of 5 °C and for 80% acceptability is of 7 °C.

For the year 2006, when measurements in the building were carried out, comfort ranges are as presented in Table 1.

3. Long-term temperature monitoring in a passive house at Sede Boqer

Within a post-doctoral research framework, a series of indoor temperature measurements was undertaken in a passive solar house during the months of January–August 2006. The building consists of a family-apartment unit and belongs to a student dormitory complex located at the Sede-Boqer Campus. The overall floor area of the building is 55 m². Openings have mainly a south-facing exposure, such that the window-to-wall ratio (WWR: net glazing area to gross exterior wall area) of the north façade is only 0.05 and in the south façade 0.14. Double-glazed doors were used in the lower floor. Except for two small windows in the lavatory and in the bathroom (net glazed area of about 0.3 m²), swing/tilt windows were used throughout (in the kitchen and in both bedrooms) and all windows include insect screens. Fig. 1 shows the plans of both floors of the two-storey building.

As for the building materials used, the building envelope (poured concrete) is covered by an insulation material, commercialized locally as Rondopan. This insulation layer
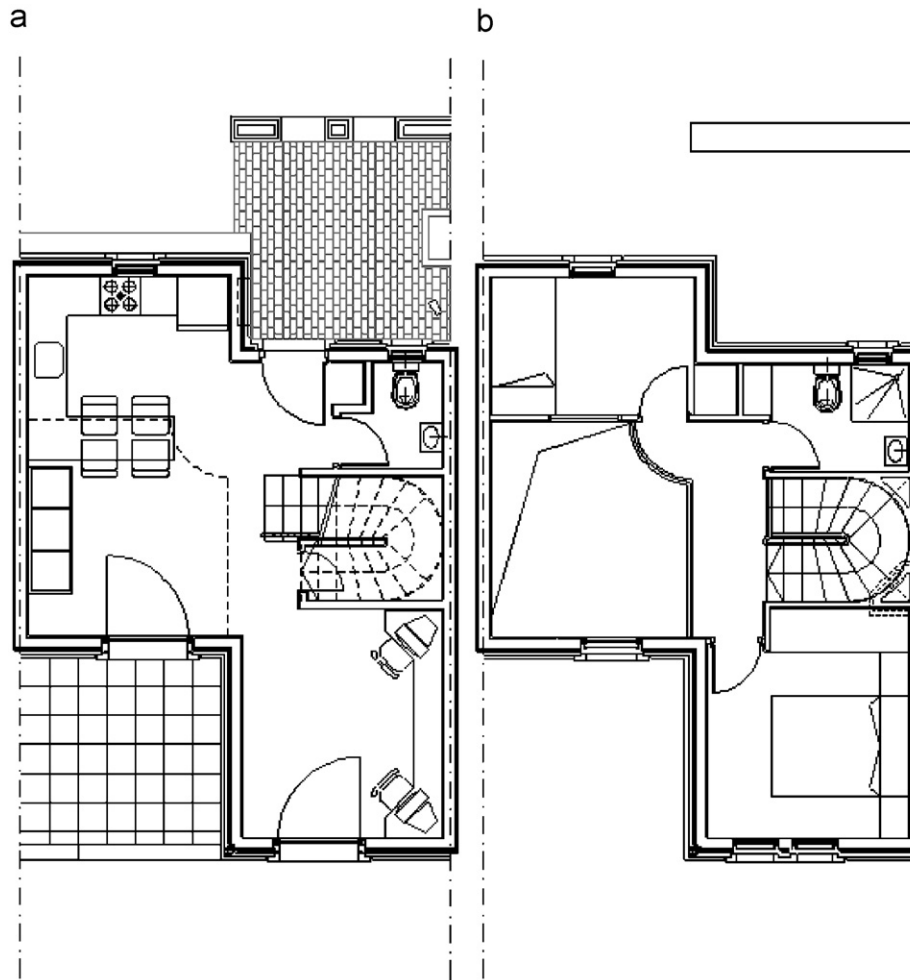
a
b

Fig. 1. The family-apartment unit.

has a conductivity of 0.026 W/m °C, and is protected by a stone veneer approximately 5 cm thick, used in external walls as exterior finish material. Windows are double-glazed with a 15 cm air gap. The composition of the envelope is shown in the table. External short wave reflectance of walls and roof was assumed to be 0.5. Table 2 presents overall characteristics of the employed materials.

The building is lined up with four other family-apartment units in an east–west row. An effort was made by the building's designers in order to allow solar gains to be maximized during the winter period. For that reason, the spacing between building rows facing south is significant.

Temperatures were measured in the building by means of copper–constantan thermocouples attached to a Campbell 21X data logger. A "monitoring log" was used, in order to keep track of the daily use of the building (occupied by a family of three), in terms of the operation of openings, electric heating (portable radiator) and cooling devices (ceiling fan, exhaust fan) (Table 3). Measured indoor air temperatures at different spots were averaged, assuming that the mean would represent a value accounting for an overall temperature distribution in the building. Beginning

in January and ending in August, measurements included winter, spring and summer periods, providing useful data for analysis. Reference data for comparisons were taken from the adjacent meteorological station.

3.1. Modes of operation

Basically, following modes of operating the building were employed in the family-apartment unit:

Winter occupation mode: all south facing shutters were kept open during the day and closed at night in order to maximize solar gains during sunshine hours and restrict heat losses during the colder period of the day.

Summer operation mode: during the hottest period of the year, shutters were left almost completely closed during the day, the building was ventilated on both floors in the evening (19:00–23:00), and during night time only in the upper floor. Although a ceiling fan was used during the day, the existent exhaust fan was practically neglected, as no significant thermal effect was perceived by the users, during and after its utilization.

As the monitored building was kept unconditioned during most of the monitoring time (in winter, a portable

Table 2
Building envelope characteristics

Layer	Conductivity (W/m K)	Density (kg/m³)	Specific heat (J/kg K)
External walls (from inside to outside)			
2 cm Plaster	0.48	1400	880
20 cm Poured concrete	2.1	2400	970
4 cm Rondopan	0.026	35	142
5 cm Stone	2.3	2515	790
Internal walls			
2 cm Plaster	0.48	1400	880
16 cm Poured concrete	2.1	2400	970
2 cm Plaster	0.48	1400	880
Floor (from inside to outside)			
2 cm Ceramic tile	0.84	1922	0.92
20 cm Poured concrete	2.1	2400	970
Roof (from inside to outside)			
2 cm Plaster	0.48	1400	880
20 cm Poured concrete	2.1	2400	970
5 cm Rondopan	0.026	35	142
2 cm Plaster	0.48	1400	880
Openings	Net glazed area (m²)	Glazing *U*-value (W/m²K)	Solar transmittance (%)
2 Double-glazed doors	2.30/unit	2.8	0.69
4 Swing/tilt windows	0.55/unit	2.8	0.69
2 Tilt Windows	0.30/unit	2.8	0.69
1 Swing window	0.7	2.8	0.69

Table 3
Example of daily use descriptions

Julian day	Weekday	Date	Descriptor
33	Thursday	2/2/2006	Free running, shutters open during day, no occupancy
73	Tuesday	3/14/2006	Day out, closed mode
127	Sunday	5/7/2006	Normal use, shutters partially open, enhanced ventilation during the day and at night
145	Thursday	5/25/2006	Normal use, shutters almost completely closed, night ventilation, ceiling fan operating during the day
154	Saturday	6/3/2006	Closed and empty all day
155	Sunday	6/4/2006	Normal use, shutters almost completely closed, night ventilation, ceiling fan operating during the day (+ EXHAUST FAN)
158	Wednesday	6/7/2006	Normal use, shutters almost completely closed, night ventilation

radiator has been used only during a few hours of the coldest days and, in summer, an electric fan was used on a few occasions in order to test the effect of forced ventilation in lowering indoor air temperatures), the adaptive comfort approach could be employed.

3.2. Winter results: effect of shading and insulating shutters

Two vacant weeks in winter (between February 2 and February 15, 2006) are illustrative for showing the effect of using the external shutters for gaining direct solar radiation during the day (Figs. 2 and 3). During the first 8 days, shutters were kept open during sunshine hours and closed at night. During the next 6 days, shutters remained permanently drawn.

Despite the varying daily ambient temperature pattern in winter, air temperatures inside the building follow a rather constant pattern, due to the high thermal mass of the envelope. The proper operation of the shutters allows solar gains, which make the indoor temperature reach comfortable conditions during the peak hours of the day. By closing the shutters at sunset, long wave radiation from the indoor surfaces can then be trapped during nighttime hours. During this vacant period and under this mode of operation, while outdoor average temperature was 12 °C with a daily swing of 9 °C, mean indoor was 18 °C with a fluctuation of about 2 °C. However, due to the fact that the building is quite massive (and that the stored energy will remain indoors for some time during the "closed mode"), careful analysis of the temperature depression between
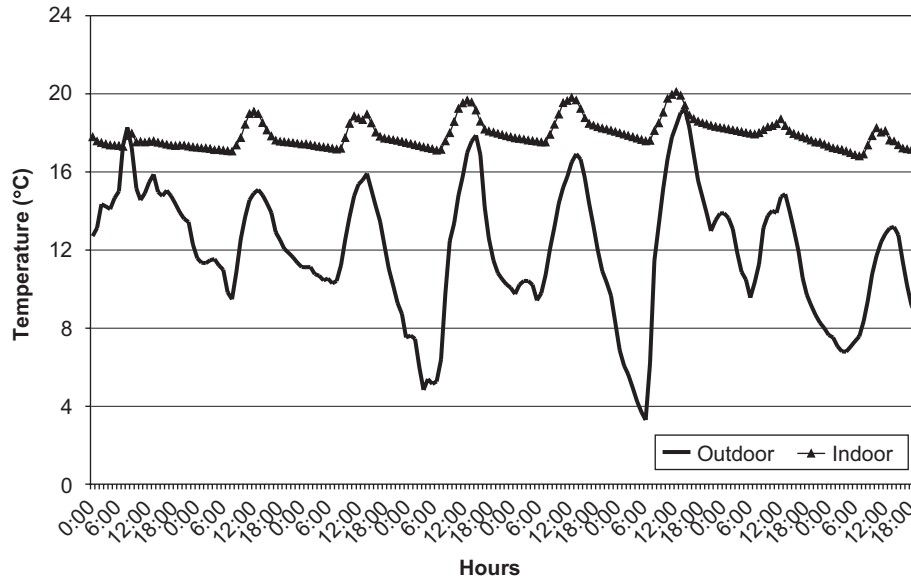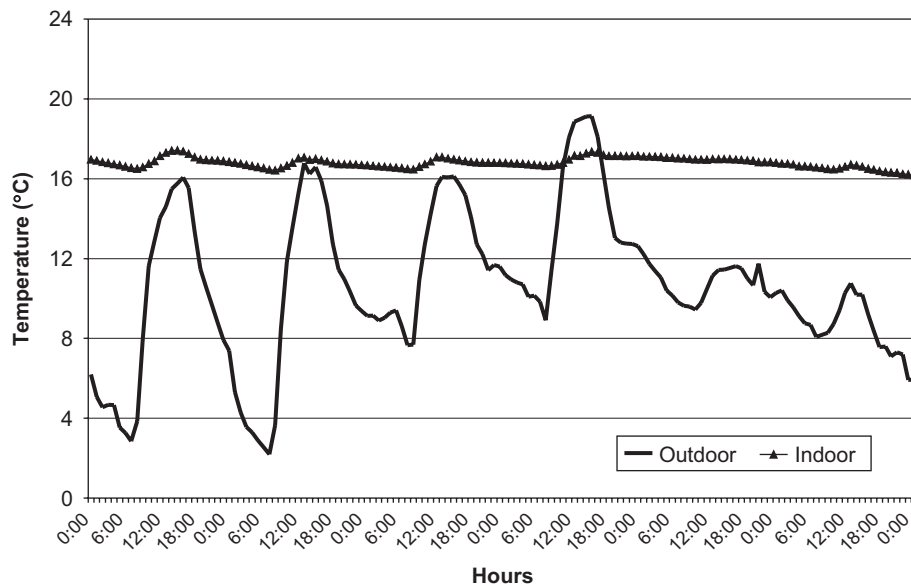
Fig. 2. Winter open mode.

Fig. 3. Winter closed mode.

indoor and outdoor air temperatures showed that the stored heat within the building envelope can be far more substantial and last longer than the daily amount of solar gain observed during the "open mode configuration".

3.3. Summer results: effect of ventilation

Night ventilation is one of the recommended passive strategies to achieve improved conditions indoors in summer. The expected effect of night ventilation is to lower indoor temperatures in summer when outside air temperature drops to comfortable conditions, which in Sede Boqer occurred usually after sunset in summer. The graph (Fig. 4) shows two different occupation modes: the

first 3 days with the building vacant (May 19–21, 2006) and the following days (May 22–31, 2006) with night ventilation. While it was being ventilated, sudden drops of the indoor temperature can be noticed. However, contrary to the expected, the indoor temperature does not drop continuously with the outdoor ambient temperature. This basically occurs due to two different reasons: (1) local wind speed decreases substantially during the nocturnal period, resulting in very low nightly air change rates, and (2) it takes considerable time for the building's structure to cool down, due to the massiveness of the building envelope.

Another aspect that prevents a good cross ventilation to occur relates to the fact that the inlet openings located on the north side of the building are quite small, so that heat
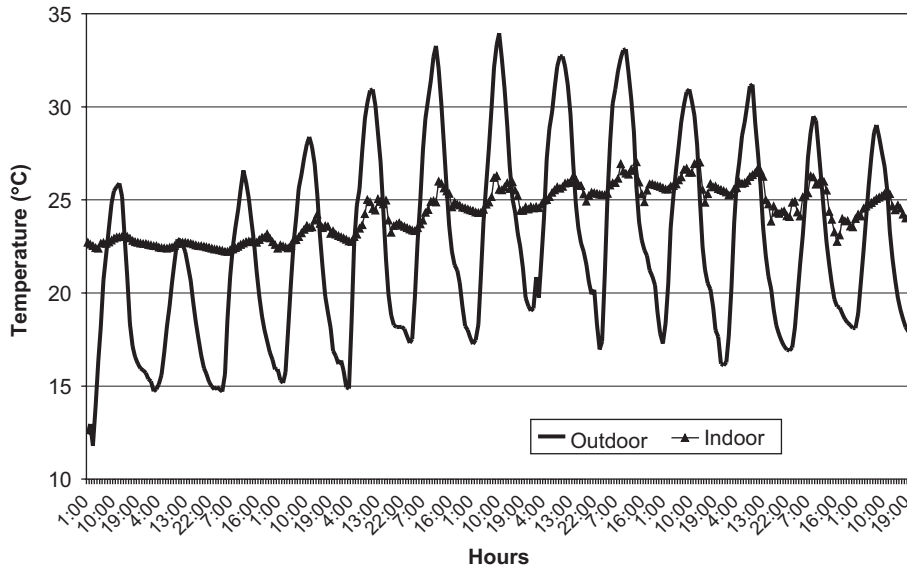
Fig. 4. Closed and ventilation mode around summer solstice (first 3 days—closed, following days with nocturnal ventilation).
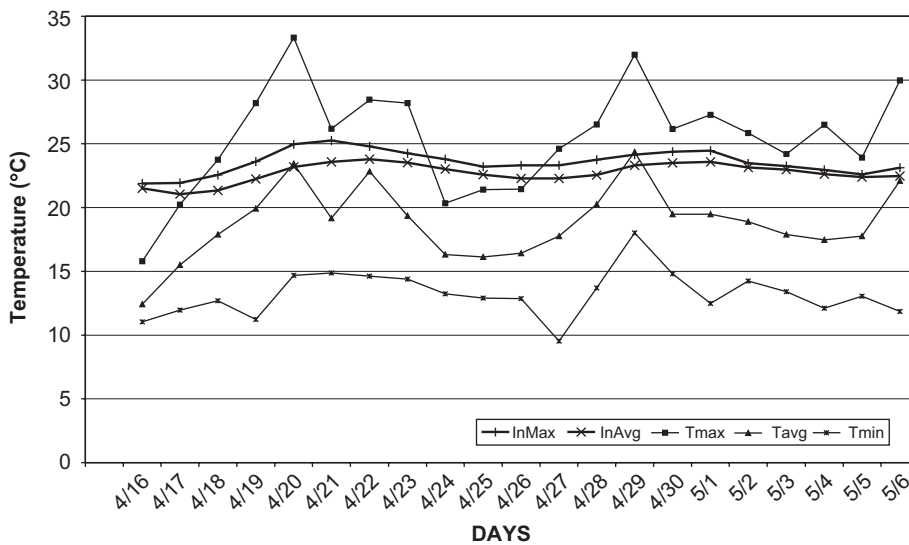

Fig. 5. Indoor average and maximum temperatures, during 3 weeks in the summer.

losses in winter can be minimized. For cross ventilation to be effective, openings must be provided on building façades located on windward and leeward sides, so that the pressure difference between both can be neutralized by air flow through the building.

4. Data analysis and generation of formulae

The fact that the building construction had materials with a high thermal mass affected the patterns of the indoor daily temperatures and the relationship between the indoor and the outdoor temperature conditions. The impact of the high mass characteristics of the building on the patterns of the indoor temperatures are discussed in this section qualitatively, before the description of the

generation and the validation of the formulae representing the indoor maximum, average and minimum temperatures.

4.1. Impact of the high mass characteristics of the building

Fig. 5 shows the indoor average and maximum temperatures of the building, during 3 weeks in the summer, plotted over the background of the respective outdoor maximum, average and minimum temperatures.

The weather conditions during this period were very variable, with sharp daily changes in the outdoor maximum, average and minimum temperatures, as well as in the daily temperature ranges (swings). The indoor temperatures, on the other hand, were much more stable, resulting from the high thermal mass of the building.
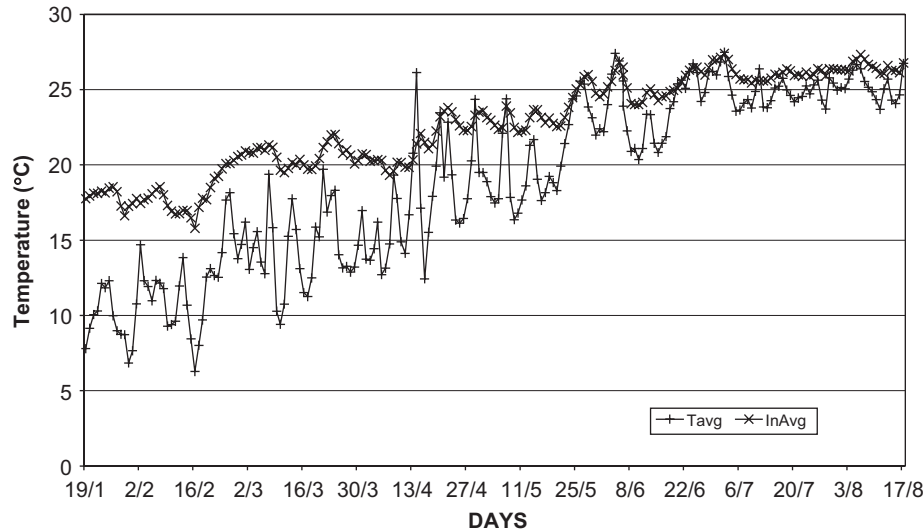
Fig. 6. Outdoor and indoor average temperatures through the monitoring period.

Analysis of this pattern has suggested that the indoor temperatures in a given day "remember" and average the conditions from several previous days. It was later decided to express this factor in a formula by a "running average (RnAvg)", which is the average of the outdoor average temperatures during the previous 3 days.

Similar analysis of the response pattern of the indoors' minimum has suggested that the minimum in a given day is affected by the drop from previous day's maximum to present day minimum, T_{drop}.

$$T_{drop} = T_{max}(n-1) - T_{min}. \tag{2}$$

The indoor minimum in a given day is the starting point for that day's temperature pattern, including the day's average and maximum. Therefore, the effect of T_{drop} on the indoor's daily average and maximum was tested and found to have a measurable effect.

4.2. Relationship between period's outdoor average and indoor average

During the winter, when the building was heated by means of direct and indirect solar gains, the occupants succeeded to maintain the indoor temperatures well above the outdoor average. This elevation is highest in the first period, January and part of February, and decreases afterwards, apparently because solar penetration through the southern windows is reduced due to the higher solar elevation. In addition, management of the shutters by the occupant helps in adjusting the indoor temperatures to their comfort needs. In this way the pattern of the indoor average temperature in the monitored building in Sede Boqer reflects the effectiveness of the solar heating in the winter and the effectiveness of solar shading and ventilation in then summer.

Fig. 6 shows the patterns of the outdoor and the indoor average temperatures throughout the monitoring period:

from January 19 to August 17. Visual inspection of the figure shows that the rise of the outdoor temperature was not smooth and around some specific dates there was a sharp rise in the outdoor temperature that was reflected also in the pattern of the indoor average. Such "jumps" have occurred around February 18, March 18, April 17, May 22 and June 20. The pattern of the indoor average is much smoother than that of the outdoor average, resulting from the high mass structure of the building.

Visual analysis of the elevation of the indoor average above the outdoor average has suggested that, from the aspect of relationship, the entire monitoring period could be divided roughly into six sub-periods: from January 19 to February 18, from February 19 to March 18, from March 19 to April 15, From April 16 to May 22, from May 23 to June 19 and from June 20 to July August 17. For each sub-period, "grand" averages (average temperature for each sub-period, GT) were computed for the outdoor and the indoor average temperatures (see Fig. 7).

It can be seen in Fig. 7 that as the outdoor average rises, the elevation of the indoor average above the outdoor's is decreased. Fig. 8 shows the indoor temperature elevation as a function of the outdoor grand temperature (GT_out). The two variables are closely correlated, which yields a R^2 value of 0.992.

This close relationship enables to "predict" the period's indoor grand temperature (GT_in) as a function of the outdoor temperature (GT_out):

$$GT\_in = GT\_out - 0.437GT\_out + 12. \tag{3}$$

4.3. Predictive formulae

Indoor temperature predictions, for a specific building but for different climatic conditions, based exclusively on outdoor climatic parameters, were shown to be possible both for non-occupied and occupied un-conditioned
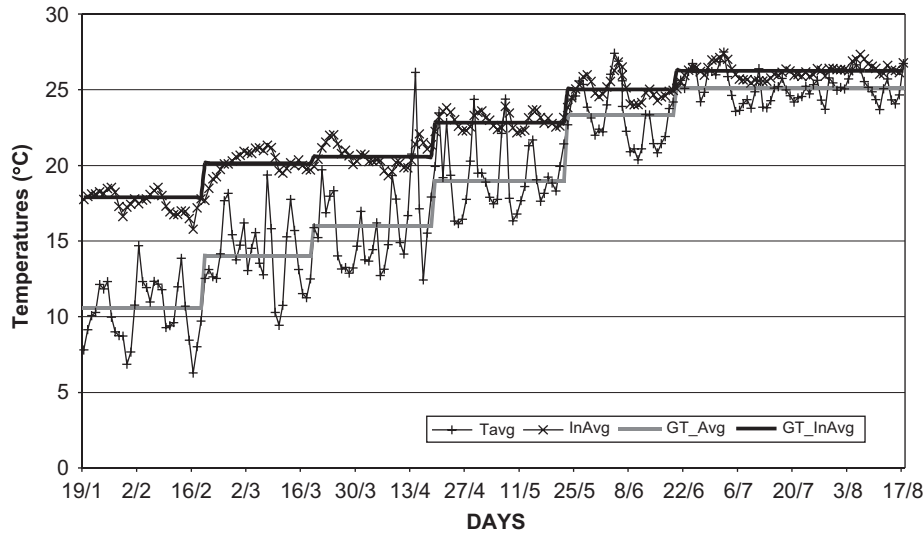
Fig. 7. Grand averages of the indoor and outdoor average temperatures.

buildings [8–10]. Such predictions are developed as simple formulae, which relate indoor daily maximum, average and minimum temperatures to external climatic factors. The constants that appear in these formulae are specific to a given building, so that there is no need to take into account the thermophysical characteristics of the building. In the case of occupied houses these are also specific to a particular family, as personal "management" of the house has a significant effect on the indoor temperatures in un-conditioned buildings.

In managing the building in Sede Boqer, the main objective in the winter was to bring up the indoor temperature, utilizing solar radiation as the main heating source. In the summer the objective was to keep the temperature down, mainly by minimizing solar radiation penetration through the windows. Therefore, analysis of the data and development of predictive formulae of the indoor temperatures was done separately for the winter (from January 19 through April 15) and for the summer (from April 16 through August 17).

The measured data of each season were then divided into two sub-periods, the first one was used to generate formulae based on the measured data (Generation) and the second sub-period was used for testing the predict-ability of the formulae (Validation) by independent measured data. In the winter the "generation" period was from January 19 to March 18 and the "validation" period was from March 19 to April 15. In the summer the "generation" period was from April 16 to June 10 and the "validation" period was from June 11 to August 17. During the validation periods the outdoor maxima were significantly higher and the diurnal swing larger than during the generation periods, following the rising pattern of outdoor temperatures as climatic conditions move toward summertime.

One objective in the development of the formulae was to use the least amount of measured data that can provide
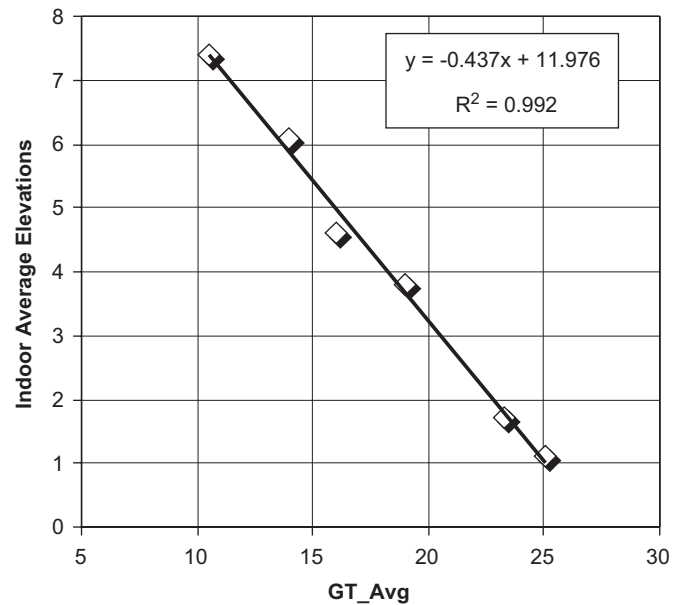

Fig. 8. Indoor temperature elevation as a function of the outdoor grand temperature.

reasonable description of indoor temperature conditions. In previous studies conducted in the USA and in Brazil it was demonstrated that formulae using only outdoor temperatures data could represent quite well measured indoor temperatures in un-occupied buildings and in occupied houses.

In winter, when direct and indirect solar gains were the main source of heating, solar data had to be included in the formulae. On the other hand, in summer, when the effect of solar radiation was minimized by shading of the windows, it was found that it is possible to get reasonable agreement between the measured and the computed indoor tempera-tures even when solar data were not included in the formulae. Following the analysis of the relationship

between the sub-periods' outdoor and indoor averages, the periods' outdoor average temperatures were incorporated in the formulae.

Such formulae were generated by multiple regression for the indoor daily maximum, average and minimum temperatures, for the winter and for the summer periods separately. An interesting finding was that, due to the high mass of the building, the indoor daily maximum and average temperatures were affected also by the outdoor average temperature during several previous days, in addition to the effects of the current day's average and maximum. Consequently, an arbitrary term RnAvg, average of 3 previous days, was introduced in the predictive formulae.

4.4. The independent variables in the formulae

Due to the opposing objectives in the cold (winter) and in the warm (summer) periods, two different sets of formulae were developed for the indoor maximum, average and minimum temperatures.

In a building heated in winter mainly by solar radiation, the amount of radiation penetrating the southern windows is an important factor. The penetrating radiation depends on the amount of radiation striking a vertical southern plane and the position of the shutters during the daytime: open, closed or partially closed (solar factor—SF).

Only the hourly horizontal global radiation was measured in this research. In order to include a simple expression of the solar radiation affecting the indoor temperatures the following procedure was applied.

The input variable was the daily total solar radiation penetrating the southern windows (sol), which is the product of three factors: horizontal radiation (radiation), the Sine of the solar angle relative to a southern facade at noon (sine of SA—$\sin \theta_z$) and the position of the shutters (SF), yielding the input variable effective solar (EfSol):

$$\text{EfSol} = I_g \times \sin \theta_z \times \text{SF}. \tag{4}$$

The values assigned to the SF (position of the shutters) were:

Shutters open during daytime	SF = 1.0
Shutters partially open	SF = 0.5
Shutters almost completely closed	SF = 0.2
Shutters closed during daytime	SF = 0

In the summer the shutters were almost closed during daytime, so that the value of SF was almost all the time zero. Consequently, solar data were not incorporated in the formulae for the summer period. The building was occupied all during the summer period so the occupancy factor was also excluded from the summer formulae.

4.4.1. Indoor maximum and average

The independent variables that were included in the formulas for the indoor daily maximum (InMax) and

average (InAvg) were: the outdoors' daily average (Avg) and maximum (Max), RnAvg and T_{drop}, the daily total amount of global radiation penetrating the southern windows (EfSol), the daily diurnal swing (Swing), and whether the building was occupied or empty (Occup).

Normal use	Occup = 1.0
Guest	Occup = 1.2
House empty	Occup = 0

As mentioned above, the EfSol and Occup factors were incorporated only in the winter formulae.

4.4.2. Indoor minimum

The indoor minimum is affected not only by the current's day minimum but also by the temperature drop from the previous day's maximum to the current day's minimum ($T_{\text{max}}(n{-}1)$–T_{min}), representing mainly the rate of nocturnal radiant cooling.

The variables included in the formulae thus were:

- Periods' outdoor average—GT_{avg}.
- Running average—RnAvg.
- Outdoor maximum—T_{max}.
- Outdoor daily average—T_{avg}.
- Outdoor minimum—T_{min}.
- Diurnal swing, (T_{max}–T_{min})—Swg.
- Effective solar, EfSol—only in winter.
- Occupancy factor—Occup—only in winter.
- Temperature drop from previous outdoor maximum, $T_{\text{max}}(n{-}1)$ to current minimum, T_{min}.

The indoor temperature formulae, generated for the *winter period*, were:

$$
\begin{aligned}
\text{Maximum } (W) = {} & 13.14 + 0.0145 GT_{\text{avg}} \\
& + 0.3078 \text{RnAvg} + 0.0537 T_{\text{max}} \\
& - 0.0115 T_{\text{avg}} + 0.0299 \text{Swing} \\
& + 0.0003 \text{EfSol} + \text{Occup}.
\end{aligned} \tag{5}
$$

The correlation coefficient, CC, for the generation period was CC = 0.9454 and for the validation period it was CC = 0.8735.

$$
\begin{aligned}
\text{Average } (W) = {} & 11.3 + 0.1477 GT_{\text{avg}} \\
& + 0.3368 \text{RnAvg} + 0.0804 T_{\text{max}} \\
& - 0.0744 T_{\text{avg}} + 0.0168 \text{Swing} \\
& + 0.0002 \text{EfSol} - 0.665 \text{Occup}.
\end{aligned} \tag{6}
$$

For the generation period, CC = 0.9579 and for the Validation period, CC = 0.8436.

$$
\begin{aligned}
\text{Minimum } (W) = {} & 13.12 + 0.3028 T_{\text{min}} \\
& + 0.2659 (T_{\text{max}}(n-1) - T_{\text{min}}).
\end{aligned} \tag{7}
$$

For the generation period, CC = 0.8129 and for the validation period, CC = 0.7481.
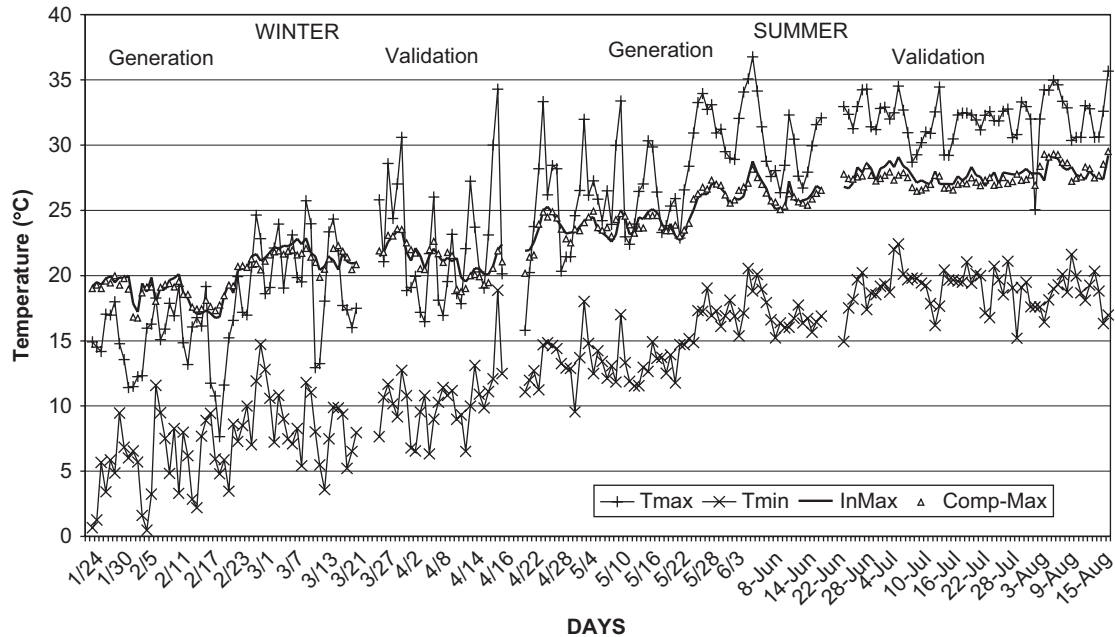
Fig. 9. Measured and computed indoor maximums and outdoor maximum and minimum temperatures.

The indoor temperature formulae, generated for the *summer period*, were:

$$\text{Maximum } (S) = 11.8 + 0.1469 \text{GT}_{avg} + 0.0167 T_{avg}$$
$$+ 0.3441 \text{RnAvg} + 0.0483 T_{max}$$
$$+ 0.1331 \text{Swing}. \qquad (8)$$

For the generation period, CC = 0.9306 and for the validation period, CC = 0.8795.

$$\text{Average } (S) = 14.1 + 0.1544 \text{GT}_{avg}$$
$$+ 0.0594 T_{avg}$$
$$+ 0.3128 \text{RnAvg} - 0.0497 T_{max}$$
$$+ 0.0287 \text{Swing}. \qquad (9)$$

For the generation period, CC = 0.9664 and for the validation period, CC = 0.9202.

$$\text{Minimum } (S) = 15.76 + 0.3611 T_{min}$$
$$+ 0.1278 (T_{max}(n-1) - T_{min}). \qquad (10)$$

For the generation period, CC = 0.8446 and for the validation period, CC = 0.7203.

Figs. 9–11 show, respectively, the measured and computed indoor maxima, average and minima in the winter and the summer periods.

5. Cooling demand in summer

The predictive formulae described in the previous Section were used to assess energy consumption for comfort cooling in the building, using two kinds of input: (1) climatic data measured at the local meteorological station; (2) climatic data from the local meteorological station and air temperature data collected outside the family-apartment unit. In order to be able to analyze the impact of using local air temperatures instead of taking measured data from the local meteorological station as a reference for building thermal performance simulations, ambient temperature was measured outside the building, in the "street canyon" between family-apartment rows.

The buildings enclosing the canyon consist of very massive constructions, with external surfaces faced with stone. The street canyons in front and behind the building row where the family-apartment unit is located have approximately in an east–west axis orientation. The aspect ratio (the relation between building height and street width, H/W) is approximately 0.6 and the length of the canyon is approximately 25 m. There is neither vehicular nor significant pedestrian traffic in the streets. The site is sparsely built and incorporates xeric landscaping with very little vegetation. Ambient air temperature measurements were taken in the middle of the street canyon behind the family-apartment unit at approximately 1.8 m (head height), about 15 m from the west end of the canyon. Ultra-fine copper–constantan thermocouples were connected to a Campbell 21X data-logger and attached to a monitoring mast. Sensors were shielded against direct radiation with cardboard cylinders covered with a thin aluminum sheet.[1] The monitoring mast was placed in the middle of the street canyon, formed by the two

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[1]This monitoring setup was later placed at the meteorological station, in order to compare temperature data side by side with conventional WMO equipment. Such comparisons yielded satisfactory results so that a calibration procedure was developed at a later stage of the research to account for a short time lag between temperature curves. In general, except for the time lag, the patterns of both curves (air temperature monitored both at the mast and inside the Stevenson screen) were roughly the same.
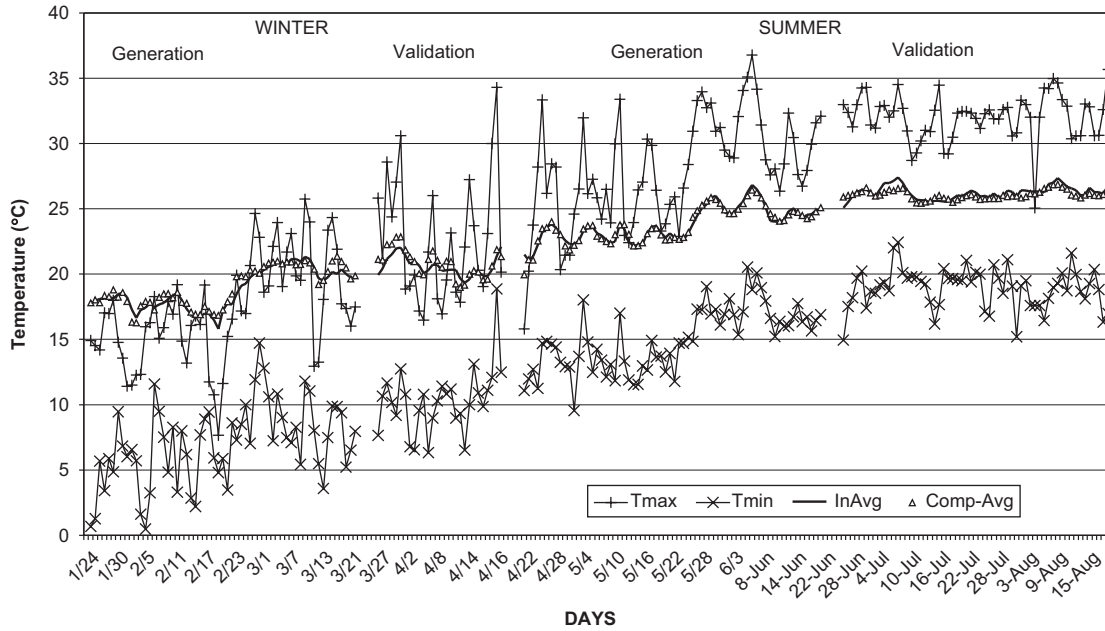
Fig. 10. Measured and computed indoor averages and outdoor maximum and minimum temperatures.
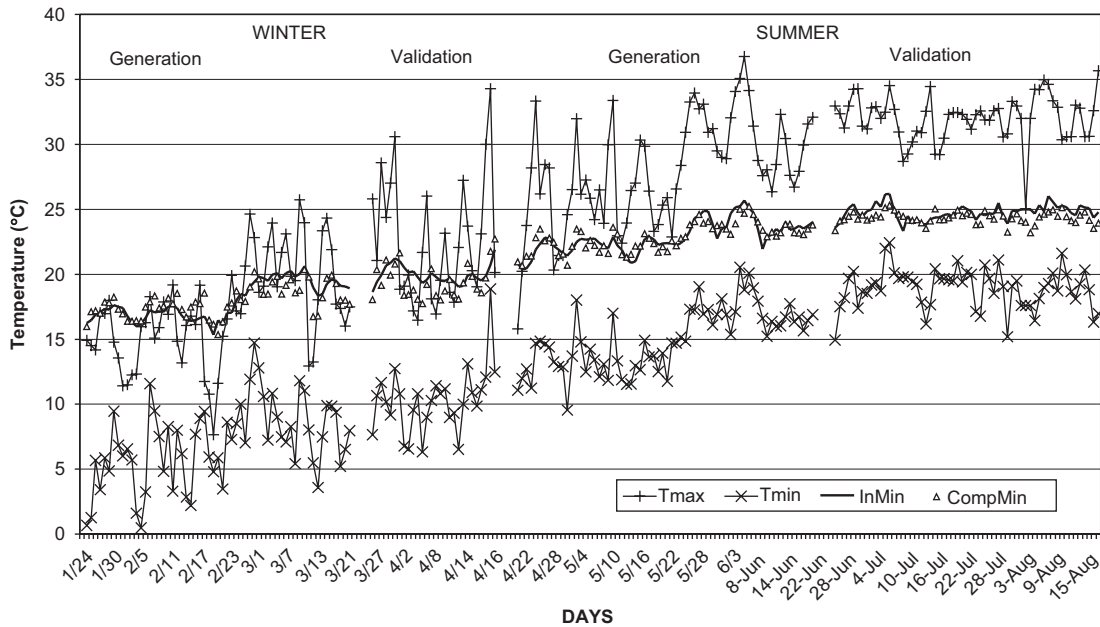

Fig. 11. Measured and computed indoor minima and outdoor maximum and minimum temperatures.

family-apartment blocks (Fig. 12). The meteorological site is located at a distance of roughly 500 m from the street canyon.

As the calculation of the building's cooling demand refers to the summer period, and as the "summer formulae" do not take into account any other climatic factor apart from air temperatures (see Eqs. (8)–(10)), only air temperatures were used in the calculations: from the meteorological station and from the street canyon. For the summer month of July, the cooling degree-days method

was employed.[2] The comfort temperature of 25.4 °C, calculated according to the adaptive comfort approach for that month, was used as a reference for degree-day

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[2]The degree-days procedure is a simplified, practical method for determining cumulative temperatures over the course of a season. Originally designed to evaluate energy demand and consumption, degree-days are based on how far the average temperature departs from a pre-defined comfort level. The number of degree-days accumulated in a day is proportional to the amount of heating/cooling to keep a building within comfort conditions.

Fig. 12. Monitoring mast with shielded ultra-fine copper–constantan thermocouple placed in the middle of the street canyon.

Table 4
Degree-day calculations

Air temperatures collected at	Outdoor cooling degree-days (July) [°C d]	Indoor temperature predictions	Indoor cooling degree-days (July) [°C d]
Meteorological station	7	Based on temperature data collected at the meteorological station	18
Street canyon	14	Based on Canyon temperatures	28

calculations. Predictions of the daily indoor average temperature were made and compared to this reference temperature for both cases (Table 4).

The difference in the magnitude of the degree-days sum for cooling outside and inside the building is consistent with Fig. 5, showing that the average indoor temperature is higher than the outdoor average throughout most of the monitoring period, although in summer this difference may be reduced. Results show that, due to a slight increase in the average air temperature in the street canyon (from an outdoor means of 24 °C in the meteorological site to 25.3 °C in the canyon, there is a corresponding increase in cooling demand for the "urban" site. It must be stressed that the impact of overshadowing within the canyon is not to be observed, as the spacing between building blocks ($H/W = 0.6$) is quite substantial. Such effect is expected to have a positive impact on canyon temperatures in desert locations, lowering those during the sun-lit hours of the day [11,12]. However, the heat island effect, though with a very small magnitude of 0.1° and a maximum around 2°, was responsible for an increase in cooling demand of 56% in the building. A simple comparison of outdoor cooling degree-days, for a base temperature of 25.4 °C, taking into account both sites, showed an increase of 100% in the street canyon, relative to outdoor temperatures measured at the meteorological station.

6. Conclusions

A series of indoor temperature measurements was undertaken in a passive solar house during the months of January–August 2006. The relationship between the indoor and the outdoor climate has resulted from the changing "management" strategy of the house, according to the changing comfort needs. In the cold period the objective of the occupants was to bring up the indoor temperature while in the hot period the objective, from the comfort aspect, was to bring it down.

Formulae were developed for predicting indoor air temperatures in the monitored building. It was demonstrated that a fairly good agreement existed between the on site measurements and the formulae representing the indoor maximum, average and minimum temperatures.

The use of predictive formulae, such as those presented here, is meant for indoor temperature predictions of a given building, with a given geometry and solar exposure, concerning different periods of the year or even exposed to different climatic conditions, provided that the building can be operated in a similar way as during its monitoring. The effect of taking measured air temperatures at the E–W street canyon right next to the monitored building as reference data for predictions was compared to that of using plain climatic data collected at the local

meteorological station. The energy consumption for air-conditioning was calculated for the building, using the predicted formulae for summer (July) and it was found that a substantial difference can be obtained in such calculations depending on the location where temperature data were collected.

Acknowledgments

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