



Assessment of current and future heat in a large hospital complex based on continuous indoor measurements and climate simulations

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Abstract. People with acute illnesses and pre-existing conditions are particularly vulnerable to heat, making hospitals an area of high concern during heatwaves. Further, extreme heat impacts critical medical infrastructure due to increased patient admissions and impacts on workforce. This study assesses indoor heat occurrence and intensity in the University Medical Centre Freiburg, Germany based on measurements and data-driven climate simulations. Measurements were taken from May to September 2023 using a distributed sensor network in 60 rooms in 11 buildings. Measured air temperatures and physiologically equivalent temperatures are evaluated in terms of location, frequency, and intensity, as well as in relation to outdoor conditions, allowing for identification of vulnerable hospital structures and functions. Slight heat stress was most frequent and observed in all rooms, with 49 rooms showing additional occurrence of moderate and 17 rooms strong heat stress during summer 2023. Three heatwaves were identified as periods with high levels of heat stress and limited night-time cooling. Spatial hotspots were found in rooms without windows or air conditioning, located on higher floors, and predominantly in buildings constructed in 1950-1990. Measurements were combined with climate model data to project room-specific future indoor heat occurrence in all 60 rooms. All levels of heat stress are modelled to become more frequent and intense in rooms without air conditioning. Moderate heat stress or higher will increase on average by an additional 24 hours in 2020-2049 relative to 1990-2019. These findings call for immediate and widespread heat adaptation measures to ensure continued provision of critical medical infrastructure.

1 Introduction

In face of climate change, outdoor air temperatures (T_a) are rising at an unprecedented rate (Intergovernmental Panel on Climate Change, 2023). Extreme heat including heatwaves have increased in frequency and intensity across most land regions since the 1950s. Also Central Europe is seeing increasingly frequent, intense and extensive heatwaves (Daalen et al., 2022). Climate models project air temperature increases until at least the middle of the 21st century, including a further increase in the frequency and intensity of extreme maximum temperatures (Intergovernmental Panel on Climate Change, 2023). Events of



extremely hot summers that were expected to occur twice a century in the beginning of the 21st century are now expected to occur every five years (Christidis et al., 2015).

People with acute illnesses and pre-existing conditions are particularly vulnerable to heat (Hertig et al., 2023), making hospitals an area of high concern during heatwaves. Exposure to heat can cause numerous negative health effects. Possible consequences include heat cramps, heat exhaustion, heat stroke, worsening of underlying cardiovascular and respiratory diseases, acute kidney injury, impacts on mental health, and death (Kovats and Hajat, 2008; Romanello et al., 2022). Heat can also have psychological consequences, including stress, anxiety and depression (Matzarakis, 2022). With air temperature being an integral factor affecting sleep, high nocturnal air temperatures have also been found to impair sleep, impacting health and quality of life (Obradovich et al., 2017). Older people, specifically above the age of 65, are at higher risk, as changes in their thermoregulatory system cause an increased vulnerability to heat (Daalen et al., 2022; Flynn et al., 2005; Kovats and Hajat, 2008). The majority of studies have found women to be slightly more affected by heat stress than men (Havenith, 2005; Kollanus et al., 2021; Kovats and Hajat, 2008; Matzarakis et al., 2011). People with underlying diseases, chronic respiratory, kidney and heart diseases are more sensitive to heat stress (Daalen et al., 2022). Individuals residing on top floors, in buildings without air conditioning (AC) or without ventilation face a higher risk of mortality during heatwaves, as do populations in urban environments compared to rural areas (Daalen et al., 2022; Holstein et al., 2005; Kovats and Hajat, 2008).

The most-studied case on heat-related mortality in Europe is the summer of 2003, during which more than 70,000 additional deaths were reported across Europe (Robine et al., 2008). Heat-related mortality is particularly prevalent in nursing homes and hospitals (Klenk et al., 2010; Kovats and Hajat, 2008; Stafoggia et al., 2008). A study of mortality from 2000 to 2014 in Finland found 76% of heat-related deaths to have occurred in healthcare facilities (Kollanus et al., 2021). These findings suggest that healthcare facilities should be considered an important focal point for heatwave interventions (Kovats and Hajat, 2008).

Further, extreme heat impacts critical medical infrastructure due to increased patient admissions and impacts on the workforce. Increased heat exposure on workers affects their health, which in turn reduces labour supply and productivity (Daalen et al., 2022). Productivity is impaired starting at air temperatures above 24-26°C, with a loss of 50% of work capacity at 33-34°C for workers performing moderate work intensity (International Labour Organization, 2019). The Committee of Workplaces (*Ausschuss für Arbeitsstätten*, ASTA), a committee of the German Federal Institute for Occupational Safety and Health housed under the German Federal Ministry of Labour and Social Affairs, sets requirements for workplaces above certain air temperature thresholds (BAuA, 2023). In the case of indoor air temperature (T_i) the threshold is at 26°C. ASTA calls for shading opportunities to block incoming sunlight, and further cooling measures if shading does not prevent T_i from exceeding 26°C. At T_i above 30°C further measures are required to reduce the strain on workers and at T_i above 35°C, rooms are deemed unsuitable as work locations without further technical and organizational measures and personal protective equipment. Germany's heat-health warning system (HHWS) uses a thermal stress index, the perceived temperature (PT), which provides an improved and more detailed indicator for the thermal state of the human body than air temperature alone (Casanueva et al., 2019; Matzarakis et al., 2020). Heat health warnings are issued when the thermal stress classes of "high heat load" and "extreme



65 heat load” according to the thermal sensation scale for PT of the German Association of Engineers (*Verein Deutscher Ingenieure*, VDI) are expected to be reached outdoors (VDI, 2022).

Several studies investigating indoor temperatures in residential buildings during summer have revealed the importance of monitoring and assessing not only outdoor, but also indoor conditions. Generally, T_i tends to show a strong correlation with outdoor air temperature with a lag effect at the beginning and the end of heatwaves (Shevchenko et al., 2025). At the same time, however, studies conducted in cities in Germany, the Netherlands and the United States have observed a large range of indoor thermal conditions for equal outdoor conditions (Kenny et al., 2019; van Loenhout et al., 2016; Quinn et al., 2014; Walikewitz et al., 2018). Despite this range of indoor thermal conditions, heat stress was detected in more than 80% of the monitored rooms during outdoor heatwaves in studies conducted in Augsburg, Germany and Berlin, Germany (Beckmann et al., 2021; Walikewitz et al., 2018). Differences in indoor thermal conditions are attributed to occupant behaviour and building characteristics. Ventilation is found to be a useful cooling method during heatwaves when conducted at night and in the early morning (Franck et al., 2013; Rosenfelder et al., 2016). A study conducted in Leipzig, Germany found warming on attic floors to be stronger than on lower floors of buildings (Franck et al., 2013). Data collected as part of a study in Berlin, however, showed no correlation between floor level and heat stress, and very weak relationships with window size and building age (Walikewitz et al., 2018).

80 A variety of studies investigating indoor thermal conditions in hospitals have been published, following diverse objectives and covering vastly different temporal and spatial scales. A first literature review on human thermal comfort in hospitals (Khodakarami and Nasrollahi, 2012) points out the challenge of reconciling different human thermal comfort preferences for the distinct groups of hospital occupants, namely patients, staff, and visitors. A second review provides an overview of the literature published up until August 2020, and identifies “health/wellbeing”, “productivity” and “energy saving” as the main aspects of studying heat in hospitals (Pereira et al., 2020). The third and most recent review identifies a significant increase in literature on human thermal comfort in hospitals from 2012 to 2019, stating that most research focuses on wards or surgery facilities (Yuan et al., 2022).

Several indoor measurements in hospitals across Europe have been reported, often focusing on thermal comfort of certain groups of users. A study focusing on thermal comfort of pregnant women in a hospital in Bologna, Italy used measurements from a single day in November 2017 (Fabbri et al., 2019). Research on the thermal comfort of nurses in a hospital in the Netherlands used measurements from July, October, and November 2016 and noted higher T_i and e rates during summer in west- compared to east-oriented wards (Derks et al., 2018). A study conducted in a hospital in southern Sweden compared the subjective perception of thermal conditions of staff and patients during both summer and winter, concluding that patients and staff must be treated as groups with different needs and preferences regarding thermal comfort (Skoog et al., 2005).

95 To our knowledge, the only studies focusing on heat in hospitals specifically in the context of heatwaves were conducted in the UK. Lomas and Giridharan (2012) report measurements from a hospital in Cambridge, where they measured T_i in wards and nurse stations during July and August 2010. Overall, T_i was found to drift with outdoor ambient temperatures. Temperatures measured near the windows were generally cooler, especially during night, suggesting that window opening



behaviour has a large effect on T_i . Overheating was observed for 10% of the recorded hours in nurse stations, which did not have windows. Iddon *et al.* (2015) report indoor temperatures in five different hospital buildings across two UK hospital sites in the summers of 2011 and 2012. East-facing wards were found to warm quickly in the morning, while west-facing wards reached their peak temperatures in the early evening. Wards constructed in the 1930s were much less affected by solar radiation and external temperature fluctuations than newer, light-weight modular buildings. Gough *et al.* (2019) measured indoor temperatures for 35 days in July and August 2018 in waiting areas, staff offices, and ultrasound scanning rooms of the Royal Berkshire Hospital's Maternity and Gynaecology building, which was constructed in the 1960s. A pronounced diurnal cycle of temperatures was observed, with highest temperatures being measured in rooms located towards the exterior of the building. In all nine rooms studied, the overheating guidelines for T_i limits were breached.

Overall, no previously published study was found to concentrate on meteorological measurements of indoor climate across different departments of the same hospital without widespread AC during summer. Furthermore, most studies use T_i alone or the PMV as a thermal comfort index, yet none of these studies considered PET or any other thermal index based on the full human energy balance (Yuan *et al.*, 2022).

The goal of this study is to investigate the following three overarching questions regarding the prevalence of indoor heat stress in the University Medical Centre Freiburg (UMCF):

1. Where and how often does indoor heat stress occur in UMCF, and how intense in this heat stress?
2. When in UMCF does indoor heat stress occur in relation to the duration and intensity of outdoor heatwaves?
3. How does heat stress vary across different rooms and buildings of UMCF, and which hospital areas and functions are most vulnerable to heat stress?
4. How are frequency and intensity of heat stress expected to change in the future due to climate change?

This study aims to identify existing spatial and temporal heat hotspots in UMCF, and to offer an insight into indoor heat stress occurring in a German hospital during a summer of the 21st century. The indoor measurements were used in a data-driven approach in combination with climate model output to project room-specific future T_i and PET in each room. Findings are expected to support the need for target-specific adaptation measures.

2 Data and methods

2.1 Study location

The study location of this project is the University Medical Centre Freiburg (UMCF). Counting 2,050 beds, approximately 15,000 employees as well as 90,000 inpatients and 900,000 outpatients every year, UMCF is the largest hospital in Freiburg and one of the largest university medical centres in Germany (Universitätsklinikum Freiburg, 2023a). Furthermore, it houses the Faculty of Medicine of the University of Freiburg and functions as a training site for medical professions. The main campus of UMCF spans approximately 0.5 km² and is located in the northwest of central Freiburg, 1.6 km from the city centre (48.006°N, 7.837°E, WGS-84). This campus houses all clinical departments of UMCF apart from the departments for mental



health and dermatology, and includes buildings constructed as early as the 1930s and as recent as 2015. The study location of this project also considers the Academy for Medical Professions (AMB), which offers study programs in medical care, and technical and therapeutic professions (Universitätsklinikum Freiburg, 2023b). AMB is part of UMCf and located at the northern edge of Freiburg, 2.7 km north of the UMCf main campus (48.030°N, 7.840°E, WGS-84).

135 2.2 Study period

Based on T_a data of the German Meteorological Service (DWD), the year 2023 was the warmest year measured to date in Freiburg with outdoor air temperatures 1.40 K and 2.26 K warmer than the reference periods of 1961-1990 and 1991-2020, respectively. In Summer 2023 three distinct heatwaves occurred in the middle of June, July and August (Deutscher Wetterdienst, 2023a). Due to the complexity of factors involved, there is no universal definition of a heatwave (Robinson, 140 2001). We used heat warnings issued for Freiburg by DWD as indicators for periods of excessive heat, hereafter referred to as heatwaves. In 2023, heat warnings were issued on a total of 21 days between June 19 – 22, July 8 – 11, July 15, and August 13 – 24. In the following, July 15 is not treated as a heatwave as no heat warnings were issued on the directly preceding and succeeding days. Cooler outdoor air temperatures were recorded especially at the end of July and beginning of August 2023. Also, September 2023 proved unusually warm, with the largest deviation from the past two reference periods of all months 145 considered in this study (Deutscher Wetterdienst, 2023b).

The period of May 15 – September 30, 2023 was chosen for analysis as it includes all heatwaves and is the range in which summer days and hot days typically occur based on the meteorological reference period 1991-2020 (Deutscher Wetterdienst, 2023c, 2023d). Given that 2023 was the record warm year to date and had an unusually large number of heat warning days, the recorded indoor heat stress may not be representative of years reaching further into the past, but summer 2023 may offer a 150 glimpse into future conditions in the context of a warming climate.

2.3 Indoor sensor systems

Indoor conditions were recorded by a network of low-cost sensor systems termed “Mobile Biometeorological System” (MoBiMet) (Sulzer et al., 2022). Each MoBiMet is based on a single-board Raspberry Pi Zero WH computer (Raspberry Pi (Trading) Limited, Cambridge, UK), and contains sensors for the measurement of the meteorological parameters of indoor air 155 temperature (T_i), vapour pressure (e), mean radiant temperature (T_{mrt}) and wind velocity (v). Each MoBiMet calculates the thermal index PET on site based on measured values of T_a , e , T_{mrt} , and v . Only two MoBiMets were equipped with a wind sensor (see appendix) because wind indoors is typically below 0.1 m s^{-1} (Kovanen et al., 1989). For PET calculation at the systems without wind measurement, v was set to 0.1 m s^{-1} . Furthermore, PET calculation was based on a standardized person (male, 35 years, 1.75 m, 75 kg) with clothing of 0.9 clo and a work metabolism of 80 W as in Sulzer et al. (2022). The measured 160 indoor temperature and the calculated PET values are displayed on an ePaper display allowing for immediate assessment on site. Every five minutes, data is stored locally on an SD card and sent to a centralized database on a server via Wi-Fi. For identification, each MoBiMet carries a unique sensor ID.



2.4 Deployment of indoor sensor systems across Hospital departments

From May to October 2023, 65 MoBiMet sensors were distributed across rooms of varying functions in 11 different departments of UMCF to continuously record indoor climates. The department buildings vary in age and total number of floors (see appendix). The locations were chosen with the goal of receiving a wide sample of rooms and uses across the different departments and buildings, including rooms on different floors and with different exposures (Figure 1). 14 sensors were placed in rooms with AC to allow for comparison between rooms with and without AC. To enable quick identification and distinction, these rooms are marked by an asterisk in the following analysis. The sensors were placed near a power supply where they would not disturb staff, patients, or students, typically on desks at a height of approximately 0.8 m, or on shelves at a height of up to 2 m.

During installation, metadata on building and room characteristics of the sensor locations were documented, including window exposure, floor number, and user groups (see Appendix A).

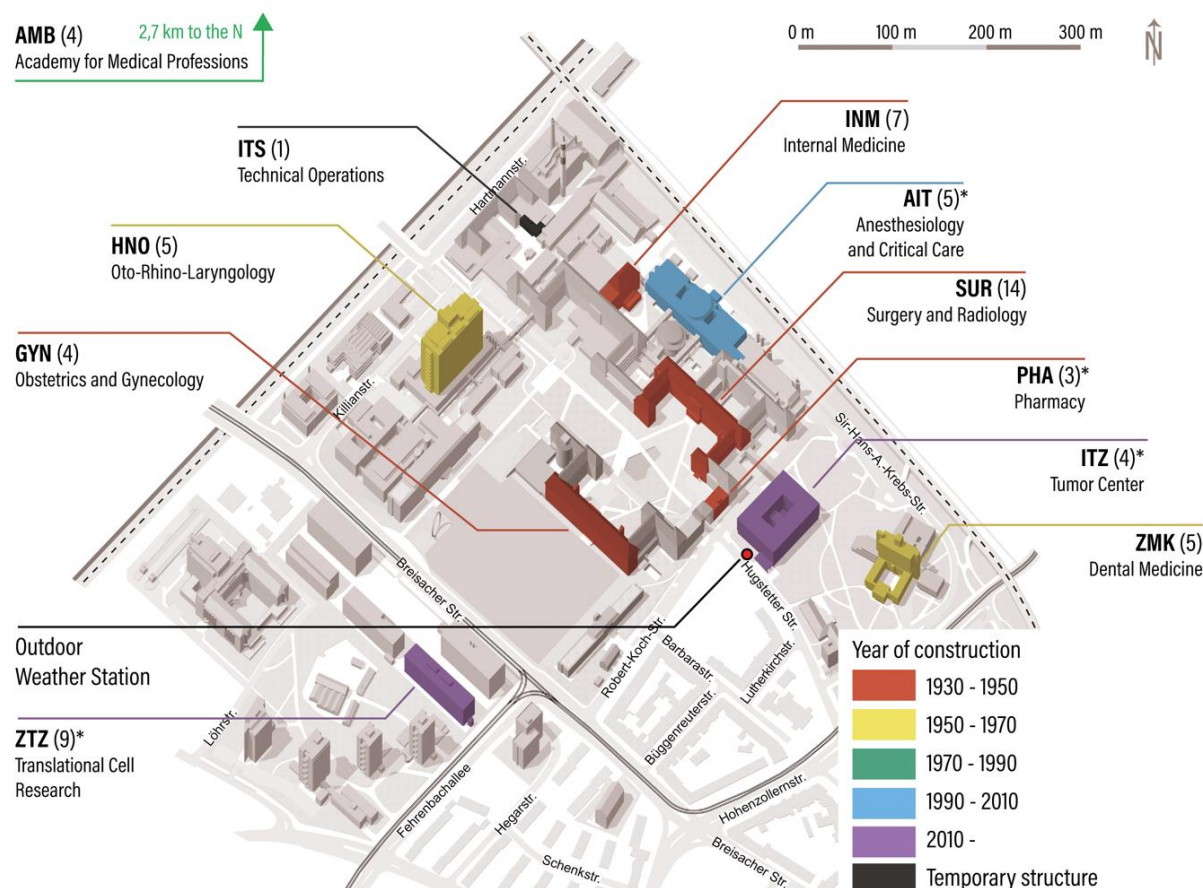


Figure 1: Map of UMCF main campus. Highlighted buildings / departments are buildings equipped with heat sensors, coloured by year of construction. Numbers in brackets refer to the number of sensors distributed in the given building / department, * indicates departments that have selected sensors placed in air-conditioned rooms.



T_i and PET measured and calculated by the sensors were used for further analysis of room microclimates. Hourly averages of T_i and PET were computed based on five-minute interval measurements. The resulting mean data availability of hourly averages in this dataset across all 65 sensors was 96.7%. Overall, 36 sensors had full data availability. Sensors with data availability of less than 87% were excluded from further analysis to avoid imprecision. This pertained to five sensors which had been distributed across the GYN, ZMK and ZTZ departments, resulting in a dataset with a total of 60 sensors and overall data availability of 98.6% (see appendix).

The remaining data gaps were filled through GBM imputation using the R function “gbmimpute” from the imputation package (R Core Team, 2023; Wong, 2013). This was performed separately for the T_i and PET datasets. In both cases, 5 was set as the number of times to iterate through the columns, 10 as the number of folds for cross validation, and 500 as the number of trees used in gradient boosting machines. To estimate the error resulting from this gap filling through GBM imputation, a control run was performed on both datasets. The mean absolute error (MAE) was calculated for each of the 24 sensors. For the T_i dataset, the mean MAE across these sensors was 0.7 K, with a maximum of 1.2 K. For the PET dataset, the mean MAE was 0.8 K, with a maximum of 1.4 K. These errors were deemed acceptable, and the complete dataset obtained using GBM imputation was used for the further analysis.

2.5 Outdoor Measurement Data

Outdoor data used in this study was collected by outdoor sensors of a street-level weather station network across Freiburg. For both T_a and PET, hourly averages for the time period of May 15 – September 30, 2023 were used. T_a was obtained from a station (LoRain, Pessl Instruments GmbH, Weiz, Austria) located outdoors in direct proximity of the ITZ building (Station FRUNIK in (Plein et al., 2024)). This sensor measures T_a , e , and precipitation every minute. Outdoor PET was calculated at three different stations (all ClimaVUE50 and BLACKGLOBE-L, Campbell Scientific, Inc., Logan, UT, USA) in Freiburg (Stations FRBRUH, FRHERD, and FRLAND in (Plein et al., 2024)) providing the variables T_a , e , v , and T_{mrt} needed for PET calculation. The computation was based on the same standardized person with the same clothing and work metabolism as for calculation of the indoor PET. The average PET values of the three outdoor stations were used for the comparison between the PET indoors and the PET outdoors.

2.6 Analysis of measured indoor heat conditions

For each room, the absolute number of hours during which T_i succeeded the thresholds of 26°C, 30°C and 35°C distinguished by ASTA, and PET succeeded the thresholds for slight, moderate, strong and extreme heat stress of 23°C, 29°C, 35°C and 41°C, respectively, were calculated. For investigation of the relation between outdoor heatwaves and occurring indoor heat stress, the daily mean, maximum and minimum T_i and PET for each room was calculated, as well as the resulting mean T_i and PET across all rooms. The data from the 60 rooms were further grouped by hospital department, building age, building floor and room exposure to allow for the identification of heat hotspots.



210 2.7. A data-driven approach to estimate future indoor heat conditions

To assess the frequency and intensity of historical and future heat in all 60 rooms, data were ingested into an artificial neural network (ANN) to develop room-specific transfer functions between T_a and T_i and PET based on the data from the 2023 measurement campaign. The room-specific ANN transfer functions were then run using historical climate data and climate projection data of future decades, similar to the methodology described in Sulzer and Christen (2024). Room-specific ANN transfer models were created for all rooms with sensors resulting in 60 predictions. Predictions for the 13 rooms with AC were analysed separately from the 47 predictions for rooms without AC. The ANN models were built with the Python package Keras using TensorFlow (Christin et al., 2019). Input data (predictors) for the ANNs are T_a and dew point temperature (T_d , °C) at 2 m above the surface, v at 10 m above the surface, and atmospheric pressure (p , hPa), global irradiance (G , $W\ m^{-2}$), and long-wave downwelling radiation (A_G , $W\ m^{-2}$) at the surface. Additionally, T_a , G , and A_G 3 h, 6 h, 12 h, and 24 h prior to the target time were used as predictors to account for hysteresis effects and delayed heating of structures. All predictors were taken from ERA5-Land reanalysis data of the grid cell of Freiburg (48.0°N, 7.8°E) at an hourly resolution (Muñoz Sabater, 2019). Based on the predictors, ANNs then simulate room-specific T_i and PET.

Simulated indoor conditions in summer 2023 (May 15 – September 30, 2023) were then compared to the measured indoor data. The MAE of the ANNs simulating T_a , overall 47 rooms without AC, was 0.78 K. MAE of the ANNs modelling the indoor PET, considering the 47 rooms, was 0.86 K.

To model future time periods of the near future (2020-2049) and the far future (2070-2099) five EURO-CORDEX climate projections were used as input, which considered the representative concentration pathways (RCP) RCP4.5 and RCP8.5 at a 3-hourly resolution (Copernicus Climate Change Service, Climate Data Store, 2019). The five climate projections used the global climate models (GCM) IPSL-IPSL-CM5A-MR, MOHC-HadGEM2-ES, and ICHEC-EC-EARTH combined with the regional climate models (RCM) KNMI-RACMO22E and SMHI-RCA4. For the simulation of the historical time period (1990-2019) ERA5-Land data of Freiburg at a 3-hourly resolution was used as input (Muñoz Sabater, 2019). Because the indoor measurements took place between May 15, 2023 – September 30, both the historical period as well as the near and far future were simulated only for the summertime period from May 15 to September 30.

3. Results

235 3.1. Location, Frequency, and Intensity of Indoor Heat Stress

Averaged over all 60 rooms, the summertime (May 15 – Sep 30, 2023) mean T_i was 25.5°C. The room with the highest summertime mean T_i was PHA-2 with 28.1°C, and the room with the lowest mean T_i was PHA-1* with 21.0°C. The highest hourly T_i was 40.0°C and measured at PHA-2 at 11:00 CEST on May 30, and the lowest hourly T_i was 14.8°C measured at ZTZ-7 at 6:00 CEST on September 25. Averaged over all 60 rooms, the summertime mean PET detected was 25.7°C. The



240 room with the highest summertime mean PET was PHA-2 with 28.8°C, and the room with the lowest mean PET was PHA-1 with 21.2°C. The highest hourly PET recorded was 43.1°C at PHA-2 at 9:00 CEST on June 12.

The temporal development of the PET values and the thermo-physiological stress classes according to PET are shown in Figure 2. Across nearly all departments, periods with high PET stand out as darker vertical stripes in the second half of June, the middle of July, a large part of later August and during the first half of September. Single rooms in AIT, ITZ, PHA and ZTZ
 245 differ from this pattern by showing either a nearly consistent PET over the entire study period, or a clearly lower PET compared to other rooms. This is particularly visible in the time periods of an overall high PET marked by dark vertical stripes. Particularly high PET values appear for longer time periods in the rooms INM-6 and INM-7, as well as in SUR-5. ZMK also catches the eye as a department with overall high PET values detected in all rooms.

Table 1 provides an absolute quantification of heat stress hours according to T_i and PET thresholds. For better visibility, a
 250 column indicating extreme heat stress with $PET > 41^\circ\text{C}$ was omitted, as this only occurred in PHA-2 for a total of seven hours spread across the months of June and July. Except for three rooms (AIT-2*, ZTZ-5*, and ZTZ-8*), the first threshold of $T_i > 26^\circ\text{C}$ was reached in all rooms. 45 of the 60 sensors recorded values of $T_i > 30^\circ\text{C}$, while six recorded values of $T_i > 35^\circ\text{C}$. The threshold of $PET > 23^\circ\text{C}$ for slight heat stress was breached in all rooms for at least 334 hours. In 49 rooms the sensors detected values of $PET > 29^\circ\text{C}$ indicating moderate heat stress, and 17 rooms crossed the threshold of $PET > 35^\circ\text{C}$ for strong
 255 heat stress.

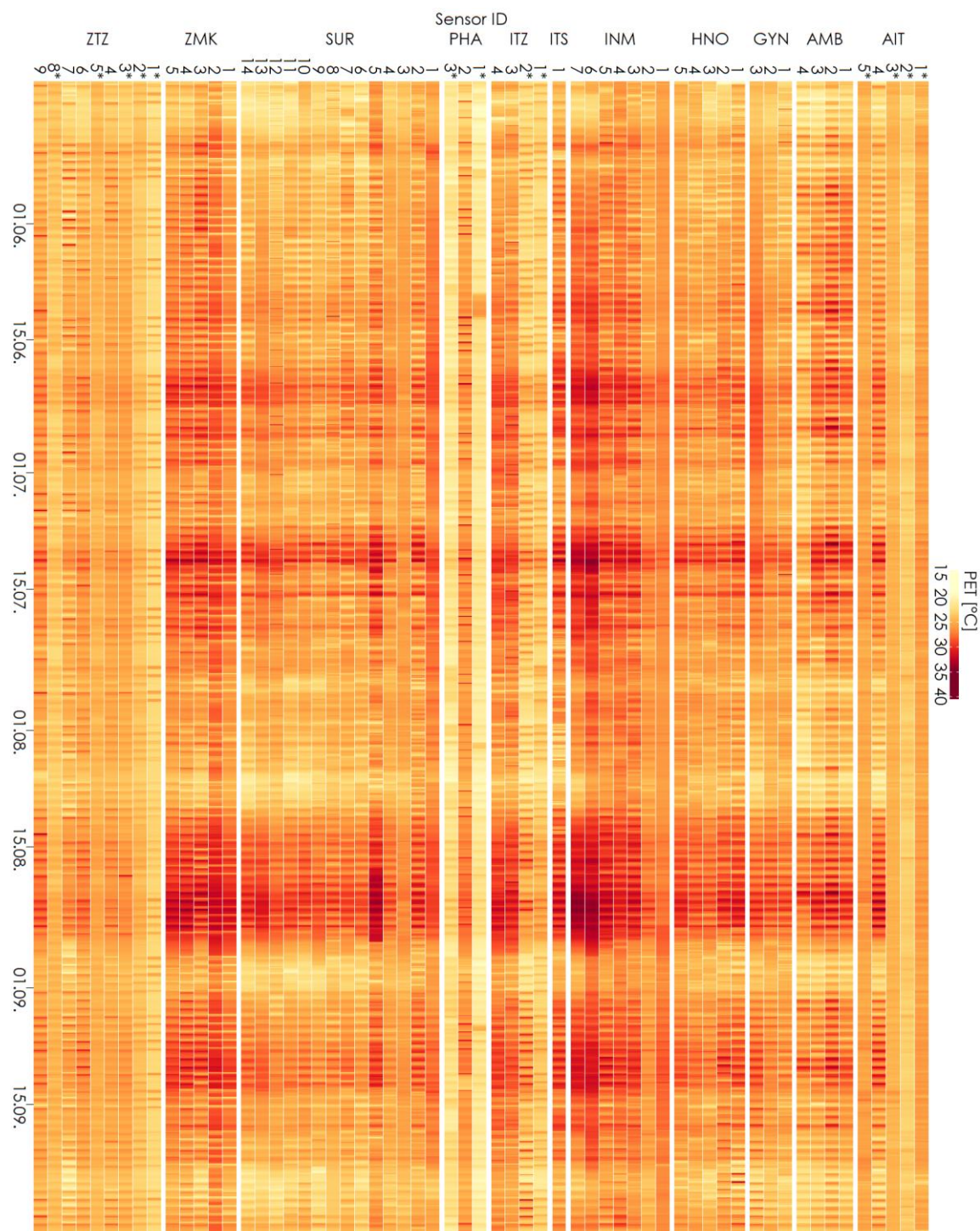


Figure 2: Heatmap of hourly PET values in 60 rooms of the University Medical Centre Freiburg across the study period



Table 1: Number of exceedance hours by room and department

Department	Room ID	Number of hours with T_i			Number of hours with PET		
		> 26°C	> 30°C	> 35°C	> 23°C	> 29°C	> 35°C
AIT	AIT-1*	421	0	0	3318	0	0
	AIT-2*	0	0	0	2326	0	0
	AIT-3*	2	0	0	3337	0	0
	AIT-4	1330	79	0	2730	291	0
	AIT-5*	1006	0	0	3337	0	0
AIT Average		552	16	0	3010	58	0
AMB	AMB-1	1906	464	0	3024	1129	27
	AMB-2	2116	841	93	3095	1385	189
	AMB-3	1869	575	4	2779	953	40
	AMB-4	1870	330	7	2437	446	13
AMB Average		1940	553	26	2834	978	67
GYN	GYN-1	1340	37	0	2806	200	1
	GYN-2	1076	34	0	2991	224	0
	GYN-3	2090	330	0	2926	729	0
GYN Average		1502	134	0	2908	384	<1
HNO	HNO-1	1806	264	0	3027	768	18
	HNO-2	1768	241	0	3090	673	8
	HNO-3	1390	70	0	3026	348	0
	HNO-4	2056	121	0	3192	453	0
	HNO-5	2556	263	0	3292	625	0
HNO Average		1915	192	0	3125	573	5
INM	INM-1	716	0	0	3329	0	0
	INM-2	241	0	0	2695	5	0
	INM-3	1125	21	0	3061	330	0
	INM-4	1467	3	0	3247	315	0
	INM-5	1407	105	0	3065	367	0
	INM-6	2064	257	0	3127	948	0
	INM-7	1932	328	0	2878	719	0
INM Average		1279	102	0	3057	383	0
ITS	ITS-1	1752	241	0	2736	586	4
ITS Average		1752	241	0	2736	586	4
ITZ	ITZ-1*	57	0	0	2861	0	0
	ITZ-2*	405	0	0	2682	61	0
	ITZ-3	1948	5	0	3302	292	0
	ITZ-4	2453	9	0	3305	385	0
ITZ Average		1216	4	0	3038	185	0
PHA	PHA-1*	65	0	0	334	15	0
	PHA-2	2952	344	7	3295	1460	90



Department	Room ID	Number of hours with T_i			Number of hours with PET		
		> 26°C	> 30°C	> 35°C	> 23°C	> 29°C	> 35°C
	PHA-3*	1	0	0	778	0	0
PHA Average		1006	115	2	1469	492	30
SUR	SUR-1	2739	50	0	3312	1114	0
	SUR-2	1710	292	0	3070	635	7
	SUR-3	1706	0	0	3218	4	0
	SUR-4	1430	48	0	3123	253	0
	SUR-5	2475	669	41	3223	1141	148
	SUR-6	939	15	0	2572	273	0
	SUR-7	1454	97	0	2887	391	0
	SUR-8	1136	60	0	2928	276	1
	SUR-9	779	18	0	2592	254	0
	SUR-10	1039	57	0	2813	383	0
	SUR-11	1265	70	0	2717	326	0
	SUR-12	1633	99	0	2783	385	2
	SUR-13	1734	173	0	2912	682	0
	SUR-14	1415	156	0	2605	533	0
SUR Average		1532	129	3	2911	475	11
ZMK	ZMK-1	1475	53	0	2972	308	0
	ZMK-2	2724	268	0	3221	735	0
	ZMK-3	1907	236	0	2887	499	1
	ZMK-4	1830	151	0	3013	458	0
	ZMK-5	1763	86	0	3150	448	0
ZMK Average		1940	159	0	3049	490	<1
ZTZ	ZTZ-1*	100	0	0	599	0	0
	ZTZ-2*	3	0	0	1942	0	0
	ZTZ-3*	868	7	0	3122	17	1
	ZTZ-4	753	5	0	3137	81	0
	ZTZ-5*	0	0	0	3272	0	0
	ZTZ-6	1118	37	0	2993	272	0
	ZTZ-7	749	65	0	2424	142	1
	ZTZ-8*	0	0	0	1957	0	0
	ZTZ-9	1660	118	4	3072	407	9
ZTZ Average		583	26	<1	2502	102	1
Total average		1327	130	3	2832	395	9

260

The relative frequency of heat stress occurrence in each room according to T_i thresholds is visualized in Figure 3. Heat stress occurred everywhere in the hospital except in three rooms equipped with AC, namely AIT-2*, ZTZ-5*, and ZTZ-8*. Averaged over all rooms, no heat stress occurred 60% of the time, while heat stress with $T_i > 26^\circ\text{C}$ accounted for 36% and heat



stress with $T_i > 30^\circ\text{C}$ for 4% of the time, respectively. In four rooms, the sensors recorded heat stress ($T_i > 26^\circ\text{C}$) during more
 265 than 75% of the time, with the sensor in room PHA-2 showing a maximum share of heat stress of 88%. Heat stress with
 $T_i > 35^\circ\text{C}$ was reached in six rooms, with a maximum of 3% in room AMB-2. Clear differences in the frequency of T_i heat
 stress levels can be recognized between rooms in the same building, and within a department.

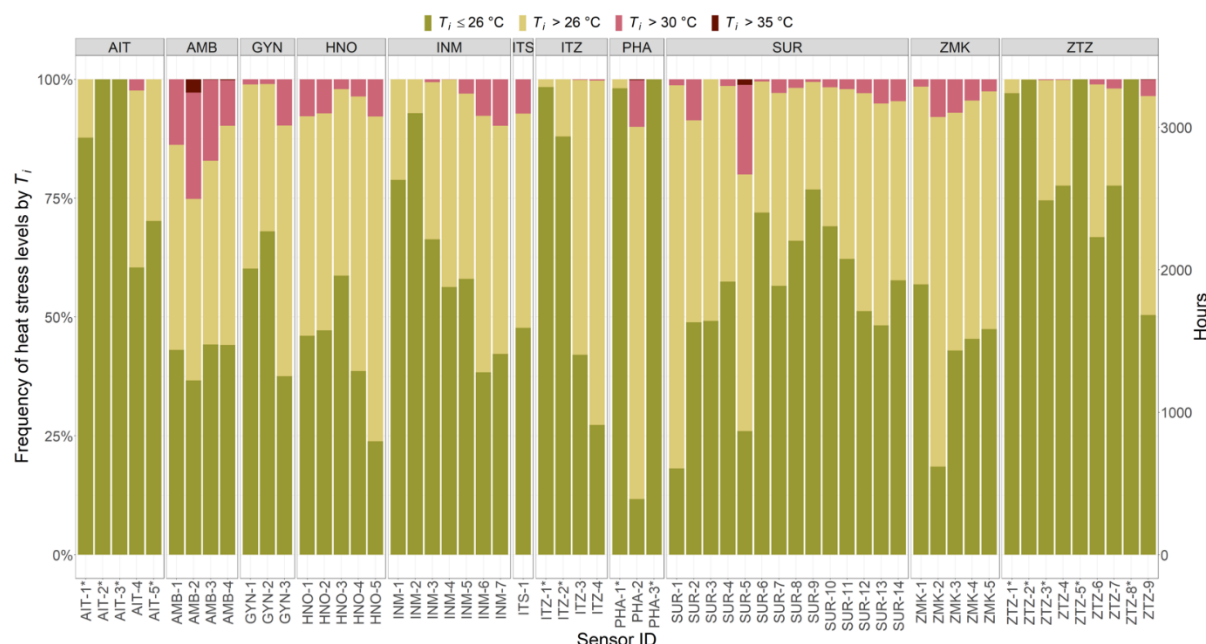


Figure 3: Frequency of heat stress levels by T_i thresholds in all rooms studied in summer 2023.

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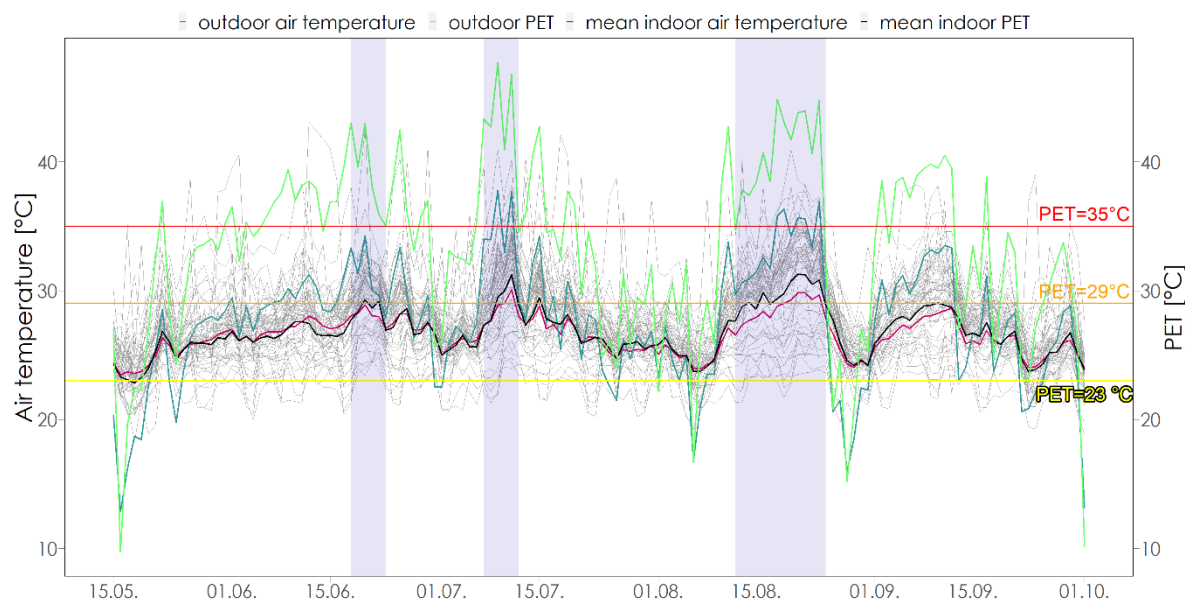
The relative frequency of occurrence of PET thermo-physiological stress levels is visualized in Figure 4. In the rooms PHA-
 1*, PHA-3*, and ZTZ-1*, no thermal stress is the most common PET stress class. In all other rooms, slight heat stress is the
 most common PET stress class. The sensors in the rooms AIT-3* and AIT-5* exclusively recorded slight heat stress. On
 average, across all rooms of the hospital, no thermal stress occurred 15% of the time, and some level of heat stress occurred
 275 85% of the time, split up into 73% slight heat stress and 12% moderate heat stress. The maximum share of moderate heat stress
 was 41% in room PHA-2, and the maximum share of strong heat stress was 6% in room AMB-2. Extreme heat stress only
 occurred in room PHA-2, for 0.2% of the time. Slight cold stress occurred in 18 rooms with a maximum of 1.7% of the time
 in room ZTZ-7. As is the case according to the T_i thresholds, differences in the frequency of PET stress levels are clearly
 visible both within and between departments.



Figure 4: Frequency of thermal stress levels by PET thresholds

3.2 Indoor Heat Stress in Relation to Outdoor Heatwaves

The daily maximum outdoor T_a , daily maximum outdoor PET, daily maximum of the mean indoor T_i and daily maximum of the mean indoor PET throughout the study period are visualized as thick lines in Figure 5. The daily maximum indoor T_i is correlated to outdoor T_a ($r^2 = 0.90$). Maximum T_a and maximum T_i are clearly higher at the end of May and beginning of June, during all three heatwaves, and in the beginning of September. After heatwaves, especially in the period August 26 – August 31, daily outdoor maximum T_a is up to 8.4 K lower than the average T_i across all rooms of the hospital for six days. The average difference between the daily maximum outdoor T_a and daily maximum of T_i during non-heatwave periods is 0.3 K, compared to 4.9 K during heatwaves. The daily maximum of the mean indoor PET largely remains within the thresholds of slight heat stress, though moderate heat stress occurs as well, almost exclusively during the heatwave periods. The daily maximum indoor PET of several individual rooms (grey lines) exceed the threshold of strong heat stress throughout the study period, with a focus from June through August.



295 **Figure 5: Daily maximum outdoor T_a , daily maximum outdoor PET, daily maximum of mean T_i , (averaged over all rooms) and daily maximum of mean indoor PET (averaged over all rooms) across study period. Fine grey lines show daily maximum indoor PET for individual rooms. Horizontal lines indicate PET thresholds for slight, moderate, and strong heat stress. Purple-shaded time periods are heatwaves based on official DWD heat warnings.**

300 The daily minimum outdoor T_a , daily minimum outdoor PET, daily minimum of the mean T_i , and daily minimum of the mean indoor PET throughout the study period are visualized in Figure 6. The daily minimum outdoor T_a is consistently lower than the daily minimum of the mean T_i . However, the average difference between the daily minimum outdoor T_a and daily minimum of the mean T_i during non-heatwave periods is 8.7 K, compared to 5.8 K during heatwaves. The daily minimum of the mean PET largely remains in the area of slight heat stress, and does not cross the threshold for moderate heat stress. However, the

305 the daily minimum of the PET peaks towards the end of all three heatwaves, reaching the highest value on August 21 during the third heatwave.

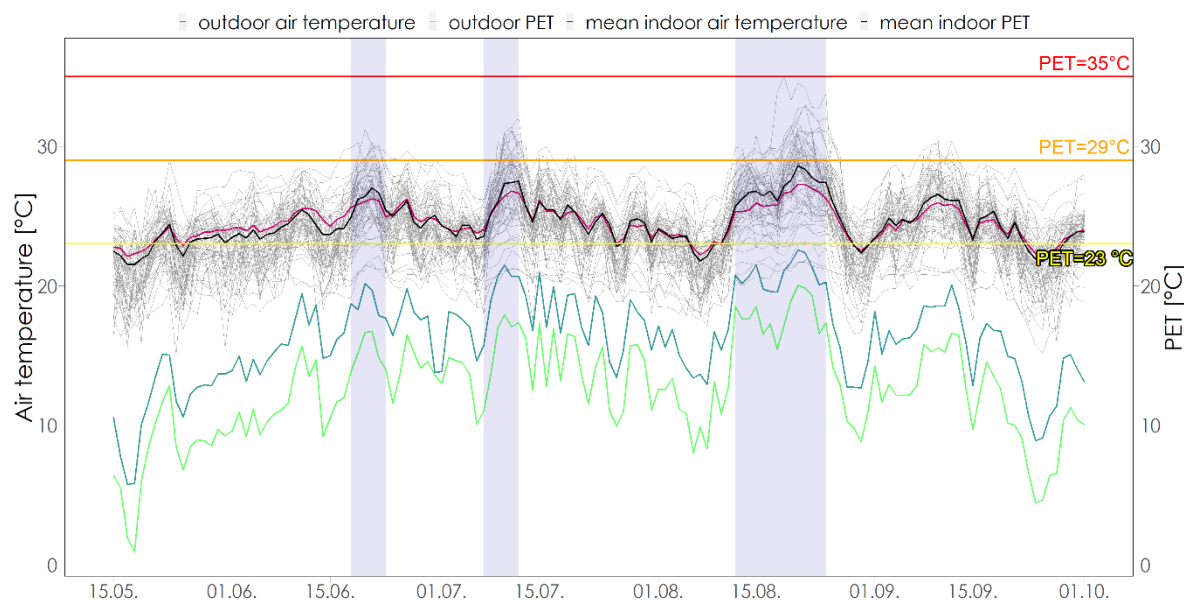
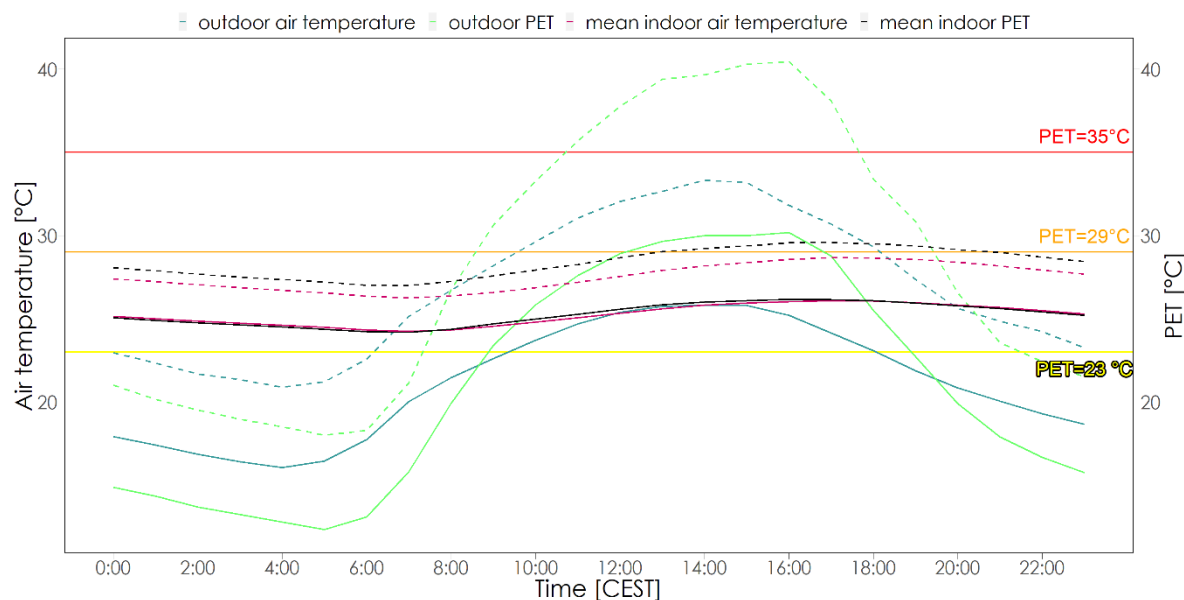


Figure 6: Daily minimum outdoor T_a , daily minimum outdoor PET, daily minimum of mean T_i , and daily minimum of mean indoor PET across study period. Fine grey lines show daily minimum indoor PET for individual rooms. Horizontal lines indicate PET thresholds for slight, moderate, and strong heat stress. Purple-shaded time periods are heatwaves as indicated by official DWD heat warnings.

Figure 7 displays the mean diurnal cycles of the outdoor T_a , outdoor PET, mean T_i , and mean indoor PET during non-heatwave periods and during heatwaves, respectively. During all three heatwaves, the daily outdoor T_a maximum is higher and the minimum lower than the daily mean T_i maximum and minimum, respectively. Furthermore, the daily outdoor T_a maximum and minimum occur earlier than the daily mean T_i maximum and minimum, respectively with an average lag of three hours. On average across the entire measurement period, the difference between outdoor T_a and indoor T_i was 3.6 K, the difference was smallest at 11:00 and 16:00 CEST and largest at 4:00 CEST. It is particularly noteworthy that the daily outdoor T_a minimum during non-heatwave periods falls below 20°C, though remains above 20°C during heatwaves, which is referred to as tropical night. During the study period, a total of 18 tropical nights were measured outdoors at UMCF, of which 13 occurred during the three heatwaves. The periods with high nocturnal minima of T_a were mirrored by the mean nocturnal T_i . While the daily mean T_i minimum during non-heatwave periods was below the T_i threshold of 26°C for heat stress, it was above this threshold during heatwaves.



325 **Figure 7: Mean diurnal cycles of outdoor T_a , outdoor PET, mean T_i , and mean indoor PET during heatwaves and non-heatwave periods. Dashed lines show mean diurnal cycles during heatwaves, solid lines show mean diurnal cycles during non-heatwave periods. Horizontal lines indicate PET thresholds for slight, moderate, and strong heat stress.**

The relative frequency of the heat stress levels according to PET thresholds varies notably between non-heatwave periods and
 330 heatwaves (Table 2). On average, heat stress occurred 96% of the time during heatwaves, opposed to 85% of the time without
 heatwaves. The third heatwave, longest in duration and intensity, showed the largest share of moderate heat stress, while the
 first and second heatwaves showed higher shares of slight heat stress.

Table 2: Relative frequency of indoor heat stress during heatwaves by PET thresholds

	Entire period	First heatwave	Second heatwave	Third heatwave
No heat stress ($PET \leq 23^\circ\text{C}$)	15%	4%	6%	4%
Slight heat stress ($23^\circ\text{C} < PET \leq 29^\circ\text{C}$)	73%	61%	56%	48%
Moderate heat stress ($29^\circ\text{C} < PET \leq 35^\circ\text{C}$)	12%	35%	37%	46%
Strong heat stress ($PET > 35^\circ\text{C}$)	0%	0%	2%	2%

335 3.3 Diurnal PET Cycles by Room and Building Characteristics

The individual rooms show varying mean diurnal PET cycles (Figure 8a). The mean diurnal PET cycle moves from a minimum
 PET of 24.6°C at 6:00 CEST to a maximum PET of 26.7°C at 16:00 CEST, showing a mean amplitude of 2.1 K. The daily



maximum PET ranges from 22.3°C in room PHA-1* to 31.7°C in room AMB-2, and the daily minimum PET ranges from 20.4°C in room PHA-1* to 27.4°C in room PHA-2. The smallest PET amplitude was measured in roomAIT-3* with 0.4 K, and the largest PET amplitude was found in room AMB-2 with 6.6 K. Most rooms with AC showed a lower PET as well as a smaller PET amplitude than the mean. While rooms with AC show a mean minimum PET of 23.1°C and mean maximum PET of 24.5°C, rooms without AC show a mean minimum PET of 24.8°C and mean maximum PET of 27.5°C.

The investigated rooms showed differing mean diurnal PET cycles when grouped by the age of the building they are located in (Figure 8b). Buildings constructed between 1950 and 1970 show the highest mean PET minimum of 25.0°C and those built between 1970 and 1990 show the highest mean PET maximum of 29.2°C. The mean diurnal PET cycle with the largest amplitude was found for buildings constructed between 1970 and 1990. Buildings constructed in 1990 or later show the lowest mean PET values, with maximum mean values of less than 26°C, occurring at 16:00 CEST.

A clear difference in the mean diurnal PET cycle was also observed between rooms located on different floors (Figure 8c). While the mean diurnal PET cycle was similar on the first, second, and third floors, the mean PET was generally higher in rooms located on the fourth and sixth floors, which both showed the highest mean PET minimum values. Rooms on the sixth floor, the highest floor sampled, showed the highest mean PET maximum of 27.7°C. Rooms on the ground floor, the lowest floor sampled, showed similar mean PET minimum values as rooms on the other floors, yet clearly the lowest and earliest mean PET maximum of 26.1°C at 15:00 CEST.

The diurnal PET cycle also varied across rooms with different exposure, with the absolute mean PET values, daily mean PET amplitude and timing of minimum and maximum of the mean PET differing observably (Figure 8d). Rooms with north-eastern exposure showed the lowest mean PET values overall and reached their mean PET maximum earliest in the day, at 15:00 CEST. The mean PET maximum was reached latest in rooms with north-western exposure, where the mean PET peaked at 18:00 CEST. Rooms with multiple windows of different exposure showed the largest mean PET amplitude of 3.4 K, and reached the highest mean PET maximum of 27.6°C. In contrast to other rooms, rooms without windows showed less of a peak in their mean PET, but rather a nine-hour period in the afternoon with a mean PET between 27.0°C and 27.2°C. These rooms also showed the highest mean PET minimum of 25.6°C.

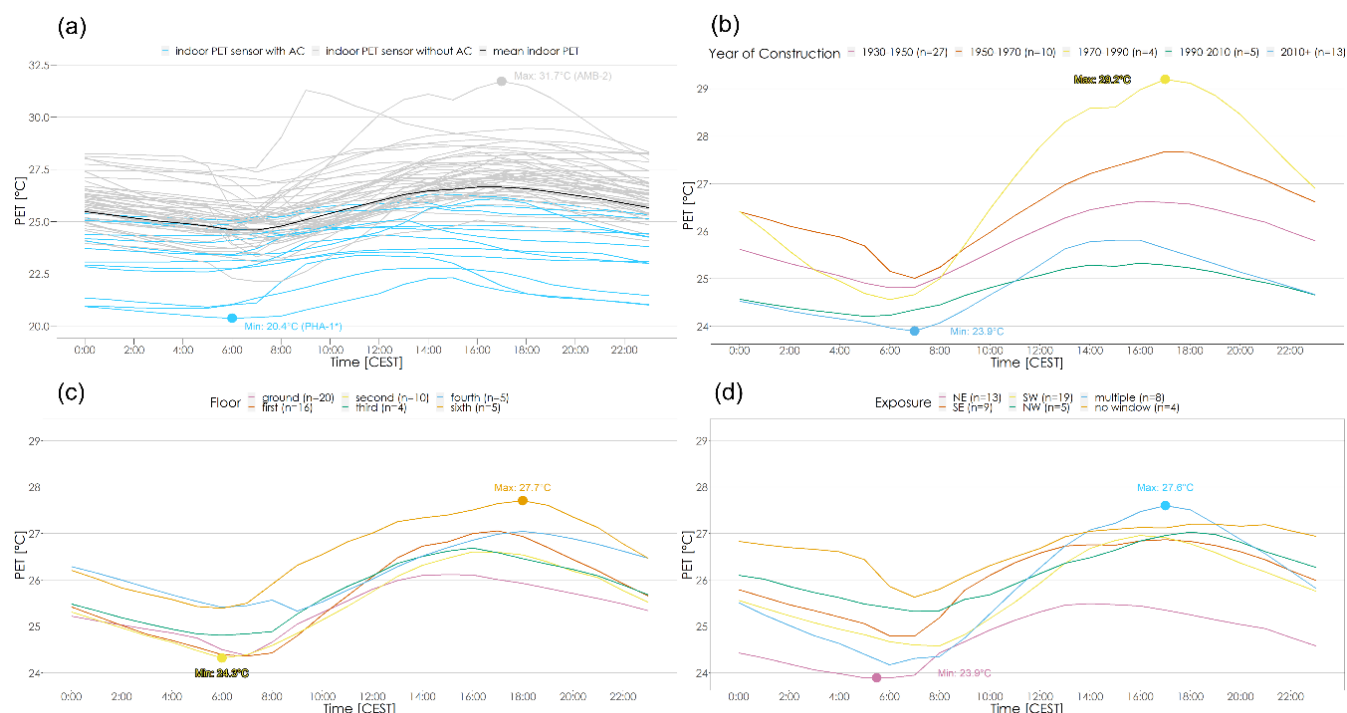


Figure 8: Mean diurnal PET cycles in rooms (a) with and without AC and grouped by (b) year of construction, (c) floor, and (d) exposure. Note. ITS was excluded from (b) due to unknown building age. Exposures with $n < 4$ were excluded from (d).

3.4 Modelled future heat stress

Based on the 2023 data, past and future climate periods were modelled to assess expected changes due to climate change. Figure 9 compares the occurrence of heat in the 47 observed rooms without AC for a historical period (1990 – 2019, blue) to the modelled near (2020 – 2049, light red) and far future (2070 – 2099, dark red), considering RCP8.5. All categories of heat stress are modelled to become more frequent in the future. Averaged over all rooms, moderate heat stress or higher has occurred during 7% of the investigated summertime in the modelled past (237 h). The average number of hours per summer exceeding the PET threshold for moderate heat stress or higher ($PET > 29^{\circ}\text{C}$) will increase by +24 h (+10%) in the near future and by +533 h (+204%) in the far future. Cold stress ($PET \leq 18^{\circ}\text{C}$) only occurred on average for four hours per summer in the modelled historical data and the near future. Cold stress is not expected to occur during summer in the far future. The average hours under comfortable indoor conditions ($18^{\circ}\text{C} > PET \leq 23^{\circ}\text{C}$) will decrease from 588 h to 503 h in the near future and to 213 h in the far future.

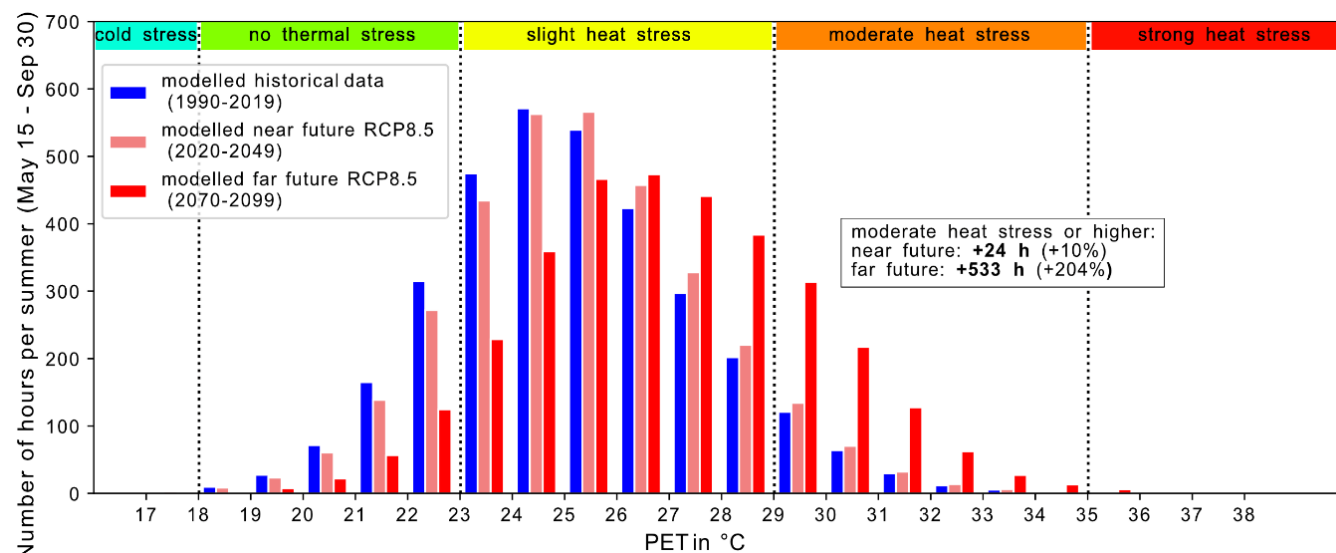


Figure 9: Mean number of hours per summer (May 15 – Sep 30) of PET (°C) in all 47 modelled rooms of the University Medical Centre Freiburg without AC. Data are shown for modelled for a historical period (1990 – 2019, blue) as well as the near (2020 – 2049, light red) and far future (2070 – 2099, dark red), as an ensemble of five different RCP8.5 climate models.

The increase in PET heat stress hours during summer in the future is not evenly disturbed in the different departments or rooms. For example, in the rooms in INM an average increase of +29 h is expected for the number of hours exceeding PET > 23°C in the near future and of +250 h in the far future, considering RCP8.5. In contrast, in AMB the number of hours exceeding PET > 23°C are expected to rise by an average of +159 h in the near future and +542 h in the far future.

The variation of T_i heat stress hours in the different departments during summer in the modelled past and future are shown in Figure 10. All of the 47 considered rooms without AC in the UMCf exceed the threshold of $T_i > 26^\circ\text{C}$ on average at least once a year in the historical period as well as in the near and far future. 63% of all rooms without AC exceeded $T_i > 30^\circ\text{C}$ in the historical period on average at least once a year, and in the near future it is expected that 66% and in the far future that 79% of the rooms will exceed $T_i > 30^\circ\text{C}$ at least once per summer. In the past, averaged over all rooms without AC, 35% of the data exceeded the threshold of $T_i > 26^\circ\text{C}$, considering RCP8.5, an increase to 38% in the near future and to 62% in the far future can be expected. In rooms without AC, the threshold $T_i > 30^\circ\text{C}$ is exceeded during 3% of the summertime in the modelled historical data, 4% in the modelled near future and 14 % in the modelled far future. In rooms equipped with AC, on average 0 h exceed the PET threshold for moderate heat stress or higher or $T_i > 30^\circ\text{C}$ in the modelled past and future periods.

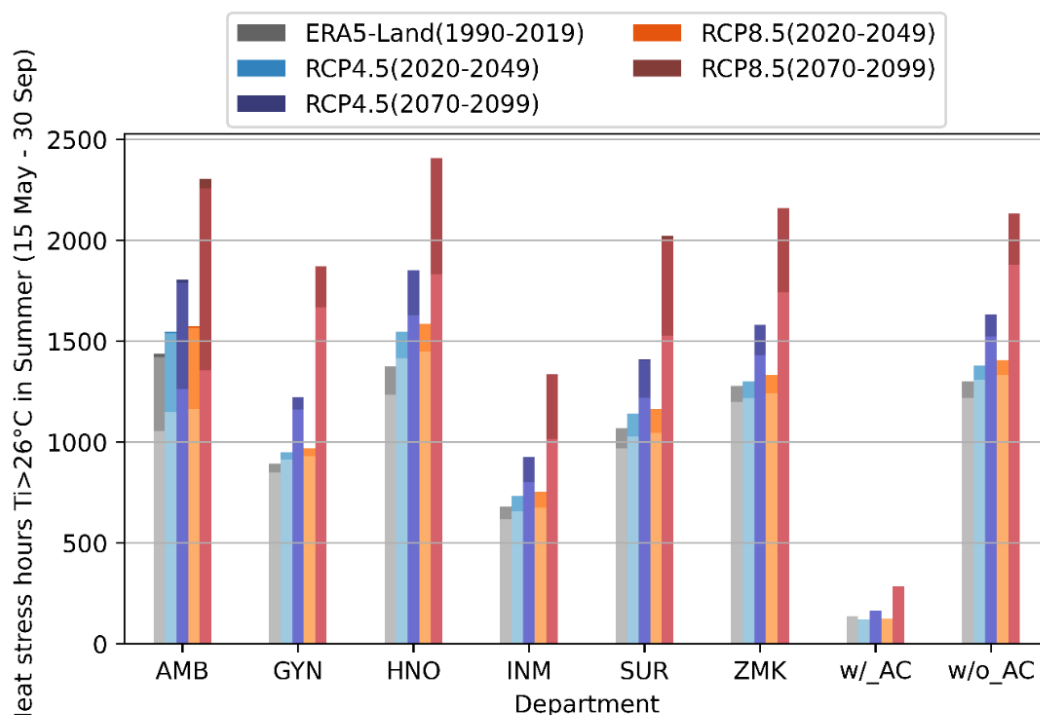


Figure 10: Average modelled heat stress hours exceeding $T_i > 26^\circ\text{C}$ during summer for rooms without air conditioning in different departments, for rooms with air conditioning (w/_AC), and rooms without air conditioning of other departments (w/o_AC) of the University Medical Centre Freiburg for a historical period (1990 – 2019) as well as the near (2020 – 2049) and far future (2070 – 2099), as an ensemble of five different RCP4.5 and RCP8.5 climate models. Darker colours indicate the exceedance of the thresholds $T_i > 30^\circ\text{C}$ and $T_i > 35^\circ\text{C}$.

4. Discussion

4.1 Indoor Heat Hotspots in University Medical Centre Freiburg

During the measurement period, heat stress occurred nearly everywhere in UMCF according to T_i thresholds, and everywhere according to PET thresholds. Heat was most prevalent and intense during the heatwaves and on days with issuances of heat warnings, and was recorded throughout the summer months of June, July and August, as well as the adjoining months of May and September. On average, heat stress was observed during more than 80% of the time from mid-May through September 2023 based on PET thresholds. Even though slight heat stress was the most frequent class, moderate heat stress was observed in the majority of rooms as well, and strong heat stress was recorded for a small part of the time in 28% of the rooms.

Indoor heat stress was observed throughout summer, though was most frequent and intense during heatwaves with elevated outdoor T_a , with heat stress occurring more than 90% of the time following PET thresholds, and an increasing share of moderate



and strong heat stress compared to slight heat stress. The lag of the indoor T_i compared to outdoor T_a keeps the daily maximum T_i below the outdoor maximum T_a during heatwaves. This implies that during the daytime heat stress indoors is less severe than outdoors. At the same time, however, a higher daily minimum T_i compared to T_a limits nocturnal cooling, indicating that
 415 during night-time, heat stress is higher indoors than outdoors. The strain of daytime heat on patients and staff is further increased in the absence of nocturnal recovery periods with lower strain on the body (Basarin et al., 2020).

The finding that rooms with north-eastern exposure show lower PET values than rooms with other exposures is largely consistent with other studies, as solar heating in north-eastern oriented rooms is generally limited to early morning hours (Derks et al., 2018; Iddon et al., 2015). The large daily PET amplitude in rooms with multiple windows / exposures suggests
 420 that these rooms follow the outdoor diurnal cycle more closely than rooms without windows, which show smaller PET amplitudes. The generally elevated PET minimum in rooms without windows suggests that window opening contributes meaningfully to nocturnal cooling, yet information on window opening behaviour is unknown and therefore does not allow us to draw a link between the role of venting and indoor heat stress (Rosenfelder et al., 2016).

Similarly, the finding that PET and heat stress increase on higher floors matches findings from previous studies, as rooms in
 425 higher floors generally receive more solar irradiance, and are heated by roof areas and warm air rising within buildings (Franck et al., 2013; Kovats and Hajat, 2008). However, it should be noted that the sample of rooms was clearly larger on lower floors than on higher floors, and that the rooms on higher floors were not widely distributed across departments. All five rooms on the sixth floor were located in the HNO department, located in a high-rise building. Furthermore, all but one of the sampled rooms with AC were located on the ground or first floor.

It is not surprising that rooms with AC show less heat stress than rooms without. The observation that rooms in buildings
 430 constructed since 1990 showed lower PET values than those in older buildings can be attributed to the prevalence of AC. Of the remaining three building age categories, the category of buildings constructed before 1950 showed the least heat stress, which is consistent with findings by Iddon *et al.* (2015) and attributed to the more massive stone structure. Here again, however, it needs to be noted that sample sizes varied largely between the categories. In particular, AMB was the only building equipped
 435 with sensors that was constructed between 1970 and 1990, and AIT was the sole building constructed between 1990 and 2010 considered in the study.

Taken together, these findings suggest that temporal indoor heat hotspots in UMCF can be located during heatwaves not only due to high T_i and PET peaks in the daytime, but also limited cooling at night. Spatial heat hotspots are located predominantly in rooms without AC, with multiple exposures or no windows, and on higher floors located in buildings constructed between
 440 1950 and 1990. The indoor climate modelling further showed that heat stress will become an even more prevalent problem at UMCF in both space and time in the near and far future.

4.2 Vulnerability of User Groups

The sampled rooms are used by different groups of people and for different purposes. The main user groups are patients, staff, students and visitors. Room types include waiting rooms, treatment rooms, offices, laboratories and lecture halls (see



445 appendix). As a consequence, the frequency, duration of use, and vulnerability of room occupants vary, resulting in differing implications of occurring heat stress. Of the rooms analysed, 15 are used by patients (patient rooms, treatment rooms and waiting rooms), while in 47 of the 60 analysed rooms, hospital staff is the largest user group. Hospital patients are among the people most vulnerable to heat stress due to their acute health, possible pre-existing conditions, and often advanced age. Temporally, inpatients belong to the groups most exposed to heat stress in the hospital as they spend day and night in the hospital building, exposing them to both daytime and night-time heat stress (Leichtle et al., 2023; Obradovich et al., 2017). Patients can be considered less physically active within the hospital than other user groups, limiting increased heat stress caused by their metabolism. At the same time, potential mobility limitations of patients must be considered. In the absence of staff assistance, these could hinder patients from improving their personal level of thermal comfort through adjustments such as relocation, window opening or removing of blankets. The severity of the occurring heat stress for patients therefore cannot
 450 be fully deferred from T_i and PET measurements alone, but requires further study of additional factors (Zhang et al., 2021). Three of the rooms used by patients were air-conditioned. For example, AIT-3*, located in the critical care unit and housing four beds, can be considered to be occupied by the patients most vulnerable to heat stress. AIT-3* detected continuous slight heat stress according to PET thresholds, yet only two hours of heat stress according to T_i thresholds. The large contrast between heat stress classification following PET as opposed to T_i thresholds is due to the fact that in the room heat stress is mainly
 455 driven by e rather than T_i . Another room of concern for inpatients is SUR-5, as it predominantly houses inpatients with limited mobility. This makes the high level of occurring heat stress particularly concerning.

Hospital staff are also vulnerable to heat stress mainly due to extrinsic factors, namely their physical activity and the nature of the buildings and rooms they work in. While the metabolism of staff with desk jobs is most likely accurately modelled in the PET calculation applied here, workers such as nurses and doctors likely have a higher metabolism than assumed in the PET modelling, intensifying their level of heat stress, as found in previous studies (Sattayakorn et al., 2017; Skoog et al., 2005). In contrast to patients that spend a limited time in the hospital, staff is generally employed over a longer time, exposing them to reoccurring heat stress throughout the entire summer. Staff rooms were distributed across all sampled departments, floors and exposures. Of the nine sampled rooms used as doctor rooms or staff rooms, two showed strong heat stress at least once. Six of these rooms showed moderate heat stress, and in all rooms heat stress was more common than periods without heat stress
 465 according to PET thresholds.

All rooms without windows showed particularly small shares of periods without heat stress according to PET thresholds, and are exclusively used by staff as offices. Staff working in these rooms is unable to ensure cooling through window opening during favourable outdoor conditions, and therefore fully exposed to the indoor thermal conditions. Room PHA-2 is an office on the ground floor which was the only room in the study to record PET values above the threshold of 41°C for extreme heat stress during seven hours in June and July. The cause of this extreme heat stress is unknown and could be due to direct solar radiation because the sensor was placed directly at the window, or could be of anthropogenic origin as highlighted by Gough
 475 et al. (2019).



4.3 Vulnerability of Hospital Areas and Functions

Based on the temporal and spatial heat hotspots and vulnerability of user groups discussed above, certain hospital areas and
480 corresponding functions were identified as most vulnerable to heat stress. Areas most vulnerable to heat stress are selected
inpatient rooms without AC, rooms located on higher floors, and offices without windows. It follows that these areas may be
unable to satisfactorily fulfil their functions of providing suitable spaces for recovery and work during summer conditions and
threaten the functionality of the hospital as a critical infrastructure. An expected rise in hospital admissions during heatwaves
presents a further stress factor to the hospital system. In the case of excessive and long-lasting heat stress, the suspension of
485 selected functions could be inevitable, as has been the case in other hospitals (Brooks et al., 2023; GreenSurg Collaborative,
2023).

4.4 Possible Measures for Prevention and Relief

Although the most urgent-needed measures to prevent future heat and resulting heat stress are measures of climate change
mitigation, several opportunities exist for adaptation. These actions are useful for prevention and limitation of indoor heat
490 stress during periods of excessive outdoor heat, and for relief from occurring heat stress. As individual conditions in each
building and room are different, there is no general solution to manage indoor heat stress (Gough et al., 2019). Possible
prevention and relief measures can be divided into short- and long-term approaches depending on their ease of implementation.
The effectiveness of these measures does not need to be judged exclusively based on the degree of cooling of the surroundings,
but should focus on cooling the body and reducing heat strain (Jay et al., 2021). In the short term, UMCF should ensure that
495 hospital-wide systems are in place to activate heat-adjusted hospital operations and individual behaviour following the issuance
of DWD heat warnings (Carmichael et al., 2012) and the development and implementation of effective heat health action plans
(Matzarakis, 2024). These measures could include increased provision of drinking water, breaks for staff, the consistent use
of existing shading opportunities such as shutters and blinds, and turning off of non-required medical equipment producing
heat (Lenzer et al., 2020b). Studies have found ventilation to have a high potential for lowering the PET, suggesting that night-
500 time and morning ventilation by fully opening windows, and alternatively, the use of fans, can help leverage indoor heat stress
(Müller et al., 2014; Rosenfelder et al., 2016). The relocation of particularly vulnerable patients to cooler areas with less heat
stress has proven effective in hospitals (Kakkad et al., 2014). Generally, alleviation of heat stress for staff can be achieved by
adjusting work schedules (International Labour Organization, 2019). Although shifting work to cooler morning or evening
hours is generally not feasible in a hospital context, sufficient rest periods in thermally comfortable rooms are of high
505 importance for reduction of heat strain. The measured indoor data can be linked together with weather forecasts and artificial
neural networks to provide forecasts of indoor temperatures and human thermal comfort (2023). This would further facilitate
prevention and preparedness for heat stress in the context and implementation of heat health action plans in the health sector
in Germany.



In the long term, measures on the scale of climate-sensitive building (re-)design could help prevent indoor heat stress, including external shading possibilities (Zielo and Matzarakis, 2018). The UMCF main campus is embedded in a park-like structure with tall trees improving the immediate outdoor climate, yet additional tress could be helpful for more recent developments including ITS, AMB, HNO, ITZ, ZMK and ZTZ. Reflective coatings on external building walls and roofs can help reduce indoor warming, as can insulation that reduces conductive heat flow (Jay et al., 2021; Lundgren-Kownacki et al., 2018).

In the present study, rooms equipped with AC showed some of the lowest levels of heat stress. Past studies have found AC to be highly effective in reducing mortality during heatwaves (Klenk et al., 2010; Kovats and Hajat, 2008). The use of AC in cases of heat stress in hospitals has been found to positively affect patients' health, leading to earlier mobilization and reducing the length of hospital stay (Lenzer et al., 2020a). However, the widespread use of AC comes with drawbacks as well. Energy demand for AC use is high, hence increasing the risk of blackouts (Daalen et al., 2022; Lundgren-Kownacki et al., 2018) and adding burden on emergency electricity supply systems (Zielo and Matzarakis, 2018). Furthermore, widespread use of AC warms the wider outdoor environment, and contributes to the emission of greenhouse gas emissions, the ultimate driver of climate change and warming temperatures (Jay et al., 2021). Cooling through photovoltaic conversion, a heat removal system driven by solar energy, is also recommended (Lundgren-Kownacki et al., 2018; Samuel et al., 2013).

4.5 Limitations

This study is the first study that has comprehensively and continuously sampled an entire hospital complex across different departments, uses and buildings. Nevertheless, the study has limitations regarding the time period, sample size and distribution, equipment, and used indexes that need to be considered when interpreting the results.

The time period of this study is limited to one summer, which cannot be representative for all summers. All four months included in the study period were warmer than in the reference periods of 1961-1990 and 1991-2020. While this warming falls into the pattern of increasing temperatures in the face of climate change, it is unknown exactly at what speed and to which degree summers in Freiburg will change.

The sample size of this study is limited to the 60 sensors / rooms included in the analysis. This represents just a small selection of all 29,107 rooms at UMCF. The variation of heat stress detected between sensors located in the same building demonstrates evidently that measurements made in one room cannot speak for all rooms located in the same building. Furthermore, the 60 sensors were not equally distributed between exposures, floors and building ages, leading to different sample sizes when comparing heat stress according to factors. Within the rooms, the individual placement of the sensor may also have influenced the results. Although placement aimed to avoid proximity to any anthropogenic heat sources, it cannot be ruled out that such punctual heat sources distorted the measurements. In addition, rooms with AC were marked in the analysis, but cool air could affect nearby areas without direct AC. The sensors have some limitations, occasional technical failure and, at times, the undesired behaviour of people on site unplugging the devices resulted in data gaps.

A further limitation lies in the choice of a suitable index for heat stress assessment. This study used both T_i and PET in the analysis of the indoor conditions. However, for outdoor conditions at the UMCF only T_a was available, and outdoor PET



needed to be averaged from measurements taken at different locations in Freiburg. Limitations of the PET calculation, such as a standard person used, should be considered as well. These standard values facilitate comparison with other studies, though adapting the calculation to the more physically active staff or to elderly patients by using modified PET (mPET) could improve the findings in the hospital context (Chen et al., 2020).

Further thermal comfort calculations should be adjusted to elderly patients and physically active staff to highlight differences in the thermal perception of different user groups. For the sake of embedding the measurements more in the context of everyday hospital operations, it could be insightful to gather information on ventilation and window-opening behaviour.

5. Conclusions

This study is the first comprehensive study sampling and modelling the distribution, frequency and intensity of heat by means of indoor T_i and thermo-physiological stress levels across an entire hospital complex in Germany. The results clearly demonstrate that the operation of critical medical infrastructure in Germany is severely affected by hot summer conditions, causing widespread and in some cases considerable indoor heat stress. Slight heat stress occurred throughout all of the 60 rooms in 11 departments studied from May 15 – September 30, 2023, with 49 rooms showing additional occurrence of moderate and 17 rooms strong heat stress. Frequency and intensity of heat stress varied between the 60 rooms located in buildings of different age, on different floors, and with different solar exposure. Spatial heat hotspots were expectedly rooms without AC, rooms located on higher floors and with limited ventilation possibilities, rooms without windows, and rooms predominantly in buildings constructed between 1950 and 1990. Heat was not only a daytime, but in particular also a nocturnal problem during three heat waves in summer 2023, when outdoor air temperatures did not cool sufficiently to provide relief or possibility for indoor cooling. Climate modelling based on a data-driven approach shows that the frequency and intensity of indoor heat stress will further increase in the near and far future. All levels of heat stress are modelled to become more frequent and intense in the near and far future if adaptation measures are not taken. Moderate heat stress or higher will increase on average by an additional 24 hours in 2020-2049 relative to 1990-2019 and by over 500 hours in 2070-2099.

The high frequency and, at times, large intensity of heat in UMCF calls for action, particularly in the light of the high vulnerability of hospital patients and burdening working conditions for hospital staff. While outdoor temperatures will continue to rise, and heatwaves will become more frequent, longer and more intense in the future, effective and widespread measures for prevention and relief are needed. The feasibility of implementation will depend on the availability of resources, with a combination of short- and long-term approaches to be seen as best for limiting future heat stress and its consequences on patient wellbeing and the provision of critical infrastructure services. The incorporation of hospitals in municipal heat health action plans in Germany is crucial for future management of summertime heat in these key institutions of the healthcare sector.



Appendix A

Table A1: Metadata of the rooms in which sensors were placed. * indicates sensors placed in rooms with air conditioning, † indicates sensors excluded from analysis due to limited data availability.

Sensor ID	Exposure	Floor	Year of construction	Use	Patient use	Staff use	Student use	Wind sensor
AIT-1*	NE	1	1990-2010	doctor room	-	yes	-	-
AIT-2*	SE	1	1990-2010	doctor room	-	yes	-	-
AIT-3*	SW	1	1990-2010	patient room	yes	-	-	-
AIT-4	SW	1	1990-2010	waiting room	yes	yes	yes	-
AIT-5*	-	1	1990-2010	break hall	-	yes	-	-
AMB-1	NE	1	1970-1990	office	-	yes	-	-
AMB-2	NE, SE, SW	1	1970-1990	break hall	-	yes	yes	-
AMB-3	NE, SE, SW, ceiling	1	1970-1990	lecture hall	-	-	yes	-
AMB-4	SE	1	1970-1990	lecture hall	-	-	yes	-
GYN-1	NE	2	1930-1950	office	-	yes	-	-
GYN-2	SW	2	1930-1950	patient room	yes	-	-	-
GYN-3	SW	4	1930-1950	office, staff room	-	yes	-	-
GYN-5†	NE	4	1930-1950	staff room	-	yes	-	-
HNO-1	SE	6	1950-1970	office	-	yes	-	-
HNO-2	NW	6	1950-1970	patient room	yes	-	-	-
HNO-3	NW	6	1950-1970	patient room	yes	-	-	-
HNO-4	NW	6	1950-1970	office	-	yes	-	-
HNO-5	-	6	1950-1970	office	-	yes	-	-
INM-1	NE	0	1930-1950	office	-	yes	-	-
INM-2	NW	0	1930-1950	doctor room	-	yes	-	-
INM-3	NE	2	1930-1950	office	-	yes	-	-
INM-4	SE	2	1930-1950	patient room	yes	-	-	-
INM-5	SW	3	1930-1950	patient room	yes	-	-	-
INM-6	NW	3	1930-1950	office	-	yes	-	-
INM-7	SE	4	1930-1950	office	-	yes	-	-



Sensor ID	Exposure	Floor	Year of construction	Use	Patient use	Staff use	Student use	Wind sensor
ITS-1	SE, SW	1	unknown	office	-	yes	-	yes
ITZ-1*	NE	0	2010 or newer	treatment room	yes	yes	-	-
ITZ-2*	SW	0	2010 or newer	treatment room	yes	yes	-	-
ITZ-3	W, ceiling	0	2010 or newer	office	-	yes	-	-
ITZ-4	-	0	2010 or newer	office	-	yes	-	yes
PHA-1*	NE	0	1930-1950	laboratory, storage	-	yes	-	-
PHA-2	SE	0	1930-1950	office	-	yes	-	-
PHA-3*	NW, SE	0	1930-1950	laboratory, storage	-	yes	-	-
SUR-1	NE	0	1930-1950	office	-	yes	-	-
SUR-2	NE, SW	0	1930-1950	office	-	yes	-	-
SUR-3	SW	0	1930-1950	office	-	yes	-	-
SUR-4	SW	0	1930-1950	patient room	yes	-	-	-
SUR-5	SW	0	1930-1950	patient room	yes	-	-	-
SUR-6	NE	2	1930-1950	office	-	yes	-	-
SUR-7	NE, SW	2	1930-1950	office	-	yes	-	-
SUR-8	NE, SW, NW	2	1930-1950	office	-	yes	-	-
SUR-9	SE	2	1930-1950	patient room	yes	-	-	-
SUR-10	SW	2	1930-1950	patient room	yes	-	-	-
SUR-11	SW	2	1930-1950	patient room	yes	-	-	-
SUR-12	NE	4	1930-1950	office	-	yes	-	-
SUR-13	SE	4	1930-1950	office	-	yes	-	-
SUR-14	SW	4	1930-1950	doctor room	-	yes	-	-
ZMK-1	SE	0	1950-1970	office	-	yes	-	-
ZMK-2	-	0	1950-1970	office	-	yes	-	-
ZMK-3	NE, SW	1	1950-1970	treatment room	yes	yes	yes	-
ZMK-4	SW	1	1950-1970	doctor room	-	yes	-	-
ZMK-5	SW	1	1950-1970	office	-	yes	-	-



Sensor ID	Exposure	Floor	Year of construction	Use	Patient use	Staff use	Student use	Wind sensor
ZMK-6†	SW	0	1950-1970	waiting room	yes	-	-	-
ZMK-7†	NW	1	1950-1970	treatment room	yes	yes	yes	-
ZTZ-1*	NE	0	2010 or newer	laboratory	-	yes	-	-
ZTZ-2*	NE	0	2010 or newer	office	-	yes	-	-
ZTZ-3*	SW	0	2010 or newer	office	-	yes	-	-
ZTZ-4	SW	0	2010 or newer	common room	-	yes	-	-
ZTZ-5*	N	1	2010 or newer	laboratory	-	yes	-	-
ZTZ-6	SW	1	2010 or newer	office	-	yes	-	-
ZTZ-7	SW	1	2010 or newer	common room	-	yes	-	-
ZTZ-8*	NE	3	2010 or newer	laboratory	-	yes	-	-
ZTZ-9	SW	3	2010 or newer	office	-	yes	-	-
ZTZ-10†	SW	3	2010 or newer	common room	-	yes	-	-
ZTZ-11*†	NE	1	2010 or newer	office	-	yes	-	-

575 Data availability

All measured indoor data shown in this study and the meta data of the corresponding rooms are available at 10.5281/zenodo.15356528.

Author contribution

Katharina Epp: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Markus**
 580 **Sulzer:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Software, Investigation, Formal
 analysis, Data curation, Conceptualization. **Daniel Steinmann:** Writing — review & editing, Investigation, Conceptualization.
Matthias Zeeman: Writing – review & editing, Software, Data curation. **Andreas Matzarakis:** Writing – review & editing,
 Supervision, Conceptualization. **Andreas Christen:** Writing – review & editing, Visualization, Supervision, Resources,
 Project administration, Funding acquisition, Conceptualization.



585 Competing interests

The authors declare that they have no conflict of interest.

Financial support

The data collection, management and analysis were funded by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 855005 "urbisphere"). The design of the low-
 590 cost sensor system was funded as part of the INTERREG V—Rhin Supérieur program "Clim'Ability Design" (8.3) by the European Union through the European Regional Development Fund (ERDF).

Acknowledgments

We would like to thank all employees working at the University Medical Centre Freiburg who helped to run the indoor measurement campaign, Olga Shevchenko and Carlotta Gertsen for collecting the metadata of the rooms equipped with
 595 MoBiMet sensors, and Marvin Plein for managing the outdoor meteorological measurements and providing data.

Nomenclature

AC	Air conditioning
A_G	Long-wave downwelling radiation (W m^{-2})
AIT	Department of Anaesthesiology and Critical Care (Klinik für Anästhesiologie und Intensivmedizin)
600 AMB	Academy for Medical Professions (Akademie für Medizinische Berufe)
ANN	Artificial neural network
ASTA	Committee for Workplaces (Ausschuss für Arbeitsstätten)
clo	Clothing insulation
DWD	German Meteorological Service (Deutscher Wetterdienst)
605 e	Vapour pressure (hPa)
G	Global radiation (W m^{-2})
GCM	Global climate model
GYN	Department of Obstetrics and Gynecology (Klinik für Frauenheilkunde)
HHWS	Heat health warning system
610 HNO	Department of Oto-Rhino-Laryngology (Klinik für Hals-, Nasen- und Ohrenheilkunde)
INM	Department of Internal Medicine (Department für Innere Medizin)
IPCC	Intergovernmental Panel on Climate Change



	ITS	Technical Operations (Rechenzentrum)
	ITZ	Interdisciplinary Tumor Center (Interdisziplinäres Tumorzentrum)
615	MAE	Mean absolute error
	MoBiMet	Mobile Biometeorological System
	mPET	Modified physiologically equivalent temperature (°C)
	p	Atmospheric pressure (hPa)
	PET	Physiologically equivalent temperature (°C)
620	PHA	Hospital Pharmacy (Apotheke des Universitätsklinikums)
	PMV	Predicted mean vote
	PT	Perceived temperature (°C)
	RCM	Regional climate model
	RCP	Representative concentration pathway
625	SUR	Surgery and Radiology (Chirurgie und Radiologie)
	T_a	Outdoor air temperature (°C)
	T_d	Dew point temperature (°C)
	T_i	Indoor air temperature (°C)
	T_{mrt}	Mean radiant temperature (°C)
630	UMCF	University Medical Centre Freiburg
	v	Wind velocity (m s^{-1})
	VDI	German Association of Engineers (Verein Deutscher Ingenieure)
	ZMK	Centre for Dental Medicine (Department für Zahn-, Mund- und Kieferheilkunde)
	ZTZ	Centre for Translational Cell Research (Zentrum für translationale Zellforschung)

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