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Dependencies of the indoor climate on the course of the seasons and derivation of regressions from long-term measurements

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Abstract

A building's indoor climate is an essential input variable for a variety of building physics computational models, simulations, and analyses. Precise knowledge of the indoor climate is necessary to minimize the risk of mold or moisture damage and is required to ensure minimum heat insulation standards in buildings. Detailed data are especially necessary for the progressive application of transient calculations, for example, concerning thermal comfort or energy consumption. While the properties of building materials and the (local) outdoor climate are known, only rudimentary information about the dynamic indoor climate is available. Most existing information in the literature about indoor climate is fairly general and forgoes a differentiation between climatic region, occupancy profile, and the utilization of rooms. In this paper, we report on indoor climate measurements in naturally ventilated apartments over a period of 1 year. The measurement results complement the existing data to provide accurate indoor climate data in buildings. The measured values of indoor temperature and relative humidity serve to derive the dew point temperature and moisture load whereby dynamic time-dependent regression functions are determined for these parameters. The evaluations are carried out separately according to room use. The comparison of living rooms and bedrooms indicates a great influence of room use on the indoor climate in residential buildings. The determined indoor climate model can be used for the planning of buildings and simulations. The classification into living rooms and bedrooms makes it possible to take user behavior into account more realistically in building physics simulations. The minimum thermal insulation in residential buildings can also be checked and designed based on realistic data. The prediction interval describes the limits in which residential rooms are free of damage with a high probability. In this way, the indoor climate model describes an approach to examine and evaluate simulation results regarding condensation risk and mold damage in naturally ventilated rooms.

KEYWORDS
dew point temperature, indoor climate, indoor climate model, long-term measurement, moisture load, user behavior, window ventilation

1 | INTRODUCTION

The knowledge of the expected hygrothermal room air conditions is essential to avoid critical surface moisture in buildings. For example, according to German regulations, the proof of the minimum heat protection at a thermal bridge is regarded as provided if room-side surface humidity, which promotes mold growth, is prevented.[1] Hygrothermal room air parameters are also essential input variables for the calculation of diffusion-related moisture quantities to prevent condensation inside building components. According to normative requirements in Germany, this verification is also carried out with stationary boundary conditions.

However, the application of stationary conditions as defined by the legislator is no longer up to date as current research results based on extensive long-term measurements have shown that the stationary conditions can only provide rough approximations.[2] Better planning of the moisture protection, the energetic optimization, or the expected building energy consumption can only take place if the usual state of use can be reproduced as precisely as possible. This assumption of simplified, as stationary temperature boundary conditions do not take the use of buildings or the different climatic regions into account.

Dynamic time-dependent calculation methods are indispensable when it comes to adequately consider the importance of the interaction between user behavior and the thermal insulation of the building envelope on the minimum thermal insulation, that is, on the mold risk or the energy requirements.

In recent years, building physics simulation programs have become an indispensable tool for the planning and evaluation of buildings. This applies, in particular, to the design of minimum thermal insulation and the energy optimization of buildings. Further, transient hygrothermal simulations are indispensable for structural damage analysis in existing buildings or to determine thermal comfort.

The use of these programs requires realistic dynamic climate data. For the outdoor climate, these data are available in high temporal resolution through weather stations close to the location or test reference years for most locations around the world.

However, the indoor climate in particular is of great importance for realistic calculation results as only by knowing the expected indoor climate is it possible to determine the risk of condensation or mold growth and thus guarantee the minimum thermal insulation. In particular, the indoor climate is the prerequisite for avoiding mold by complying with various standards[3] or mold growth models.[4,5] Furthermore, realistic energy demand calculations are only possible if valid data on the user's preferred indoor air temperature or information on ventilation behavior is available.

The indoor climatic needs of users have been investigated in various research projects. In Ref. [6], it was shown that the user group has a significant influence on the indoor climate. Flats occupied by senior citizens have higher air temperatures throughout the day than those occupied by families with working parents and school-age children. Elderly people in nursing homes prefer an even higher indoor air temperature than elderly people in flats.[7] The requirements described in Ref. [8,9], especially for bedrooms, show that the use of the room also has a significant influence on the indoor climate. Further general information is available in the literature, for example, on the production of moisture during everyday processes such as showering or cooking, or on the moisture emitted by people.[6,10]

Practical implications

- The evaluation of long-term hygrothermal measurements shows considerable differences in indoor air temperature between the living room and the bedroom.
- A sinusoidal function is very well suited to describe the indoor climate over the course of the year.
- The results of the investigation can be used as an input variable for building physics calculations.
- The determined model of the dew point temperature enables the evaluation of the critical humidity on room-side building component surfaces.

However, representative data on the indoor climate considering the use of the room, region, or the specific living situation in the form of a dynamic reference indoor climate do not yet exist. In contrast to the outdoor climate, only rough approximations are available for the indoor climate.[11–14] This is especially true for the strongly user-dependent indoor air conditions in residential buildings.

In various research approaches, in addition to short climate measurements, data surveys on the perception of the indoor climate conditions were evaluated. In this context, optimal comfort ranges are to be defined and thus findings on the user-induced indoor climate are to be collected. However, such studies were mostly conducted in non-residential buildings whereby the aim was to gain information on productivity and room hygiene in rooms with higher occupancy. In Ref. [15] for example, short right-now surveys were performed during the measurement, and the results showed no agreement between the measured and subjective data. In residential buildings, surveys were conducted with 160 participants[16] and room climate measurements were carried out in parallel in several of the participants' living rooms. In this case, the comparison between the survey and measurements showed no agreement. This underlines the fact that long-term measurements of the indoor climate are indispensable to draw valid conclusions about the indoor climate and to derive user-dependent comfort ranges.

In this paper, the results of long-term measurements of the indoor climate of different dwellings are presented. In particular, the influence of room use on the indoor climate is investigated and evaluated. Furthermore, the measurement results of living rooms and bedrooms are compared and regression functions of hygrothermal conditions in buildings are presented for each type of room.

TABLE 1 Specifications of the analyzed rooms in Weimar

Object	Occupants	Living room	Volume m³	Windows	Facade orientation	Glazing m²	Bedroom	Volume m³	Windows	Direction	Glazing m²
1	2	*L 1*	51.4	1	South	1.5	*B 1*	44.6	1	South	1.5
2	3	*L 2*	75.0	1	East	2.2	*B 2*	42.0	1	East	2.2
3	4	*L 3*	93.0	2	South/East	7.7	*B 3*	51.0	1/2	North – East/West	4.6
4	5	*L 4*	61.4	1	South	2.1	*B 4*	32.2	2	North	3.4
5	2	*L 5*	81.2	3	South/West		*B 5*	39.3	1	West	1.9
6	2	*L 6*	40.8	1	East	2.2	*B 6*	37.6	1	East	1.7
7	2	*L 7*	77.4	2	East	3.6	*B 7*	66.0	2	West	3.7
8	4	*L 8*	83.2	2/2	North/West	5.2	*B 8*	54.0	2	South/West	2.7
9	2	*L 9*	40.6	1	West	2.2	*B 9*	36.0	1	East	1.7

2 | METHODS

The presented hygrothermal field measurements were conducted in nine households in different multi-family houses in Weimar, Germany. The city of Weimar is located in the center of Germany at an elevation of approximately 200 m above sea level. The stock houses were built in the years before 1980. The nine selected buildings are brick constructions, which is very common for German stock houses. These nine different buildings were energetically retrofitted during the years 1997–2005 whereby the windows and the heating systems were renewed. The buildings' roofs and windows were thermally insulated along with the building facades in conformity with the standards required for protected monuments.

The apartments are occupied by couples and families with up to three children including senior citizens with high presence and families with working parents and school-aged children. In this study, we merged very different resident groups to cover the usual occupancy profile and to get a representative scope for the indoor climate in stock houses. A survey[16] was realized in order to obtain information about the occupants' usage behavior, for example, concerning ventilation and heating. In addition to the dwellings presented here, the occupants of 160 dwellings took part in this survey.[16]

The characteristics of the presented living rooms and bedrooms such as air volume, window area, and the number and presence of occupants, are presented in Table 1. All rooms are naturally ventilated by windows without any mechanical exhaust and did not show any mold or moisture damage during the measurement period.

The presented indoor and outdoor climate measurement includes data from January to December 2012. The evaluation period is set for 1 year to obtain an annual distribution and to evaluate the influence of different outdoor conditions on the indoor climate. With a yearly outdoor temperature above the average, 2012 was a warm year which shows parallels to the current higher outdoor temperatures due to climate change. At the same time, some months of the year were characterized by extreme weather situations. These include an unusually cold spell at the beginning of February, a hot spell in July and August with outside air temperatures often exceeding 30°C, and an early onset of winter. This allows the influence of the outdoor climate on the indoor climate to be shown for different climate scenarios over the course of a year.

To evaluate the influence of the outdoor conditions on the indoor climate, the data of a weather station operated by the Deutscher Wetterdienst (DWD) were used. This weather station is located up to 3 miles away from the measurement objects.

The data logger, a Lufft Opus 10, registered indoor temperature and relative humidity every minute and logged the minimum, maximum, and average values at 10-min intervals. The logger position in the rooms was at a height of approximately 1.8 m and as far away as possible from outside walls, heating units, direct solar radiation, windows, and doors. In periodic intervals of up to 4 months, the data loggers were checked for functionality and tested in a calibrated climate test cabinet. The logger accuracy is ±0.3 °K or ±2.5% r.H., according to the manufacturer.

3 | RESULTS

For further analysis, hourly and daily means were calculated using the 10-minute interval values of the indoor air temperature and moisture. Figure 1 shows the measured indoor air temperature of the living and bedrooms in the year 2012. During the winter period in the 1st and 4th quarters, the hourly means in living rooms are in a range between 16 and 23 °C.

Because of the user behavior and heating systems, even extreme outside conditions such as those in February or December do not show a significant impact on the indoor air temperature.

Compared to the living rooms, the bedrooms in Figure 1 do show a much lower indoor air temperature level in a range of about 12–20 °C. These results are comparable to the output of a survey[16] with 160 participants, which includes the residents presented here. In this survey, most participants claimed that they open their bedroom windows at night and either heat very rarely or never turn on the heating systems in their bedrooms at all.

During the summer period, that is, the 2nd and 3rd quarters, when the outside temperature rises and the windows are opened more often and for a longer period of time, the indoor air temperature increases, until the relation between inside and outside conditions is almost equal.

In summer, the heating is switched off and all residents have comparable ventilation behavior. This leads to smaller deviations of the hourly means from the daily mean. In winter, the greater deviations of the apartment-specific hourly averages from the daily average indicate a more individual user behavior. This effect also appears in the living rooms and the bedrooms and is shown by the hourly means in Figure 1.

Figure 2 shows the relative humidity inside all the rooms as well as the outside relative humidity. Contrary to expectations, the hourly means of the bedroom and living room relative humidity are almost equal. For the living rooms, the measurements mostly show values between 40% and 60% r.H. respectively 40%–65% r.H. in the bedrooms. In contrast to the indoor air temperature, there is a significant relationship between extreme outside conditions as found in February or December to the inside relative humidity. The warmer the outdoor air, the more water particles change into a gaseous state and are absorbed by the air as water vapor. Depending on the air temperature, the air can only absorb a limited amount of water vapor. This means that warm air is able to absorb more water vapor than cold air. Because of the much dryer climate outside during cold temperatures, the inside humidity is also very low and thus highlights the strong relationship between inside and outside humidity.

The daily, monthly, quarterly, and annual averages were derived from the measured values by arithmetic averaging. These values are shown separately for selected variables for living rooms and bedrooms in Table 2. For the winter half-year, that is, the 1st and 4th quarters of each year, a daily mean indoor air temperature of θ_i = 22.1 °C was calculated for the living rooms. Due to the different types of users, the measured values vary more around the mean value than when considering individual apartments. This leads to a double standard deviation of $2\sigma = \pm 3.8$ K in the winter half-year. In the living rooms, both monthly and daily mean values rarely drop below 20°C indoor air temperature, and if so, only slightly. In contrast, significantly lower daily mean indoor air temperature values of θ_i = 17.0°C were recorded in the bedrooms during the winter half-year. Due to diverse user behavior and the influence of the outdoor climate in March and October, the double standard deviation is $2\sigma = \pm 4.4$ K.

The influence of the occupants can very clearly be seen in the monthly mean values during the cold snap in February. Besides the typical winter temperature difference of about 3 K between both

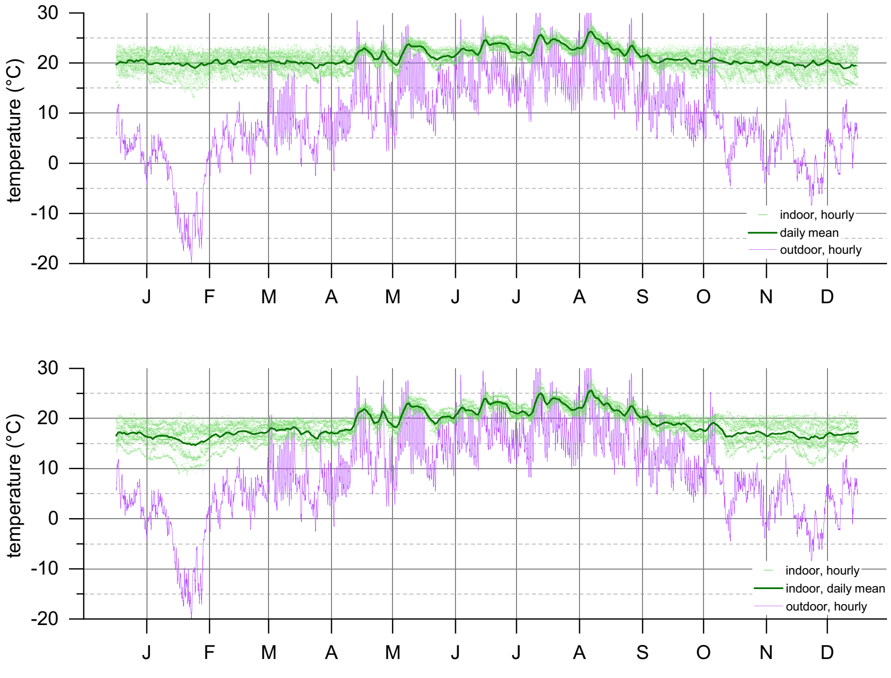

FIGURE 1 Course of outdoor and indoor air temperature; hourly/daily mean values based on 10-min measuring in analyzed living rooms (top) and bedrooms (bottom)

FIGURE 2 Course of outdoor and indoor relative humidity; hourly/daily mean value based on 10-min measuring in analyzed living rooms (top) and bedrooms (bottom)

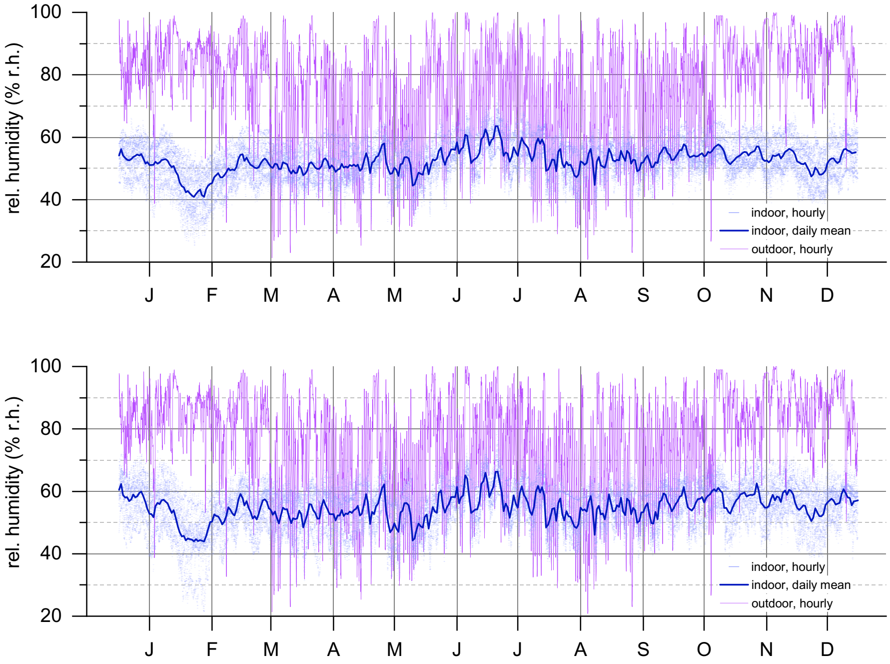

TABLE 2 Calculated monthly, quarterly, and semi-annual mean values for select exterior and interior climatic parameters incl. the double standard deviation for the testing period; 9 living rooms; 9 bedrooms; Weimar

	$\theta_e \pm 2\sigma$	$c_e \pm 2\sigma$	$\theta_i \pm 2\sigma$		$c_i \pm 2\sigma$		$\theta_{d,i} \pm 2\sigma$	
			(°C)/(K)		(g/m³)		(°C)/(K)	
Time	(°C)/(K)	(g/m³)	Living rooms	Bedrooms	Living rooms	Bedrooms	Living rooms	Bedrooms
January	1.5 ± 9.1	4.6 ± 2.7	20.1 ± 3.9	16.6 ± 4.3	9.1 ± 2.6	8.0 ± 3.2	9.9 ± 4.5	7.7 ± 6.6
February	−3.5 ± 17.6	3.6 ± 4.2	19.8 ± 3.8	16.1 ± 5.2	7.8 ± 2.9	6.7 ± 3.1	7.6 ± 5.6	5.1 ± 7.3
March	7.5 ± 8.0	5.7 ± 2.4	20.3 ± 3.1	17.5 ± 2.9	9.0 ± 2.3	8.0 ± 2.4	9.8 ± 4.0	8.0 ± 4.7
April	8.5 ± 11.3	5.6 ± 2.9	20.1 ± 3.5	17.6 ± 3.9	8.8 ± 2.3	8.0 ± 2.8	9.5 ± 3.9	7.8 ± 5.5
May	14.6 ± 11.4	8.2 ± 4.3	22.0 ± 3.2	20.8 ± 3.7	9.9 ± 2.7	9.5 ± 3.1	11.3 ± 4.3	10.6 ± 5.3
June	15.4 ± 9.0	10.0 ± 4.5	21.9 ± 2.6	20.9 ± 2.9	10.7 ± 2.9	10.5 ± 3.1	12.5 ± 4.1	12.0 ± 4.5
July	17.5 ± 8.2	10.9 ± 4.3	23.3 ± 2.9	22.5 ± 3.1	11.9 ± 3.2	11.6 ± 3.3	14.2 ± 4.3	13.7 ± 4.6
August	19.2 ± 9.4	10.2 ± 4.0	24.1 ± 2.6	23.2 ± 2.9	11.3 ± 3.0	11.1 ± 3.0	13.5 ± 4.2	13.1 ± 4.2
September	14.5 ± 9.1	8.5 ± 3.1	21.6 ± 2.8	20.3 ± 3.1	10.1 ± 2.3	9.6 ± 2.4	11.6 ± 3.5	10.8 ± 3.9
October	8.8 ± 10.2	6.9 ± 3.3	20.4 ± 3.3	18.0 ± 3.6	9.7 ± 2.5	8.8 ± 2.7	11.0 ± 3.9	9.3 ± 5.0
November	4.9 ± 6.5	5.8 ± 2.0	20.0 ± 4.0	17.0 ± 4.0	9.5 ± 2.6	8.5 ± 2.7	10.5 ± 4.2	8.7 ± 5.1
December	1.6 ± 9.2	4.7 ± 2.8	19.7 ± 4.5	16.6 ± 4.5	8.9 ± 2.8	7.9 ± 2.7	9.5 ± 4.9	7.5 ± 5.8
Year	9.2 ± 17.0	7.0 ± 5.8	21.1 ± 4.4	19.0 ± 6.1	9.7 ± 3.5	9.1 ± 4.0	10.9 ± 5.6	9.6 ± 7.2
1st Quarter	1.9 ± 15.1	4.6 ± 3.6	20.1 ± 3.6	16.8 ± 4.5	8.7 ± 2.8	7.6 ± 3.1	9.1 ± 5.1	7.0 ± 6.7
2nd Quarter	12.8 ± 12.3	7.9 ± 5.4	21.3 ± 3.6	19.8 ± 4.7	9.8 ± 3.0	9.3 ± 3.6	11.1 ± 4.8	10.1 ± 6.2
3rd Quarter	17.0 ± 9.7	9.9 ± 4.3	23.0 ± 3.5	22.0 ± 3.9	11.1 ± 3.2	10.8 ± 3.4	13.1 ± 4.6	12.5 ± 4.9
4th Quarter	5.1 ± 10.6	5.8 ± 3.3	20.1 ± 4.0	17.2 ± 4.2	9.4 ± 2.7	8.4 ± 2.8	10.3 ± 4.5	8.5 ± 5.5
Winter	3.5 ± 13.4	5.2 ± 3.7	20.1 ± 3.8	17.0 ± 4.4	9.0 ± 2.9	5.3 ± 3.1	9.7 ± 5.0	7.8 ± 6.3
Summer	14.9 ± 11.8	8.9 ± 5.2	22.2 ± 3.9	20.9 ± 4.9	10.5 ± 3.4	8.9 ± 3.8	12.1 ± 5.1	11.3 ± 6.1

room types, the bedrooms show a much higher double standard deviation. Even though the vast majority of apartment users do not usually heat their bedrooms, they change their behavior when the outdoor temperatures are very low. Since not all apartment users follow this trend, this leads to an increase in the double standard deviation.

From April onwards, and in parallel to the rising outdoor temperatures, an increase in the daily mean temperature of the indoor air can also be observed in both room types as Figure 3 shows. With daily maximum temperatures above 28°C, August has the highest monthly mean temperatures with θ_i = 24.1 °C in the living rooms and θ_i = 23.2°C in the bedrooms (Table 2). One cause of this difference is the orientation of the rooms. While living rooms are usually oriented toward the south, the window surfaces of bedrooms often face north, and the use of space in living rooms, for example, by electrical appliances, causes additional heat to enter the room. In addition, according to the survey in Ref. [16], all residents claimed to sleep with open windows in summer, which promotes cooling of the air temperature in the bedroom. For the summer half-year, that is, the 2nd and 3rd quarters, this resulted in θ_i = 22.2°C in the living rooms and θ_i = 20.9°C in the bedrooms. The lower double standard deviation of monthly indoor air temperatures in summer, in contrast to winter, can be attributed to the increased window ventilation in all apartments.

Water vapor from the outside air enters the room through window ventilation or infiltration air exchange, that is, by uncontrolled air exchange through the building envelope. In the building itself, plants, cooking, showering, or drying laundry, and also the occupants, represent additional sources of moisture. According to Figure 4, the daily mean values of the resulting relative humidity range between φ_i = 40 and 63% r.H. in the living rooms and between φ_i = 43 and 67% r.H. in the bedrooms.

For the monthly mean values, a range between φ_i = 46 and 59% r.H. was determined in Figure 4 for both room types, namely living rooms and bedrooms. Both for the summer and the winter half-year, the monthly mean values of the bedrooms show somewhat higher relative room air humidities. For the whole year, this also results in the annual mean value of φ_i = 52% r.H in the living rooms and φ_i = 55% r.H. in the bedrooms. Contrary to previous investigations[17] in bathrooms, the daily mean curve here runs in the middle range of the measured values. This suggests that there are no short-term moisture inputs in these room types which are promptly aired out again. The influence of the cold but dry outside air on the resulting room humidity in window-ventilated rooms, as described above, is very clearly visible in February.

The dew point temperature is the critical variable for determining the risk of condensation on surfaces—if the surface temperature falls below the dew point temperature, condensation will precipitate. From the measured values, the water vapor saturation pressure of the room air is first calculated according to.[12] The ratio of water vapor partial pressure to water vapor saturation pressure is given by the relative humidity φ. Accordingly, the water vapor partial pressure and subsequently the dew point temperature can be determined.

For seasonal variation, Figure 5 shows the daily and monthly mean dew point temperatures for living rooms (top) and bedrooms (bottom). The outdoor air contains less water vapor in the cooler winter months, and thus the dew point temperature in both room types is lower in winter than in the warmer, humid summer months. During the winter months, the daily mean temperatures of the living rooms vary between 5°C and 12°C and between 8°C and 17°C in the summer. A comparable range of daily mean values can be observed in the bedrooms with 2°C to 11°C in winter and between 6°C and 17°C in summer.

By ventilating a room, the room air is replaced by outside air. As a result, the dew point temperature of the room air can only drop to the dew point temperature of the outside air. The influence of the outdoor climate on the moisture content of the room air and thus also on the dew point temperature of the room air becomes particularly clear at the beginning of February or the beginning of December. During this period, the outside air temperatures drop as low as −20°C and −10°C,

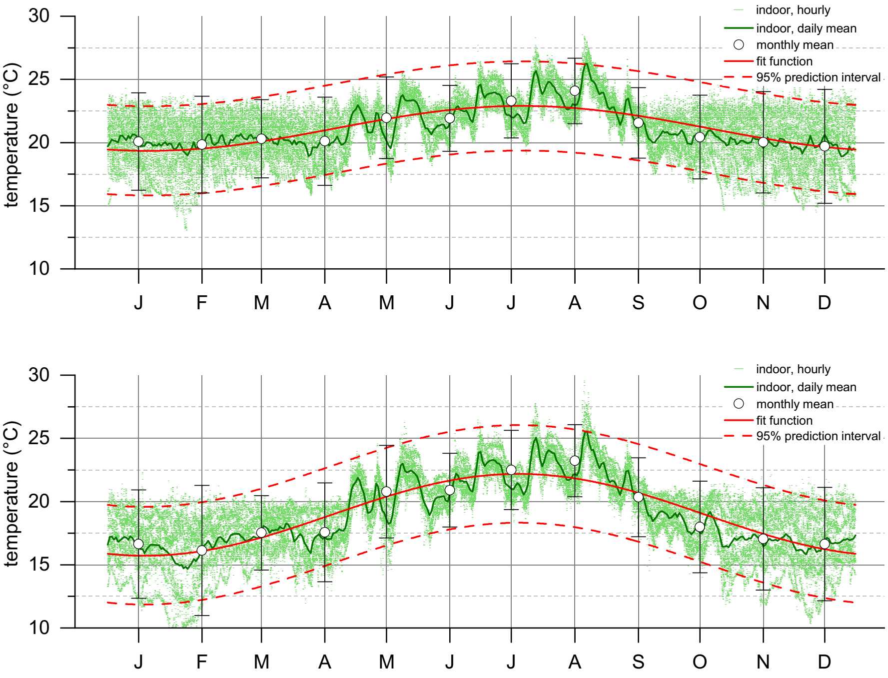

FIGURE 3 Indoor air temperature, hourly mean, daily mean, monthly mean with double standard deviation, fit function of the investigation period and 95% prediction interval, living rooms (top) and bedrooms (bottom)

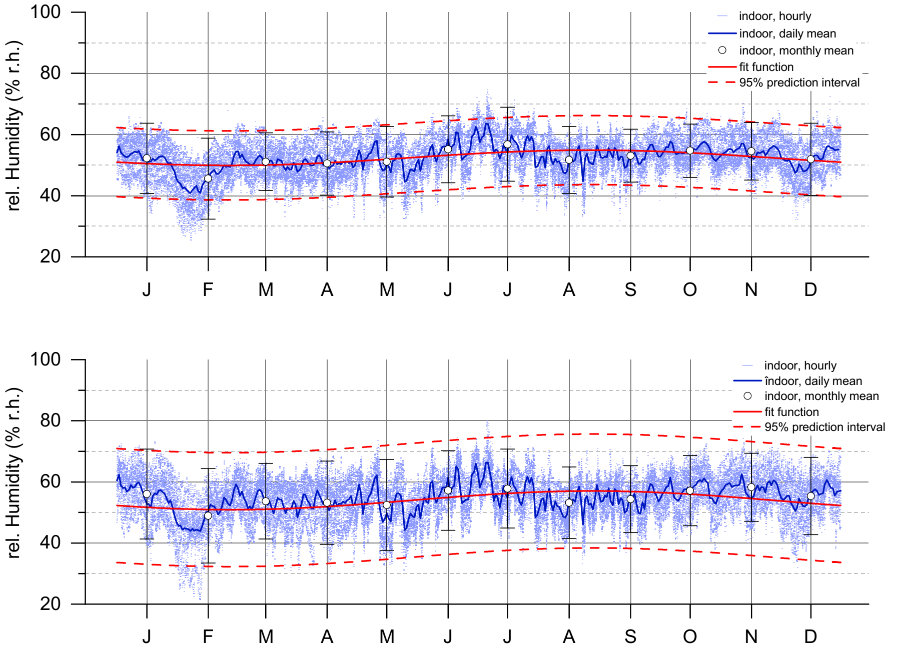

FIGURE 4 Indoor relative humidity, hourly mean, daily mean, monthly mean with double standard deviation, fit function of the investigation period and 95% prediction interval, living rooms (top) and bedrooms (bottom)

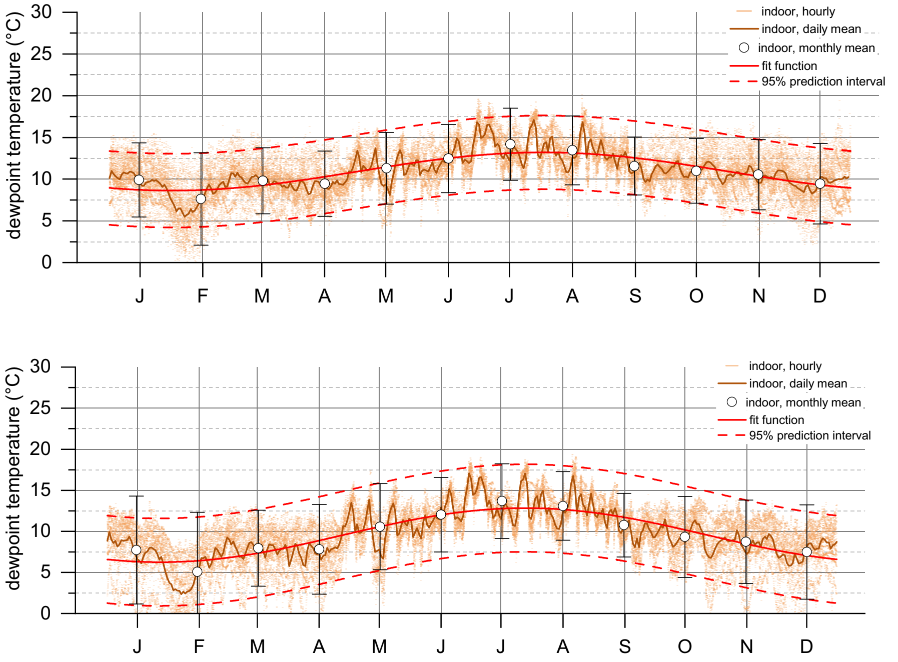

FIGURE 5 Indoor dew point temperature, hourly mean, daily mean, monthly mean with double standard deviation, fit function of the investigation period and 95% prediction interval, living rooms (top) and bedrooms (bottom)

respectively. During these cold snaps, the outside air contains only a little amount of water vapor which causes a drop in absolute humidity and low dew point temperatures in all rooms. Extremely low dew point temperatures of less than 2°C were measured, for example, during ventilation processes. This relationship is also shown in Figure 6.

According to Table 2, the evaluation of the dew point temperature for the winter half-year resulted in mean values of θ_d = 9.7°C in the living rooms and θ_d = 7.8°C in the bedrooms. Comparing the results of both rooms in Figure 5, the overall lower level of dew point temperature in the bedrooms is clearly visible during the winter months.

Since considerably lower indoor air temperatures were found in the bedrooms, the dew point temperatures underline a significantly lower humidity level in the bedrooms. For example, the average indoor air temperatures between living rooms and bedrooms differ by about 3.1 K in winter, as Table 2 shows. This suggests that when bedrooms are in use, the ventilation is more intensive than in the living rooms. On the other hand, in the warmer summer months, the humidity conditions in all rooms are similar, as shown in Table 2.

The absolute humidity or water vapor concentration indicates the amount of water actually present in a given volume. The absolute humidity can be calculated according to[12] and thus enables the humidity conditions in a room to be described.

For the living rooms and bedrooms, Figure 7 shows the calculated absolute humidities over the course of the year. The seasonal influence of the outdoor climate can also be observed here. Bedrooms and living rooms have qualitatively comparable courses but differ significantly in humidity levels. The lowest monthly average was determined for both rooms in February, with 7.8 g/m^3 for the living rooms and 6.7 g/m^3 for the bedrooms. The maximum monthly average is 11.9 and 11.6 g/m^3 in July, respectively.

The room air humidity is significantly influenced by the absolute humidity in the outside air and the humidity load in the room whereby the humidity load describes the amount of water vapor produced as a result of room use. In rooms with a low air exchange rate and high moisture production, a high moisture load occurs. In well-ventilated rooms, on the other hand, lower values can be assumed in conjunction with low moisture production. Therefore, the humidity load in the room can be determined as the difference between the absolute outdoor air humidity and room air humidity. The hourly, daily, and monthly mean values of the humidity load calculated in this way are plotted separately for the living room and bedroom in Figure 8, together with the prevailing absolute outdoor air humidity.

As expected, the measurement curve of the humidity load runs in the opposite direction to the external absolute humidity. Since cold air contains less water vapor than warm air, there is a clear dependence of indoor air humidity on outdoor temperature. Intensive window ventilation in the warmer months causes the humidity production in the room to be vented and the humidity ratios between indoor and outdoor air to be equalized.

According to Table 2, the highest monthly mean values were calculated in January with 4.5 g/m^3 for the living rooms and 3.4 g/m^3 for the bedrooms while the lowest humidity averages were recorded in June with 0.7 and 0.5 g/m^3, respectively. As soon as the absolute humidity of the outdoor air exceeds the value of the indoor air, the values of the moisture load drop into the negative range. This can be observed particularly well in summer and can result from rainfall or rapid temperature fluctuations. Overall, the seasonal pattern in Figure 7 illustrates the influence of seasonal ventilation behavior, which is also reflected in the hourly mean

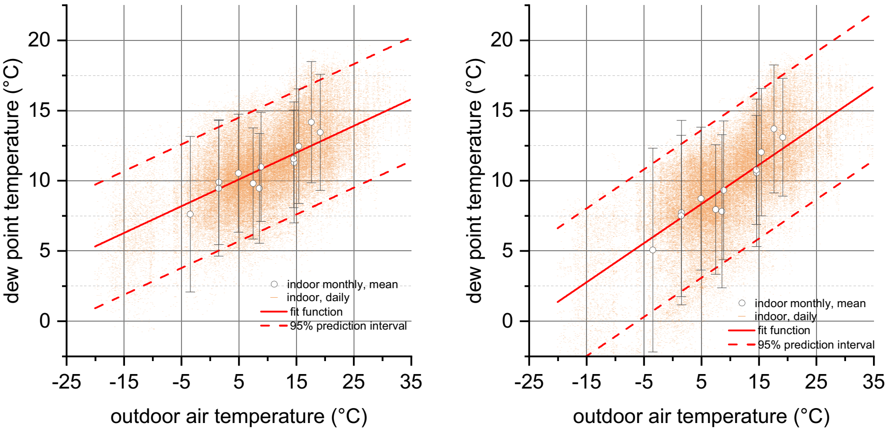

FIGURE 6 Indoor dew point temperature as a function of outdoor air temperature, hourly mean, monthly mean with double standard deviation, fit function of the investigation period and 95% prediction interval, living rooms (left) and bedrooms (right)

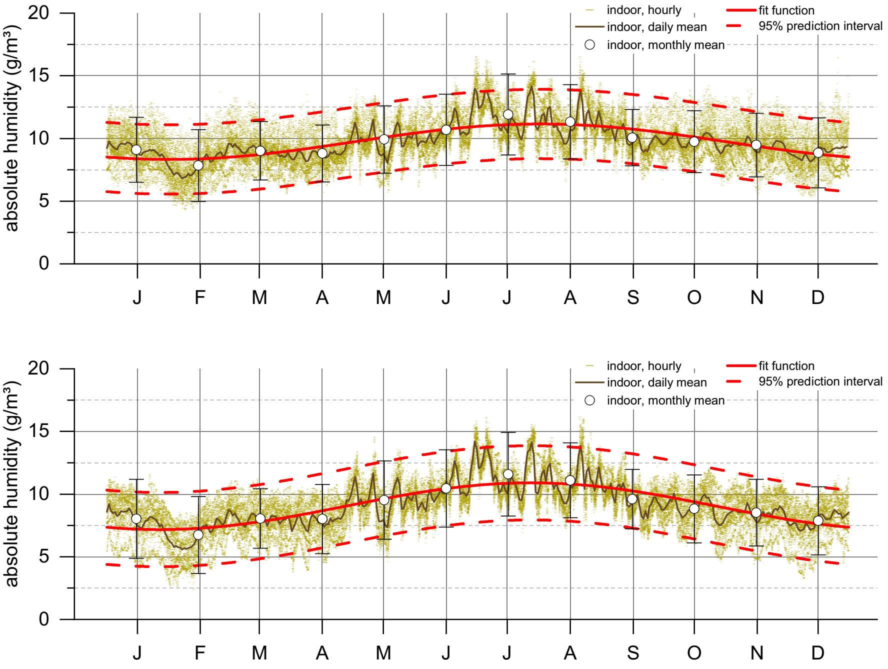

FIGURE 7 Absolute humidity, hourly mean, daily mean, monthly mean with double standard deviation, fit function of the investigation period and 95% prediction interval, living rooms (top) and bedrooms (bottom)

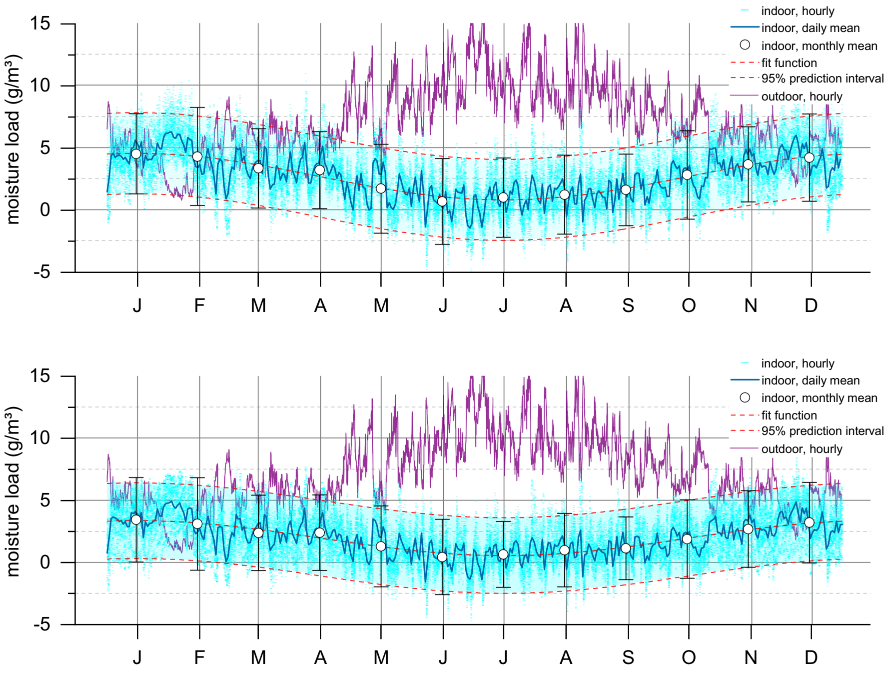

FIGURE 8 Moisture load, hourly mean, daily mean, monthly mean with double standard deviation, fit function of the investigation period and 95% prediction interval, living rooms (top) and bedrooms (bottom)

TABLE 3 Comparison of the parameters of the compensation curves determined for living rooms and bedrooms over the measurement period, with the mean value including the 95% prediction interval

	$y_i = a_1 + a_2 \cdot \sin\left(\pi \frac{t - a_3}{t_0}\right)$			
	Mean value a_1 **°C**	**Amplitude a_2** **K**	**Phase a_3** **d**	t_0
Air temperature θ_i				
Living rooms	21.1 (±3.5K)	1.8	202	
Bedrooms	19.0 (±3.3K)	3.2	95	
Air rel. humidity φ_i				
Living rooms	52.4 (±11.3K)	2.5	133	
Bedrooms	54 (±18.6K)	3.1	134	
Dew point temperature $\theta_{d,i}$				
Living rooms	10.9 (±4.4K)	2.3	108	182.625
Bedrooms	9.5 (±5.3K)	3.3	104	
Absolute humidity c_i				
Living rooms	9.8 (±2.7K)	1.4	108	
Bedrooms	9.0 (±3.0K)	1.8	103	
Moisture load Δc				
Living rooms	2.7 (±3.3K)	1.9	274	
Bedrooms	1.95 (±3.0K)	−1.4	159	

values of the rooms which show a wider spread in winter than in the summer months. When looking at the curves and the monthly averages, it becomes apparent that moisture is produced or introduced into the room throughout the year due to the individual use of the rooms. It is also interesting to note the difference in the average moisture load between the living room and the bedroom, which amounts to approx. 1 g/m³ in the winter months and 0.2–0.5 g/m³ in the summer months.

Time-dependent compensation functions are derived from the hourly mean values of the measured values, which should support the comparability of the measured values. Furthermore, the influence of the outdoor climate and that of the room use shall be shown. In the present work, a sinusoidal regression is used, the adjustment of which is carried out according to the method of the minimum mean square error. The free parameters in Equation 1 describe the mean value (a_1), the amplitude (a_2), and the phase shift (a_3), while t_0 indicates the period of the oscillation and is defined as $t_0 = 182\,625$ d, and t indicates the time.

$$y_i = a_1 + a_2 \cdot \sin\left(\pi \frac{t - a_3}{t_0}\right) \tag{1}$$

a_1, mean value; a_2, amplitude; a_3, phase shift; t, time; t_0, period duration.

The compensation functions calculated in this way are plotted in Figures 3-7 or the spatial-climatic parameters presented. In addition, the 95% forecast interval was calculated which describes the respective value range of 95% of the future observed values. The measured monthly mean temperatures closely align with the calculated compensation function for all variables.

For example, for the room air temperature of the living rooms in Figure 3, the compensation function was calculated with a mean temperature of $a_1 = 21.1°\mathrm{C}$ and an amplitude of $a_2 = 1.8\,\mathrm{K}$. The phase shift of $a_3 = 202\,\mathrm{d}$ results in a maximum of 22.9°C on 21 July. The measured daily mean temperatures are closer to the compensation function in the cooler months than in the warmer summer months. As a result of increased window ventilation from May to September, the strong fluctuations in outdoor air temperature are also measurable indoors.

The forecast interval runs at a distance of 3.5 K from the compensation curve. In the cooler 1st and 4th quarters, the scatter of the hourly measured values reflects the different user behavior which is especially evident in comparison with the daily mean value curve. In contrast, the hourly indoor air temperatures show a much smaller scatter in summer, which suggests longer window opening times with rising outdoor temperatures. In winter, on the other hand, the room air temperatures are individually controlled with the heating in a narrower temperature range. The calculated parameters for all compensation curves are shown in Table 3.

Figure 9 directly compares the compensation functions of the room air temperature of the living rooms with those of the bedrooms whereby the bedrooms have a significantly lower average room air temperature than the living rooms. While the living rooms are usually heated continuously, the heating in the bedrooms is generally never switched on. This leads to deviations in the compensation curves of up to 3.5 K in winter. In summer, the maxima of both rooms equalize due to the influence of window ventilation. Due to the same outdoor climate, the compensation curves have their extreme values in the same period.

The various annual variations in absolute humidity are shown in Figure 7. In the winter months, that is, the 1st and 4th quarters, the discrepancy of the absolute humidities due to room use becomes clearly visible and amounts to 1.2 g/m³ in January. Overall, the living rooms have higher absolute humidities than the bedrooms throughout the year. While the living rooms are usually only supplied with fresh air a few times during the day by shock ventilation, the bedrooms are often slept in with the windows tilted. In times of very low outdoor temperatures, ventilation processes in the bedroom are also reduced before and after sleeping. However, these are long enough to remove the accumulated moisture. Besides this room-specific ventilation behavior, the room air humidity is also influenced by the duration of use.

Furthermore, warm air can absorb more moisture than cool air. As living rooms have higher room air temperatures overall, they can also absorb more moisture before the air quality is perceived as unpleasant by the room occupants and they open the windows. In addition, air volumes can be transported from room to room within a dwelling and moisture arising from bathroom use or cooking processes can also enter the living room through open doors. In summer, the humidity level equalizes with the outdoor climate and amounts to approximately 11 g/m³ in both room types.

The different humidity ratios are also evident in the critical value of the dew point temperature plotted in Figure 10. Accordingly, the living room with the higher absolute humidity over the course of the year also has the highest dew point temperatures. In addition to these dew points, the temperatures at which surface humidities of 80% r.H. are reached are decisive for the minimum thermal insulation of buildings. These are presented above the dew point temperatures and can be derived according to.[18,19]

In order to prevent mold formation, a prediction model was developed in Ref. [4] that describes the hygrothermal growth conditions of a mold spore. The temperature and humidity conditions are described by an isopleth model and coupled with a biohygrothermal model which allows the germination and mycelial growth of a fungal spore to be simulated. This model not only considers favorable growth conditions but also effects such as the renewed desiccation of the spore. In contrast to a rigid limit value of the surface humidity, the isopleth model thus enables a more realistic determination of the mold risk or description of existing mold damage.

In addition, it must be considered that in the bedrooms with a low dew point temperature, the room air temperatures are also lower and, accordingly, the surface temperatures are also lower. An increased risk of mold formation for the bedrooms can therefore be determined using a dynamic evaluation.

The actual moisture production in the room can be derived from the difference between the internal and external absolute humidity. This so-called moisture load is plotted in Figure 11 and shows a

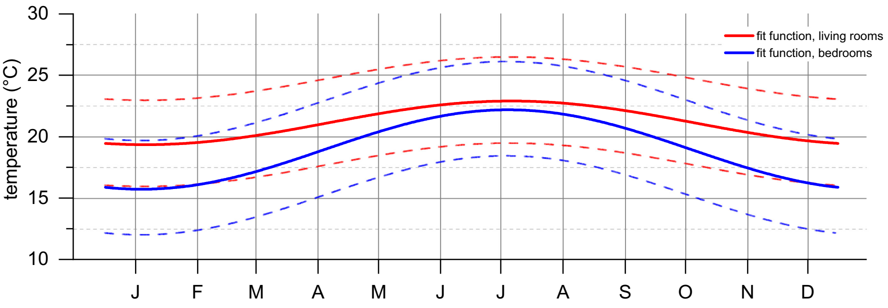

FIGURE 9 Comparison of the compensation functions for the indoor air temperature of living rooms and bedrooms

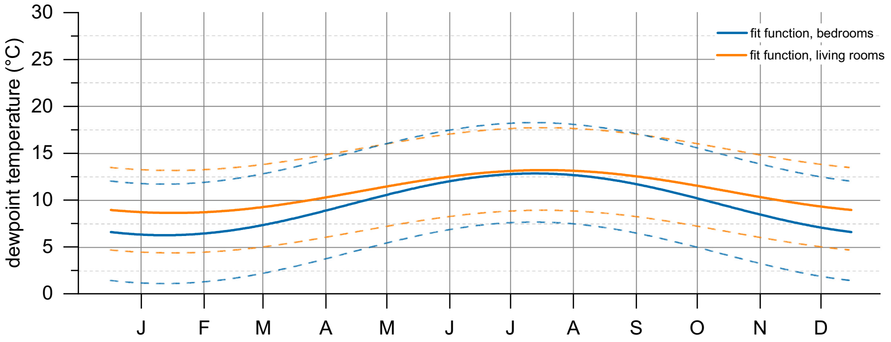

FIGURE 10 Comparison of the compensation functions for the dew point temperature of living rooms and bedrooms

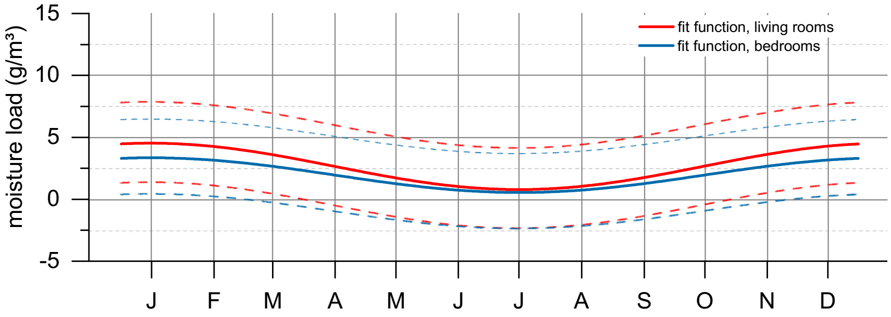

FIGURE 11 Comparison of the compensation functions of the moisture load for living rooms and bedrooms

slightly higher moisture production for the living rooms than for the bedrooms during the 1st and 4th quarters.

4 | CONCLUSIONS

As part of long-term measurements,[20] indoor climate measurements from nine different apartments in Germany were presented and evaluated over a period of one year. The measurement results were summarized for a representative overview of user behavior. The evaluation was carried out separately for living rooms and bedrooms according to room use. The resulting scattering of the measurement results makes it possible to take the diverse individual user influences into account and to derive generally valid statements for comparable stock buildings in the moderate German climate. For other climate regions in Germany, comparative results are in preparation.

As expected, the seasonal course of the measurement results of the indoor air climate reflects the seasonal influence of the outdoor climate. During the summer months, the rising outside temperatures also lead to an increase in window ventilation and thus to an adaptation of the indoor climate conditions to the outside air. In winter, the indoor air temperatures are adjusted by the occupants via the heating system. The wide dispersion of the measurement results underlines the user-specific heating and ventilation behavior in the individual apartments.

Compensation functions were derived from the measured values for indoor air temperature, relative indoor air humidity, and internal dew point temperature, in addition to the humidity load and absolute indoor air humidity. The results confirmed that the annual indoor climate can be described very well by a sinusoidal function.

By considering living rooms and bedrooms separately, it was also possible to demonstrate the influence of room use on the indoor climate. During the winter half-year, consistently higher indoor air temperatures were determined in the living rooms than in the bedrooms. The average temperature difference between the two room types is 3.1 K. This correlation is also clearly visible in the derived compensation curves. In Ref. [21], daily variation curves for different room types were developed from extensive measurement results whereby a similarly large difference between living rooms and bedrooms was found, especially for the winter months.

Comparable values for both room types, on the other hand, were determined for the relative room air humidity. Depending on the outdoor climate, the relative humidities in the bedrooms reach somewhat higher values than in the living rooms. However, the different indoor air temperatures result in different absolute humidities in the investigated rooms. The higher absolute humidities were measured in the living rooms. Consequently, the dew point temperatures and the moisture load were also higher there than in the bedrooms. In general, the measurements showed that there is year-round moisture production in the rooms.

In Ref. [6], the influence of different specific occupancy profiles could already be demonstrated. In addition, the present results show that for a determination of the room climate, the consideration of the room occupancy is also indispensable. The entire spectrum of the investigated parameters in the rooms is quantified by the determined compensation functions and their prognosis intervals.

In addition to the dew point temperature, the temperature at which the surface humidity on the room side exceeds 80% r.H. is decisive for the assessment of the minimum thermal insulation of buildings. Compensation functions for the parameters of the indoor climate, air temperature, and absolute/relative humidity allow for an estimation of the minimum surface temperatures required for moisture protection. Furthermore, the presented results can also be used as input parameters for simulation programs to calculate the thermal behavior of components or the energy demand. The 95% prediction interval that was determined serves as a safety margin, depending on the application.

To increase the accuracy of the results, further hygrothermal measurements from 245 living areas are currently being evaluated whereby the user profiles, room use, and climate region are the focus of the investigation.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Author elects to not share data. Research data are not shared.

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