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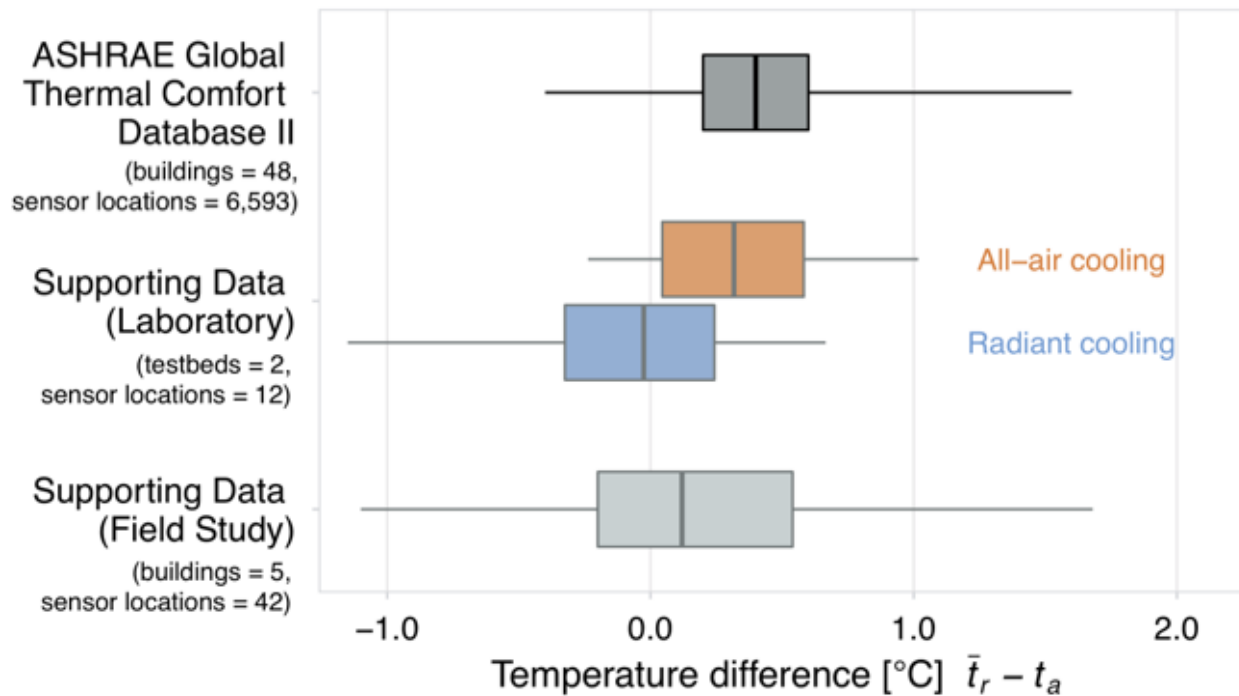**Copyright Information**

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Comparison of mean radiant and air temperatures in mechanically-conditioned commercial buildings from over 200,000 field and laboratory measurements

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ABSTRACT

We assessed the difference between mean radiant temperature ($\bar{t}_r$) and air temperature (t_a) in conditioned office buildings to provide guidance on whether practitioners should separately measure $\bar{t}_r$ or operative temperature to control heating and cooling systems. We used measurements from 48 office buildings in the ASHRAE Global Thermal Comfort Database, five field studies in radiant and all-air buildings, and five test conditions from a laboratory experiment that compared radiant and all-air cooling. The ASHRAE Global Thermal Comfort Database is the largest of these three datasets and most representative of typical thermal conditions in an office; in this dataset the median absolute difference between $\bar{t}_r$ and t_a was 0.4 °C (with 5th, 25th, 75th, and 95th percentiles = 0.2, 0.2, 0.6, and 1.6 °C). More specifically, the median difference shows that $\bar{t}_r$ was 0.4 °C warmer than t_a (with 5th, 25th, 75th, and 95th percentiles = -0.4 °C, 0.2 °C, 0.6 °C, and 1.6 °C). The laboratory experiments revealed that in a radiant cooled space $\bar{t}_r$ was significantly ($p<0.05$) cooler than t_a (average difference -0.1 °C), while in the all-air cooled space $\bar{t}_r$ was significantly ($p<0.05$) warmer than t_a (average difference +0.3 °C). These observations indicate that $\bar{t}_r$ and t_a are typically closer in radiant cooled spaces than in all-air cooled spaces. Although the differences are significant, the effect sizes are negligible to small based on Cohen's d and Spearman's rho. Therefore, we conclude that measurement of t_a is sufficient to estimate $\bar{t}_r$ under typical office conditions, and that separate measurement of $\bar{t}_r$ or operative temperature is not likely to have practical benefits to thermal comfort in most cases – this is especially true for buildings with radiant systems. Furthermore, spatial and temporal variations in t_a can be greater than or equal to the difference between $\bar{t}_r$ and t_a at any one location in a thermal zone, thus we expect that such variations typically have a greater impact on occupant thermal comfort than the differences between $\bar{t}_r$ and t_a.

GRAPHICAL ABSTRACT

ASHRAE Global Thermal Comfort Database II
(buildings = 48, sensor locations = 6,593)

Supporting Data (Laboratory)
(testbeds = 2, sensor locations = 12)

Supporting Data (Field Study)
(buildings = 5, sensor locations = 42)

All–air cooling

Radiant cooling

Temperature difference [°C] $\bar{t}_r - t_a$

Air temperature is practically equal to mean radiant temperature

KEYWORDS

Thermal comfort, mean radiant temperature, operative temperature, air temperature, HVAC, laboratory experiment, field study, radiant heating and cooling.

HIGHLIGHTS

- Assessed the difference between $\bar{t}_r$ and t_a from over 200,000 pairs of measurements

- Median absolute difference between $\bar{t}_r$ and t_a is 0.4 °C

- t_a is an appropriate estimate of $\bar{t}_r$ in mechanically-conditioned offices

- Spatial and temporal variations in air temperature can be greater than $t_a - \bar{t}_r$

- Operative temperature sensors would not likely benefit thermal comfort

1.INTRODUCTION

Under typical thermal conditions in an office, the human body releases about 58 to 60 % of sensible heat in the form of radiation [1], therefore mean radiant temperature ($\bar{t}_r$) and air temperature (t_a) have approximately equal effect on thermal comfort [1,2]. Mean radiant temperature is defined as "the temperature of a uniform, black enclosure that exchanges the same amount of heat by radiation with the occupant as the actual surroundings…" [3], and is used in thermal comfort models such as Fanger's Predicted Mean Vote (PMV), which provides the general guidance for the thermal comfort standards ASHRAE 55, ISO 7330, and EN 15251 [1,4–6]. The definition underwent an important update for ASHRAE 55-2017, which modified it from only accounting for long-wave radiation heat exchange with enclosure surfaces to also including short-wave radiation heat exchange (e.g., lights, solar). Although long-wave radiation from internal heat gains is still not captured in the definition, the modification is closer to fully capturing radiant heat gains in a space; however, the measurement protocols in ASHRAE Handbook of Fundamentals and ISO 7726 allows $\bar{t}_r$ to be calculated only from surrounding surface temperatures, omitting these other sources of radiant heat exchange [1,7].

Even though $\bar{t}_r$ has an important impact on occupant thermal comfort, most practitioners use thermostats to control heating and cooling systems. These thermostats are meant to measure t_a, but there are several factors that can influence their measurement, including location and construction of the thermostat housing. Thermostats are used to control both all-air and radiant systems – although radiant buildings sometimes use a combination of thermostat measurement and slab or loop water temperature to control the system [8,9].

The importance of $\bar{t}_r$ has been prominently underlined by researchers and practitioners focused on radiant heating and cooling systems. To improve thermal comfort and account for internal, solar, and other radiant heat gains, some researchers have recommended using operative temperature sensors to control radiant systems [2,10–13]. Operative temperature combines the effects of t_a, $\bar{t}_r$, and air velocity. The suggestion for an operative temperature sensor implies that researchers believe there is a significant and practical difference between $\bar{t}_r$ and t_a in radiant heated or cooled spaces. However, recent studies have produced mixed results on whether an operative temperature sensor would be more appropriate to achieve thermal comfort than t_a for radiant system operation [11,14]. In practice, an operative temperature sensor is not necessary for radiant buildings, since there are a growing number of buildings with radiant heating or cooling, and very few, if any, use operative temperature sensors and have shown to provide thermal conditions that are at least as satisfactory as all-air buildings [15,16].

The questions at hand are whether $\bar{t}_r$ and t_a are significantly different in typical office settings, whether the difference depends on the type of heating or cooling system (radiant or all-air), and whether the difference is large enough to warrant the use of an operative temperature sensor. Many studies using energy simulations, controlled laboratory experiments, and field studies have assessed the differences between $\bar{t}_r$ or operative temperature and t_a in thermal zones conditioned by radiant or all-air systems:

- The 2016 ASHRAE HVAC Systems and Equipment Handbook uses the metric average uncooled (unheated) surface temperature (AUST), which is similar to $\bar{t}_r$ but only accounts for surfaces that are not internally cooled or heated (i.e., not active radiant surfaces) [17]. The handbook states that in a typical commercial building, AUST is close to the indoor t_a, except in instances where the main heat gain is through the walls, or where envelopes are dominated by glazing [18]. With the increasing stringency of envelope requirements in energy codes, heat transfer through the envelope may not be prominent and more spaces may meet this criterion if they are relatively new and meet ASHRAE 90.1 prescriptive envelope requirements.

- Studies suggest that interior surface temperatures and $\bar{t}_r$ may not be close to indoor t_a in spaces with direct solar heat gains [18–22], but that solar heat gain can have a lesser effect on internal surface temperatures where a radiant cooled floor is present compared to the same conditions with an all-air cooling system [18,21,20].

- Using, energy simulations, Feng et al. [23] found that for cooling in a heavyweight zone with south-facing windows, t_a and operative temperature are closer to one another for a radiant ceiling in cooling than for an all-air system in cooling.

- Jia et al. [14] conducted laboratory experiments with radiant ceiling panels and radiant slab with internal heat gains and solar heat gains from the south. The experiment measured temperatures at various points in the testbed and found that the maximum difference between operative temperature and t_a was 0.2 °C for the ceiling panels and 0.6 °C for the radiant slab.

- A laboratory experiment by Catalina et al. [24] with radiant ceiling panels under steady state conditions found that the maximum difference between operative temperature and t_a was 0.8 °C from 96 measurement points in a 3.10 x 3.10 x 2.40 m test cell. The radiant ceiling panel temperature was varied while the surface temperatures of the remaining five surfaces was maintained at 26 °C.

- Lastly, Lin et a. [25] conducted a controlled field study in three adjacent rooms using an all-air heating system, a radiator, and radiant floor heating and found that the difference between t_a and $\bar{t}_r$ was within ±0.5 °C for all system types.

As exemplified by its very definition, $\bar{t}_r$ is a theoretical value that represents the net radiant flux between a human body and the surrounding environment. Notably, the studies referenced comprise different heat gain types, sources, and proportions, different sensor locations, sensor types and methods used to calculate $\bar{t}_r$ or operative temperature. As described in ISO 7726 [7], there are multiple methods to calculate $\bar{t}_r$. Many field studies have used a fast response grey 40 mm ping pong ball and in laboratory experiments it is common to use a black globe thermometer of 150 mm diameter. Some studies did not allow direct solar or other heat gain sources into the space; and some used multiple sensors, while others used a single sensor. Several studies have shown that factors including room geometry [2,26,27], sensor placement [2,28,24,26,27], and heat gain types result in different $\bar{t}_r$ values when all else remains constant. Differences in measurement technique, such as sensor placement, affect whether or not measurement of all

physical parameters in a space (e.g.:$\bar{t}_r$, t_a, and air velocity) will accurately represent the entire space.

Furthermore, Guo et al. [29] and Meggers et al. [30] suggest that the traditional methods of measuring and calculating $\bar{t}_r$ may not be accurate, even at low air velocities. Simone et al. [27] found that there are similar challenges for measuring operative temperature. Lastly, energy simulation engines such as EnergyPlus do not account for the direct component of radiant heat gains for $\bar{t}_r$. Instead it uses one of three calculation methods based on surrounding surface temperatures [31]; therefore, direct radiant heat gains such as solar, lights, and other internal sources that would impact an occupant are not captured.

The objectives of the study presented in this article were to (1) assess the difference between $\bar{t}_r$ and t_a across varying indoor environments(including all-air and radiant cooled spaces), (2) understand if the difference is statistically significant, and (3) understand if accounting for the difference (i.e., by using an operative temperature sensor) would likely have practical benefits to occupant thermal comfort. We achieved these objectives by assessing measured data in the ASHRAE Global Thermal Comfort Database II (Comfort Database) [32], and then by assessing finer-grained time-series data from two projects to support the findings: a controlled laboratory experiment that compared radiant and all-air cooling [33,34] and a series of field studies of radiant and all-air buildings.. To our knowledge, this study assembles the most comprehensive group of data to compare t_a and $\bar{t}_r$ measurements in typical office spaces, and provide evidence on whether operative temperature sensors likely to have practical benefits to occupant thermal comfort. This dataset comprises a wide range of measurement techniques and heat gain scenarios experienced in typical office settings, which, thereby providing high confidence that the statistical results are not bias by the measurement and study techniques highlighted above. Additionally, this study provides context to designers, building operators, and those investigating thermal comfort on how to appropriately estimate $\bar{t}_r$ in typical circumstances.

2.METHODOLOGY

The difference between $\bar{t}_r$ and t_a was calculated for three separate datasets:

- 6,593 pairs of point-in-time temperature measurements from 48 office buildings in nine Köppen climates in seven countries on five continents and all four seasons (summer and winter as the majority) from the ASHRAE Global Thermal Comfort Database II (Comfort Database) [32]

- Five test conditions from a controlled laboratory experiment conducted at Lawrence Berkeley National Laboratory's (LBNL) FLEXLAB using side-by-side radiant and all-air (but otherwise identical) testbeds in cooling mode. The experimental variables were the proportions of convective, radiant, and solar heat gains in the space [33,34]. There are 190,344 pairs of one-minute interval temperature measurements (dry bulb and globe) from six specified locations for all five test conditions in each testbed.

- Five field studies in two radiant and three all-air office buildings located in California with between four and fifteen temperature measurement locations in each building for a total of 42 measurement locations. Four of the studies collected data for two to three

weeks and one study for ten weeks. The studies were not intended to be comparisons between buildings. Studies occurred during varying times of the year and some in different years: three in summer, one in fall, and one in winter. There are 41,691 pairs of 15-minute interval temperature measurements (dry bulb and globe) from the five field studies.

We calculated both the absolute and relative differences between $\bar{t}_r$ and t_a ($\left| \Delta T \right| = \left| \bar{t}_r - t_a \right|$ and $\Delta T = \bar{t}_r - t_a$). The absolute difference describes the magnitude of the difference between $\bar{t}_r$ and t_a, regardless of which is cooler or warmer. The outside conditions and system operating mode (i.e., cooling or heating) can differ between buildings in the Comfort Database and the Field Studies; considering the absolute difference between temperatures ensures that we properly capture differences instead of canceling out positive and negative differences. The relative difference simply provides the observed differences in temperature during the analysis period, accounting for direction.

There are benefits and limitations to each of the datasets. We base our conclusions primarily on the Comfort Database and we use the laboratory and field study data as supporting evidence to further explicate the findings. The Comfort Database represents a broad range of building construction, HVAC systems and operation, and climates. The laboratory experiment is exceptionally accurate and offers a carefully controlled comparison of radiant cooling and all-air cooling, but it only represents a handful of scenarios in one climate and in one thermal zone. Similarly, the field studies represent a handful of specific scenarios and cannot be directly compared to one another. The field study dataset is a result of combining data from five independent field studies that were not collected with the intent of comparison in mind. Consequently, the number of sensors, sensor locations, system operation, study period, HVAC system and building types are not consistent between studies.

The laboratory and field study data are continuous measurements, while the Comfort Database is composed of point-in-time measurements. For the laboratory and field studies, $\bar{t}_r$ and t_a are measured at the same locations; for the Comfort Database we can confirm that measurements were taken at the same height, but cannot confirm that they were at the same location; although this is assumed based on standard practice. For each pair of $\bar{t}_r$ and t_a measurements, we calculated the temperature differences at each sensor location. The Comfort Database only includes data from occupied hours, and for the laboratory and field study data we only considered measurements for typically occupied hours (06:00 – 18:00). We only investigated system type for the controlled laboratory experiment and the field study data; although the Comfort Database indicates whether or not each building includes mechanical cooling, it does not provide information about mechanical system type.

2.1. Measurements and Calculations

For the laboratory experiment and field studies, the t_a was measured using a fast response thermistor that is protected from radiant heat by thin radiant shield. Operative temperature was measured using a small globe sensor, which has the same thermistor placed at the center of a 40 mm ping pong ball painted grey with 95% emissivity. Studies have shown this is an accurate

approach to measure operative temperature with a fast response time [27,35,36]. We used a bi-directional anemometer to measure air velocity in the field studies and an omni-directional anemometer in the laboratory experiment. Instruments were slightly different in the laboratory experiment and field studies, and we provide the types and uncertainty details in Section 2.2 Laboratory Experiment and Section 2.3 Field Studies.

Using t_a, globe temperature (t_g), and air velocity (v) measurements, $\bar{t}_r$ can be calculated. As described by Humphreys [35] and Fanger [4], operative temperature (t_o) can be calculated as the simple mean of t_a and $\bar{t}_r$, Equation 1 [1], when v is below 0.2 m/s, as also specified in ISO 7726 [7]. When t_g is measured with a globe sensor of diameter 40 mm and 95% emissivity, t_g is representative of t_o.

$$t_o = \frac{(t_a + \bar{t}_r)}{2}, \#(1)$$

where t_o is measured with the 40 mm globe sensor. This can be rewritten to solve for $\bar{t}_r$ in Equation 2:

$$\bar{t}_r = (2 \times t_o) - t_a \#(2)$$

When v is greater than 0.2 m/s, convection at the globe surface increases, and $\bar{t}_r$ is calculated using Equation 3 [37].

$$\bar{t}_r = \left[(t_g + 273)^4 + \frac{1.1 \times 10^8 \times D^{-0.4} \times v^{0.6}}{\varepsilon} \left(t_g - t_a \right) \right]^{0.25} - 273, \#(3)$$

where t_g is the globe temperature measurement of any size globe, D is the globe diameter (m), v is the air velocity (m/s), and ε is the globe emissivity.

For the Comfort Database, we eliminated entries where air velocity is greater than 0.2 m/s and used Equation 2 because the database does not provide enough information about the globe sensors. This eliminated 10% of the complete air-conditioned office building entries, the large majority of which were in Australia and India where fans may be in use. Air velocity measurements were taken in three of the field studies (one radiant building and two all-air buildings), and of those, only 3% of measurements were greater than 0.2 m/s. We used Equation 3 in those instances. We expect that the majority of air velocities would be low in the remaining two buildings and so we used Equation 2 to calculate $\bar{t}_r$ when air velocity was unknown. In the laboratory experiment, air velocity was measured once for each test condition, but not recorded continuously. Air velocity was below 0.2 m/s for all test conditions; therefore, Equation 2 was used to calculate $\bar{t}_r$.

2.2. Laboratory Experiment

We used data from a controlled experiment that Woolley et al. [33,34] conducted in a pair of side-by-side testbeds at Lawrence Berkeley National Laboratory FLEXLAB [38]. The experimental facility and system operation are described in [33]. A summary of the key parameters relevant for this analysis is provided below. The testbeds are equivalent in all aspects except for the cooling system type: one with radiant cooling using internally cooled metal ceiling

panels (Twa model MOD-RP1), and the other with air cooling through overhead diffusers. Although the experiment used low mass metal ceiling panels, they covered 72% of the ceiling area, and we expect that the $\bar{t}_r$ and t_a produced in these experiments is very similar to what would be produced on average by a radiant system with somewhat different percent surface area coverage, such as 100% with a higher thermal mass slab. Although the overall heat transfer dynamics are different between a low mass and high mass radiant system, the surface temperatures required to maintain an operative temperature setpoint would be the same given all other conditions are the same.

For each of the five test conditions, they operated the two testbeds simultaneously, imposed equivalent internal gains, and controlled each system to maintain equivalent operative temperatures at 26 °C during all periods that required cooling. Each test condition had the same total amount of heat gain, with different proportions of convective, radiant, and solar heat gains. For this study, we only used typical hours of occupancy (06:00 to 18:00) to depict the temperatures occupants would experience in the space.

The experimenters recorded air and operative temperature measurements at six locations on measurement trees along the centerline of each testbed. The sensors were located at 0.6 m and 1.1 m in height at horizontal distances of 3.45 m, 5.3 m, and 7.16 m from the south wall, which has 33% window-to-wall ratio. The sensors captured continuous temperature measurements and recorded one-minute averages. Table 1 in Woolley et al. [33] provides the sensor types and measurement uncertainty. Using these uncertainties, Table 1 provides the uncertainty of calculated metrics

Calculated Metric	Uncertainty (Equation 2)
Mean radiant temperature ($\bar{t}_r$)	± 0.04 °C
Temperature difference ($\bar{t}_r - t_a$)	± 0.05 °C

Table 1. Uncertainty of measurements and calculated metrics for laboratory experiments

2.3. Field Studies

The field study data comes from studies that the Center for the Built Environment conducted between 2011 and 2013. We collected indoor environmental measurements for two- to ten- week periods in five office buildings located in California: two with radiant heating and cooling and three with all-air heating and cooling. Table 2 provides a summary of the field studies. Studies occurred in different California climate zones and during various seasons, meaning some of our data may be from buildings in heating mode, while other are from buildings in cooling. Measurement periods may not be fully representative of the full range of temperatures experienced in each space over the course of all seasons.

Building ID	System Type	Measurement Period	Season	No. of sensor locations

b1 [39]	Radiant heating and cooling	26 May – 13 Jun 2011 (19 days)	Spring/Summer	4
b2 [40]	Radiant heating and cooling	18 Jan – 01 Apr 2014 (74 days)	Winter/Spring	2
b3	All-air heating and cooling	31 Aug – 20 Sep 2012 (21 days)	Summer	9
b4	All-air heating and cooling	06 Nov – 25 Nov 2012 (20 days)	Fall	15
b5	All-air heating and cooling	06 Jun – 19 Jun 2013 (14 days)	Summer	12

Table 2. Field study site summary

The field study teams acquired measurements using indoor climate monitors, shown in Figure 1, which included a dry bulb temperature sensor (t_a) and a globe sensor (operative temperature) – among other instruments; bi-directional anemometers were included in three of the studies. Heinzerling et al. [41] provide measurement instruments and uncertainties, and Table 3 provides the uncertainties of calculated metrics. Although equipment was calibrated prior to deployment, the sensors were not installed in fixed positions, and so we cannot be certain that they were not moved by occupants or influenced by other factors. We cannot quantify this uncertainty.

Calculated Metric	Uncertainty (Equation 2)	Uncertainty (Equation 3)
Mean radiant temperature ($\bar{t}_r$)	± 0.13 °C	± 0.09 °C
Temperature difference ($\bar{t}_r - t_a$)	± 0.14 °C	± 0.11 °C

Table 3. Uncertainty of measurements and calculated metrics for field studies

We placed these indoor climate monitors in occupied spaces at seated or standing height, typically on top of desks or tables in workstations or common areas (e.g., conference rooms). Some indoor climate monitors may have been at locations that received intermittent direct solar radiation. A data acquisition system in each climate monitor measures each sensor continuously and records one-minute average values. For this study, we only used typical hours of occupancy (06:00 to 18:00) to depict the temperatures occupants would experience in the space, and used fifteen-minute average measured values.
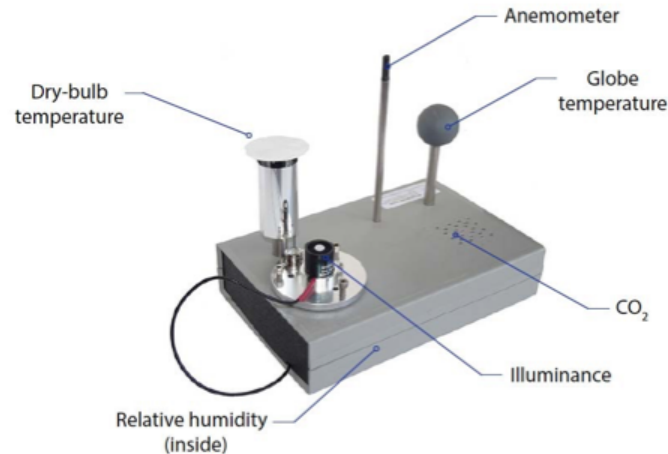
Figure 1: Indoor climate monitors may include some or all of the pictured sensors, and at minimum, have dry bulb and globe thermometers. Dry bulb sensors are shielded from radiation with a thin mylar sheet. None of the monitors included CO₂ sensors.

2.4. ASHRAE Global Thermal Comfort Database II

The open-source database includes approximately 107,000 sets of physical measurements of indoor thermal environments, with accompanying "right-here-right-now" subjective evaluations of thermal comfort and preference from building occupants.

We filtered the data for office buildings with mechanical cooling, including mixed-mode (i.e.: uses both passive and mechanical cooling) when air conditioning was active; all buildings also have mechanical heating. We eliminated duplicate entries where a single set of indoor environmental measurements were applied to a group of occupant responses. Lastly, we eliminated entries where t_a and operative temperature were the same as a precaution against potential reporting errors where t_a measurements were used for operative temperature; this slightly increases the magnitude of our findings about the absolute difference between $\bar{t}_r$ and t_a. The final dataset has 6,593 entries from at least 48 office buildings in nine Köppen climates in seven countries on five continents, and all four seasons (53% in summer, 24% in winter, 23% spring/fall).

Additional characteristics about the buildings, such as HVAC system type, size, year of construction or renovation, and envelope features are not known; however, we expect that nearly all of the office buildings in the dataset use all-air systems for heating and cooling. The database does not include information about measurement methods, sensor types, calibration, and measurement uncertainty; there is additional uncertainty in these measurements due to potential methodological differences between studies. We cannot quantify this uncertainty.

2.5. Data Analysis

We analyzed the data using R version 3.5.0 software [42].

For the laboratory tests, we performed statistical analysis of the difference between t_a and $\bar{t}_r$ in each testbed. The number of data points was larger than recommended to carry out a Shapiro-

Wilk test for normality; instead we used a Q-Q plot. We determined that the data is not normally distributed (which is not surprising because the test conditions maintained operative temperature), and so we used a Wilcoxon Rank Sum and Signed Rank Tests to compare $\bar{t}_r$ and t_a in the radiant and all-air testbeds.

For the Comfort Database, we reviewed the distribution of data using various methods to ensure it was a representative sample and that factors such as study author, season, country and climate did not mask important trends. This was done to ensure that a few studies or prolific researchers with a large portion of the measurements did not skew the analysis. We performed a 10-fold cross-validation ten times (i.e., 100 samples) after randomizing the data order, and reviewed the distribution of our metric of interest: $\Delta T = \bar{t}_r - t_a$. Second, we looked at the ΔT distribution (i.e., median, interquartile range, and mean) for each study. The results suggest that there is some variance between studies, but that the mean and median ΔT is consistent across groups. Lastly, we evaluated ΔT versus the monthly outside air temperature, which was available for 20% of the dataset and ranged from -5 °C to 33 °C. The results of each test did not identify any clear trend or indication that the data was skewed by particular studies, study author, season, or outside air temperature. See the Appendix Figure A-1, Figure A-2, and Figure A-3 for detailed results.

For all figures and descriptions of the analysis, the data distributions are shown with box-and-whisker plots (the thick horizontal line is the median, the whiskers are out to the 5th and 95th percentiles). Graphs were prepared using "GGplot2" [43]. We report numeric summary as the median value with the 5th, 25th, 75th, and 95th percentiles in parentheses (e.g. 0.4 °C (0.2, 0.2, 0.8, and 2.2 °C)).

3. RESULTS AND DISCUSSION

3.1. Difference between mean radiant and air temperatures

Figure 2 presents results for the absolute temperature difference ($\left| \Delta T \right| = \left| \bar{t}_r - t_a \right|$). The median absolute value for the Comfort Database was 0.4 °C (0.2, 0.2, 0.6, and 1.6 °C). The Comfort Database is the most diverse data source, and therefore most representative of distribution of typical thermal conditions in office buildings. The median value for the field study data was 0.4 °C (0.0, 0.2, 0.8, and 1.8 °C), the median value for the laboratory testbed with all-air cooling was 0.3 °C (0.0, 0.2, 0.6, and 1.0 °C), the median value for the laboratory testbed with radiant cooling was 0.3 °C (0.0, 0.1, 0.6, and 1.2 °C). Considering all datasets, $\bar{t}_r$ is generally within 0.4 °C of t_a measurements regardless of building type, system type or system operation. The 75th percentile values of each dataset are less than 1.0 °C. The 95th percentile values in the Comfort Database and the Field Study are larger than the Laboratory study. Although we cannot definitively conclude the cause of this larger distribution, it could be the result of sensor exposure to direct sunlight or instrumentation calibration errors. . It is also crucial to note that the absolute temperature differences are very close to the calculated measurement uncertainty for the field study data.
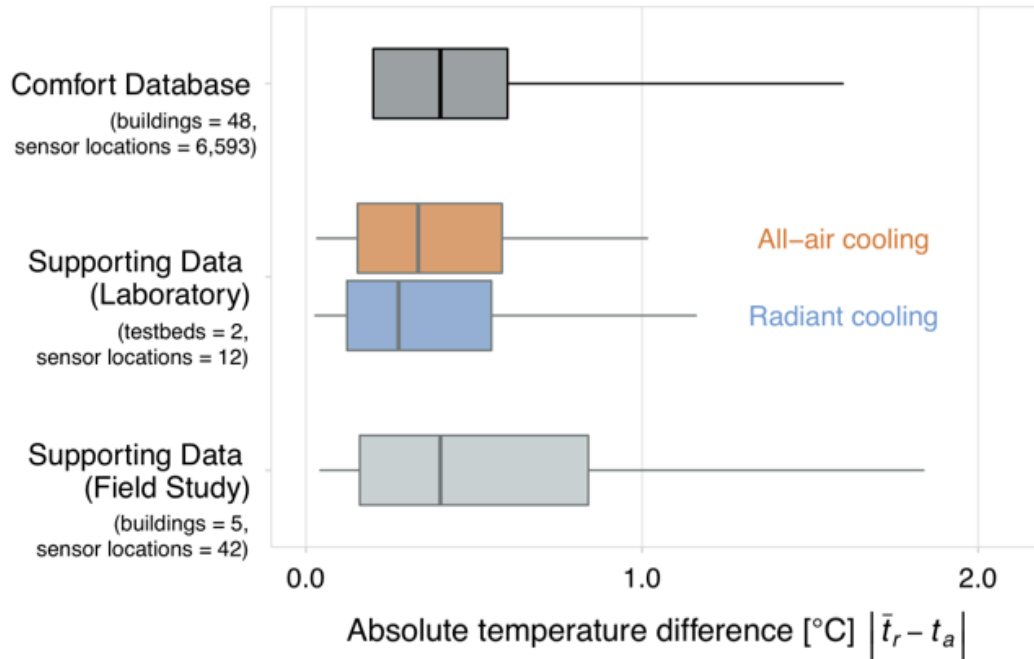
Figure 2: Absolute temperature difference ($|\Delta T| = |\bar{t}_r - t_a|$) for all datasets. The box represents the interquartile range (i.e., 25th to 75th percentiles) and the whiskers represent the 5th and 95th percentiles. The field study and laboratory data consist of continuous measurements at each of the sensor locations, which are at 15-minute intervals for the field studies and one-minute intervals for the laboratory. The field study and laboratory data support the Comfort Database results.

Figure 3 provides the relative temperature difference ($\Delta T = \bar{t}_r - t_a$), which shows that $\bar{t}_r$ was typically slightly warmer than t_a for all datasets except the radiant testbed in the laboratory experiment. The Comfort Database median value was 0.4 °C (-0.4 °C, 0.2 °C, 0.6 °C, and 1.6 °C), the field study data median value was 0.1 °C (-1.1 °C, -0.2 °C, 0.5 °C, and 1.7 °C), the laboratory all-air testbed median value was 0.3 °C (-0.2 °C, 0.0 °C, 0.6 °C, and 1.0 °C), and the laboratory radiant testbed median value was 0.0 (-1.1 °C, -0.3 °C, 0.2 °C, and 0.7 °C). These values are very close to the calculated measurement uncertainty for the field study data.

Each dataset shows some instances where $\bar{t}_r$ was cooler than t_a, which is expected for radiant buildings in cooling, but can also occur due to exterior heat loss and cooler surfaces during cold weather in either an all-air or radiant building. Considering all datasets, the median values indicate that $\bar{t}_r$ is generally close to t_a across different buildings, seasons, and system operations; the range between the 5th and 95th percentiles in the Comfort Database is 2.0 °C: -0.4 °C to 1.6 °C, meaning that only 10% of the 6,593 entries in the dataset have instances where $\bar{t}_r$ and t_a are farther apart than these values.

For the laboratory experiments, we performed a statistical comparison of $\bar{t}_r$ and t_a for each testbed under all test conditions using a two-sided Wilcoxon test. For both testbeds, we found that the mean $\bar{t}_r$ is statistically different ($p<0.05$) than the mean t_a. However, the effect size (using Pearson's rho and Cohen's d) for the radiant testbed is negligible ($\rho = 0.1$, d=0.1) and the effect size for the all-air testbed is negligible to small ($\rho = 0.3$, d=0.3). We used effect size interpretations suggested from Cohen [44] and Ferguson [45]. The difference in mean values

(mean $\bar{t}_r$ – mean t_a) for the all-air and radiant testbeds from the Wilcoxon tests were 0.3 °C and -0.1 °C, respectively. The effect sizes indicate that there is negligible to small practical importance to the difference in temperature values.
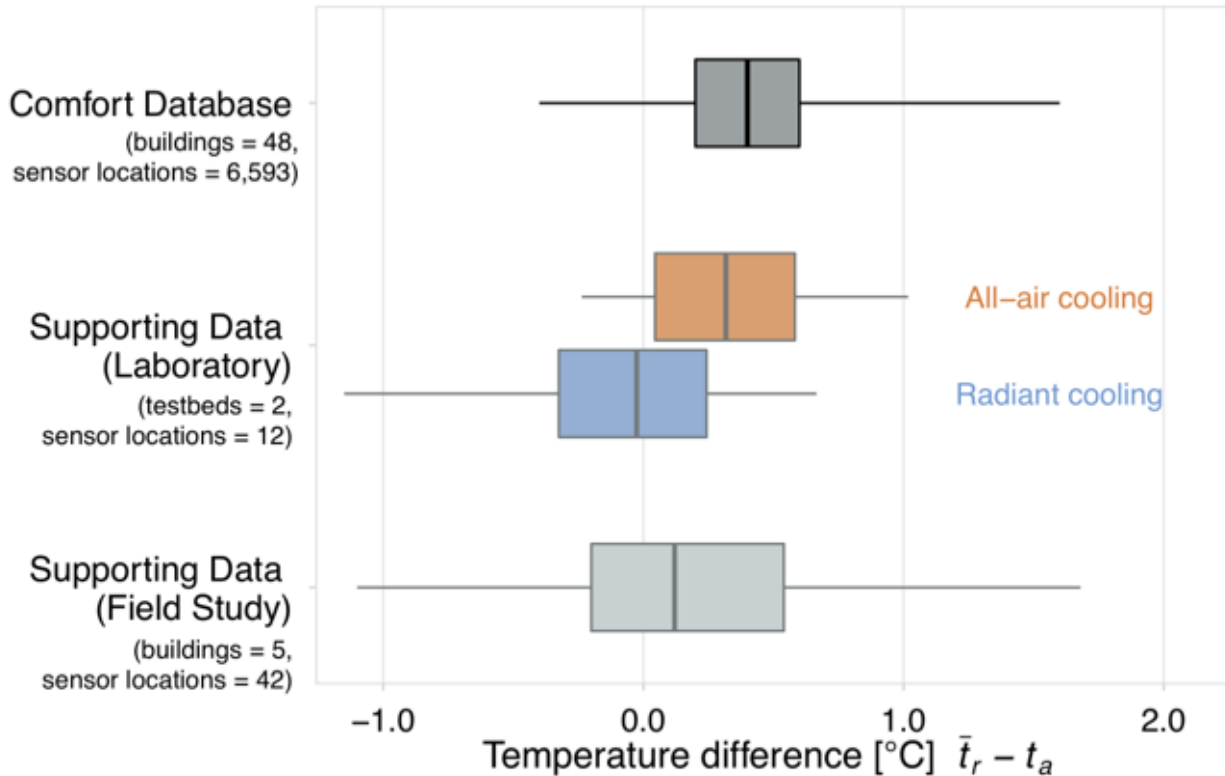

Figure 3: Relative temperature difference ($\Delta T = \bar{t}_r - t_a$) for all datasets. The box represents the interquartile range (i.e., 25th to 75th percentiles) and the whiskers represent the 5th and 95th percentiles. The field study and laboratory data consist of continuous measurements at each of the sensor locations, which are at 15-minute intervals for the field studies and one-minute intervals for the laboratory. The field study and laboratory data support the Comfort Database results.

In the laboratory experiment with radiant cooling, there were instances when $\bar{t}_r$ was warmer than t_a . Through closer examination, we identified that this occurred when radiant heat gains dominated the heat gain mix, which directly affected the $\bar{t}_r$ and resulted in $\bar{t}_r$ warmer than t_a. However, as Woolley et al. [33] show, the interior surface temperatures in the radiant testbed were always cooler than those in the all-air testbed, and cooler than the operative temperature setpoint, even when $\bar{t}_r$ was warmer than t_a. This highlights an important error produced by calculating $\bar{t}_r$ from surface temperatures, which does not capture direct radiant heat gains to occupants, such as any heat sources that have a radiant component.

The distribution of relative temperature differences from the field study data has an interquartile range centered around zero (meaning in some instances $\bar{t}_r$ is lower than t_a) because data includes different system types (i.e., radiant and all-air) operating in different seasons (and therefore heating or cooling) and collected at different sensor locations (i.e., interior and perimeter). The

Comfort Database also includes different seasons but does not result in temperature difference distribution crossing zero. Additionally, we did not establish a strong trend between $\bar{t}_r$ and t_a compared to outside air temperature from the Comfort Database (see Appendix Figure A-3); therefore, we conclude that the system type and sensor location (particularly at the perimeter) primarily affect this observation for the field study. We assessed the field study data in aggregate, as shown in Figure 3, because there were too many uncontrolled variables between studies to make direct comparisons feasible. We considered the difference between $\bar{t}_r$ and t_a at each sensor location in the field studies to understand the variability when assessed over time. The results show that $\bar{t}_r$ and t_a are practically equivalent in the majority of locations and instances. See the Appendix Figure B-1 for results of this analysis. A feature of the field study data is that it includes continuous measurements. We provide examples of the evolution of $\bar{t}_r$ and t_a at select field study sensor locations in the Appendix Figure B-2, which also explains some of the challenges with using field study data, such as when sensors experience periodic direct solar radiation

3.2. Spatial and temporal variation of air temperature

To better understand whether or not the difference between $\bar{t}_r$ and t_a has practical implications to occupant thermal comfort, we compared the results to spatial and temporal variations in t_a. . ASHRAE Standard 55 allows for some variation in t_a. For example, t_a from the ankle to the head region can vary by 3.0 °C at any given time for a seated occupant and the operative temperature can drift by as much as 3.3 °C over the course of 4 hours, if it does not change by more than 1.1 °C within 15 min [3]. These allowances are larger than the differences we found between $\bar{t}_r$ and t_a. We investigated the field study and laboratory continuous measurement data further to determine if any of the difference was due to t_a variation. We used the field study data to assess temporal changes during typical hours of operation, and the laboratory data to assess spatial variations because the field studies provide the most realistic example of what would occur in an office setting, but we do not have enough sensor locations to assess spatial variation within a zone.

The results of the field study temporal variation assessment, which are further explained in the Appendix Figure C-1, show that the median daily range of air temperature (maximum t_a – minimum t_a for each day) recorded at each sensor location during typical hours of occupancy ranged from 0.8 °C to 3.2 °C for sensors located in interior zones. It is important to note that at least one of these field studies was testing demand response control algorithms that involved relatively large changes in indoor air temperatures. We only looked at interior zones to avoid influence from direct solar radiation. Furthermore, the results of spatial variation in air temperature analyzed using the laboratory data show that the median difference in t_a between any two sensor locations at the same height and at the same time ranged from a minimum of 0.1 °C to a maximum of 0.4 °C in the all-air testbed and a minimum 0.1 °C to a maximum of 0.3 °C in the radiant testbed, similar to the difference found between $\bar{t}_r$ and t_a. The laboratory tests represent a single zone that is carefully controlled, and we would expect larger spatial variation in real circumstances. Further details can be found in the Appendix Figure C-2. These results support findings from Kim et al. [46] that show within the same thermal zone of an all-air office

building controlled to maintain air temperature between 22 to 25 °C, temperatures at occupant workstations varied from the zone mean by more than 0.2 °C 50% of the time, and by more than ± 0.4 °C 25% of the time. Kim et al. [46] also found that within the building (not necessarily the same zone), temperatures at occupant workstations varied by 1.1 °C or more 50% of the time, and that temperature at individual workstations varied by 0.5 °C from the zonal thermostat readings.

The difference between $\bar{t}_r$ and t_a is smaller than that of temporal variation of t_a at a single location and is similar to the spatial variation of t_a within a zone. The t_a temporal and spatial analyses show that there are variations in t_a within a typical office thermal zone which can have implications to occupant thermal comfort. This also shows that the difference between $\bar{t}_r$ and t_a is not just caused by changes in $\bar{t}_r$. It appears from the data that the non-uniformity of thermal comfort conditions within the same thermal zone – both spatial and temporal – will have a larger impact on thermal comfort than the assumption that $\bar{t}_r$ and t_a are the same in most cases.

4.RECOMMENDATIONS

This analysis strongly implies that under typical conditions in office buildings for both radiant and all-air buildings, t_a is a close approximation for $\bar{t}_r$, and more specifically, $\bar{t}_r = t_a + 0.4\ °C$ based on the Comfort Database, which includes a variety of building structures, climates, seasons, and system operations. The literature has suggested using operative temperature sensors to control radiant system operation and improve occupant thermal comfort. This analysis proves that separately measuring $\bar{t}_r$ or operative temperature would not provide practical benefit to occupant thermal comfort for most cases in typical office scenarios. Although not specifically analyzed, there are likely exceptional scenarios where one could reasonably expect larger and more practically impactful differences between t_a and $\bar{t}_r$. Such exceptional scenarios could include: design day conditions, locations close to surfaces with unusually high or low temperature (e.g., next to a window on a cold day), scenarios with very high heating or cooling loads, and locations with direct solar heat gains as identified in ASHRAE Standard 55 – 2017 and SolarCal in the CBE Thermal Comfort Tool [3]. We did not analyze any of these particular scenarios and cannot conclude whether or not that the field measurements from the Comfort Database or the Field Studies captured design day conditions. Contrary to the suggestion of many previous researchers, the laboratory comparison of radiant cooling and all-air cooling shows that if operative temperature sensors were used to control mechanical systems, they would benefit thermal comfort in spaces with all-air cooling more than spaces with radiant cooling. Moreover, t_a variations within a thermal zone suggest that properly placed thermostats relative to occupant locations could be more impactful to thermal comfort than measuring $\bar{t}_r$ or operative temperature.

For thermal comfort investigations, it is appropriate to estimate $\bar{t}_r$ from t_a measurements for both all-air and radiant heated and cooled buildings for typical office conditions if more detailed data is not available. However, detailed data should be used to assess thermal comfort under the exceptional scenarios mentioned, such as for locations next to a window. The median difference between $\bar{t}_r$ and t_a revealed by this study (0.4 °C) translates to a small difference in PMV. For

example, in summer clothing (0.5 clo), metabolic rate 1.1, and low air velocity (0.15 m/s), a difference of 0.4 °C between $\bar{t}_r$ and t_a results in a PMV difference of 0.04 when t_a is 23.0 °C and 0.06 when t_a is 21.0 °C.

5.CONCLUSION

We calculated the difference between $\bar{t}_r$ and t_a from three data sources, resulting in a substantially sized dataset of temperature measurements across different climates, building types, system types, system operations, and measurement methods. Considering only the Comfort Database, which is the largest and most representative dataset, the results show that under typical thermal conditions in mechanically-conditioned office buildings, $\bar{t}_r$ is 0.4 °C (with interquartile range = 0.4 °C) warmer than t_a. Considering system type (i.e., radiant and all-air), there was a significant ($p<0.05$) difference between $\bar{t}_r$ and t_a for both the radiant and all-air laboratory testbeds operating in cooling, but with negligible effect size in the radiant testbed and a negligible to small effect size in the all-air testbed; meaning there is not practical implication of the differences in mean values. Therefore, there would be no clear benefit from measuring operative temperature or $\bar{t}_r$ to control heating and cooling systems to improve thermal comfort, especially not for radiant systems, for which the difference between $\bar{t}_r$ and t_a is negligible. It may be more important for thermal comfort to consider the appropriate placement of thermostats than to measure $\bar{t}_r$ or operative temperature because the spatial and temporal variations of t_a in a thermal zone could have a greater impact on occupant thermal comfort than the small differences between $\bar{t}_r$ and t_a.

6.ACKNOWLEDGMENTS

7.DECALARATION OF INTERESTS

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Appendix

A. Analysis of Comfort Database

To ensure that the results from the Comfort Database were not skewed by any particularly large studies, we randomly shuffled the data entries and performed a 10-fold cross validation for ten times, resulting in 100 random sample groups consisting each of 10% of the data. For each sample group, we calculated the mean, median, 25th percentile, and 75th percentile of the difference between $\bar{t}_r$ and t_a. As seen in Figure A1, the median, 25th percentile, and 75th percentile are consistent for most of the sample groups and the mean is within 0.2 °C. This is showing that the 0.4 °C difference is robust and not affected by a specific study.
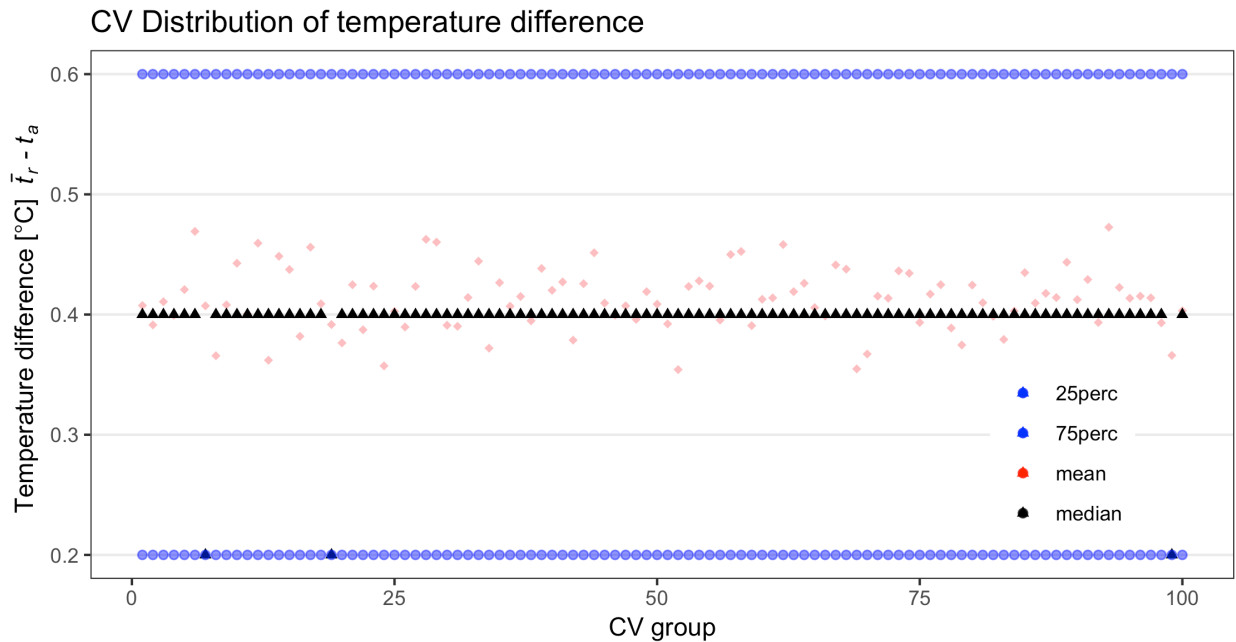
Figure A1. Cross-validation results for 100

Figure A2 shows the distribution of temperature difference between $\bar{t}_r$ and t_a for each of the Comfort Database studies and identifies each study by the season the study was conducted. The seasons are based on the month of the study, while the actual outside air temperature for each of the studies will have varied based on actual location. The figure shows that although there is some variation between studies, most studies support the conclusion that t_a is a close approximation for $\bar{t}_r$.
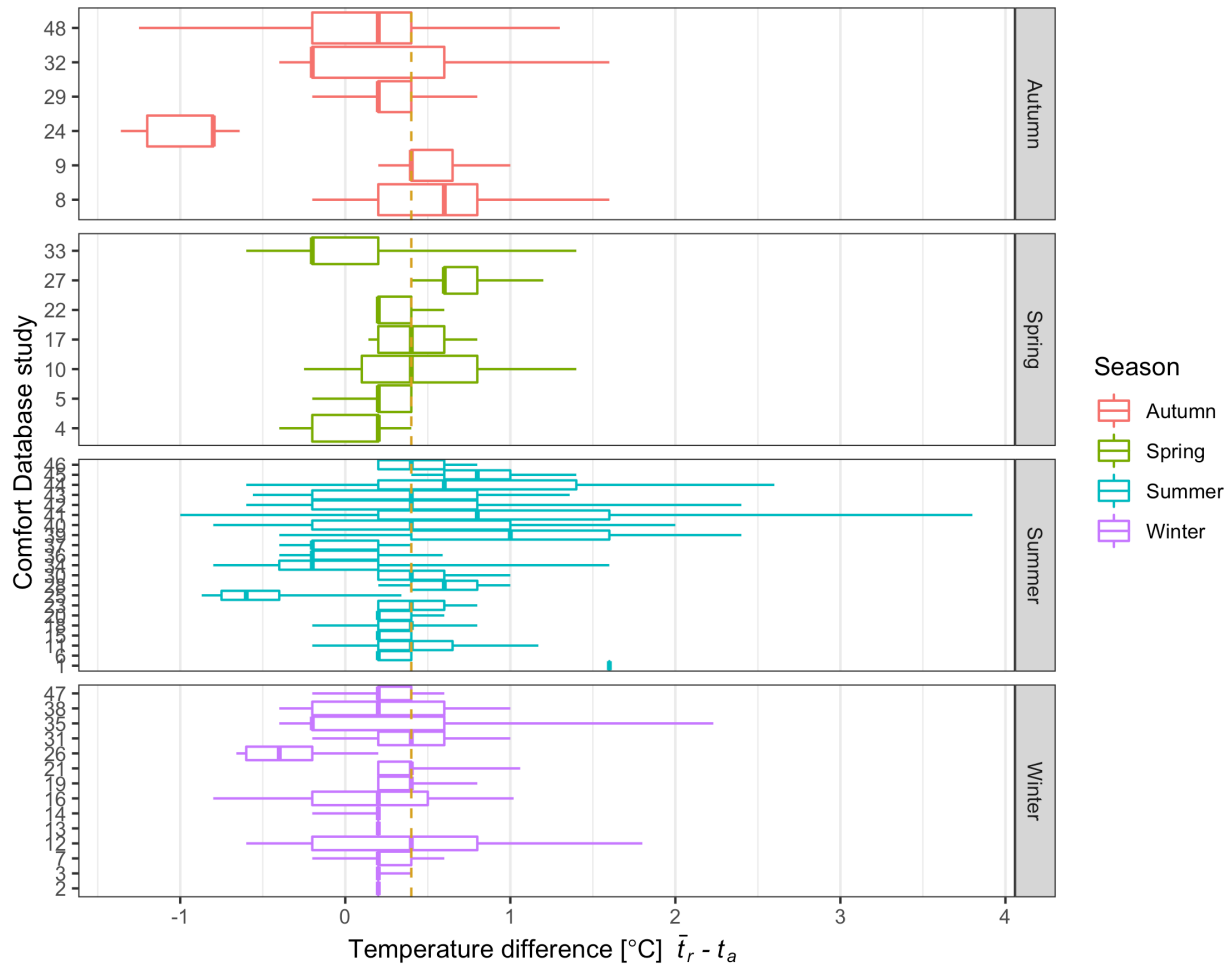
Figure A2. Distribution of temperature difference between $\bar{t}_r$ and t_a by Comfort Database field study, identified by season of study. The dashed red line is at 0.4 °C, which is the median value calculated for the entire database. As seen, there is some variation by study, but most studies support the calculated value of 0.4 °C.

Lastly, to test against possible bias due to the majority (53%) of the Comfort Database measurements being from summer periods, we looked at the difference between $\bar{t}_r$ and t_a versus the average monthly outdoor air temperature in the study period, shown in Figure A3. This value was available in the Comfort Database for 20% of the data entries and ranges from -5 °C to 33 °C. Real time outdoor weather data was not available. Figure A3 shows that there is not a clear and relevant trend between monthly average outdoor temperature and the difference between $\bar{t}_r$ and t_a, even at the more extreme weather conditions observed, which is further supported by the local regression line.
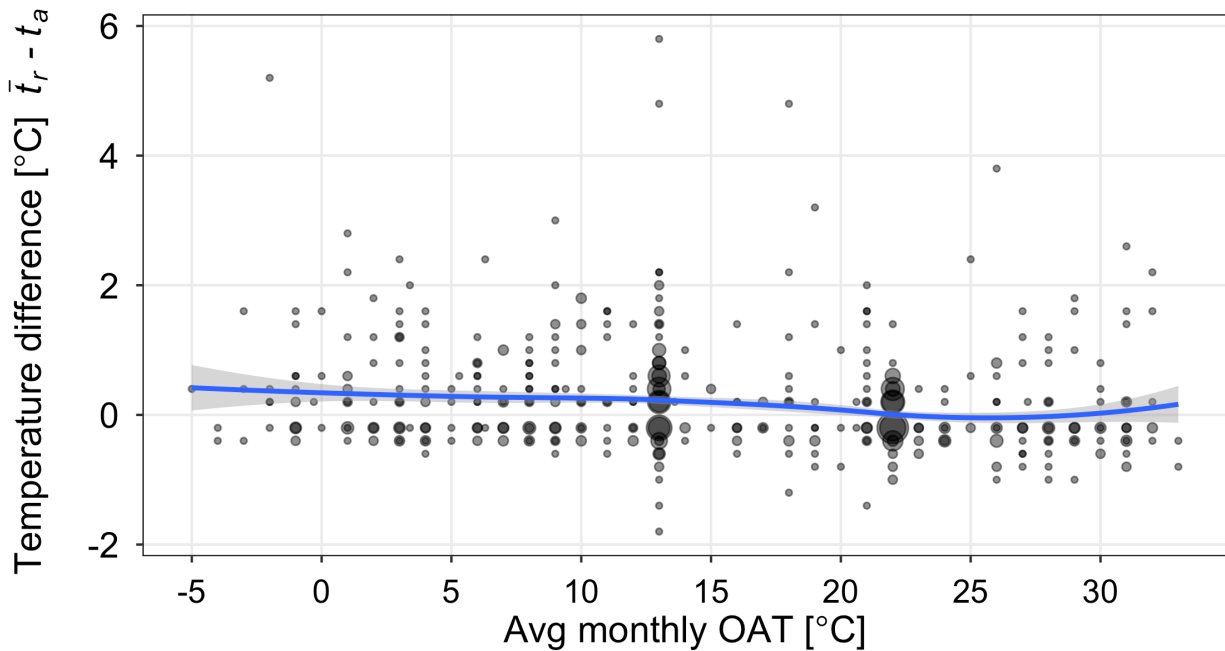
Figure A3. Difference between $\bar{t}_r$ and t_a versus average monthly outdoor air temperature shows that there is not a strong influence of outside temperature on the difference between the two internal temperatures. Even at outside air temperatures below 0 °C, there are instances where $\bar{t}_r$ is greater than t_a, and vice versa. The fitted line uses local regression with a 95% confidence interval.

B. Field Study supporting data

The field study data provides useful insight into the variability of the difference between $\bar{t}_r$ and t_a at each sensor location over time due to the continuous measurements at each location. This is important to consider because the Comfort Database represents temperature measurements at a point in time, but in reality, it is likely the temperatures vary over time. However, the field studies are limited in that they only represent five buildings in California and the studies were not designed in a way to compare between buildings; the number of and placement of sensors in each building is noticeably different and the system operation is different. For example, one building was testing demand response which involved relatively large changes in indoor temperatures, some buildings were likely operating in heating, and others in cooling.

In Figure B1, we plotted the distribution of the difference between $\bar{t}_r$ and t_a during typical hours of operation (Monday through Friday from 06:00 to 18:00) for each sensor location and identified the relative location within the building (i.e., interior, perimeter, and unknown where location could not be verified). In some instances, perimeter sensors are located directly next to windows, and direct solar heat gains likely influence the measurements. We did not identify sensors by system type (i.e., radiant or all-air) because there are too many uncontrolled differences between the field studies to make reasonable comparisons between system types. The results show that there is indeed variation by building and sensor location, but that in most instances, there is relatively small difference between $\bar{t}_r$ and t_a, supporting the study's

conclusion. The per sensor location results show that $\bar{t}_r$ can be higher than t_a in both radiant and all-air buildings, both at the perimeter and at the interior.
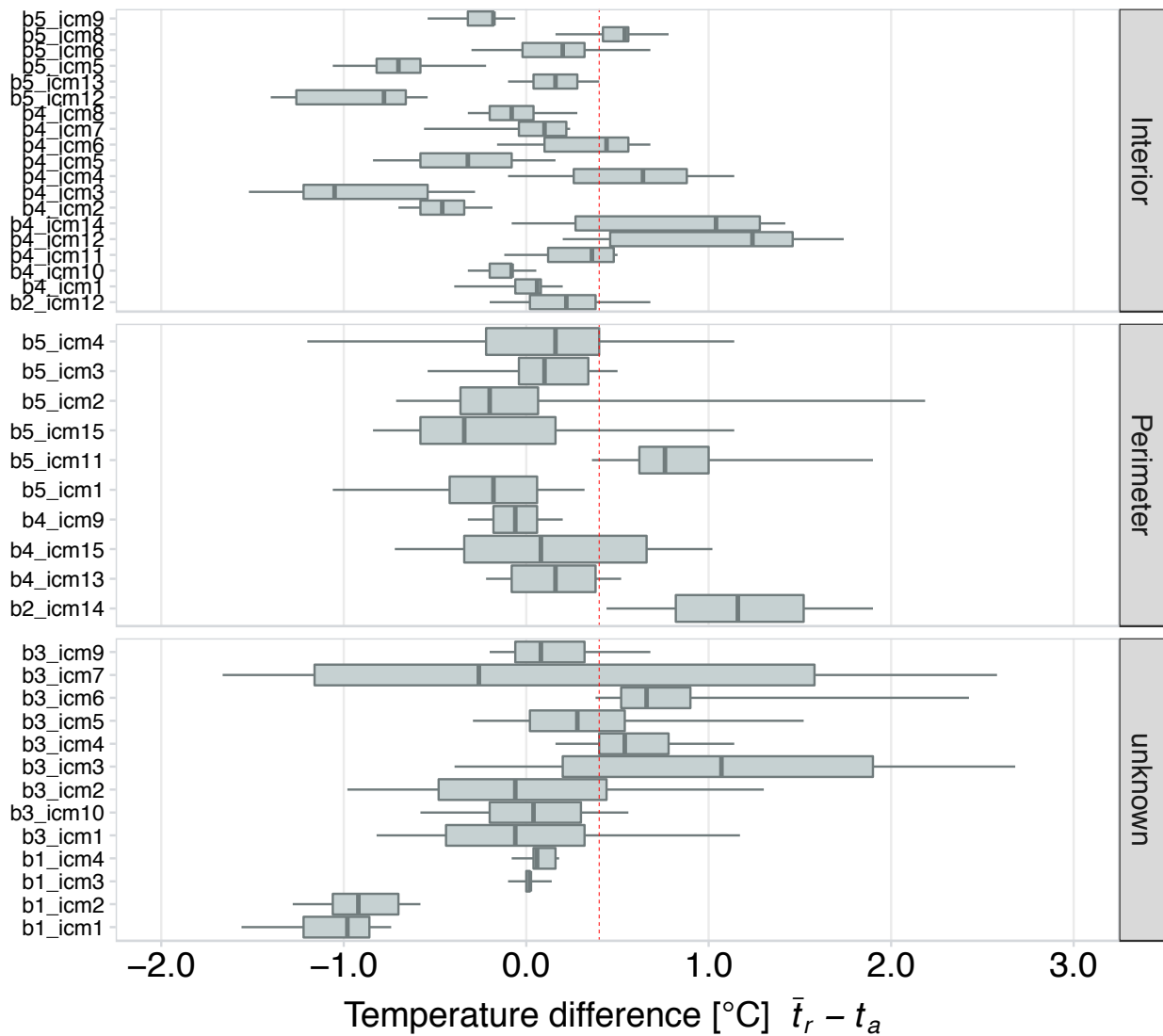

Figure B1. Distribution of the temperature difference at each sensor location for the field studies. The sensor locations are identified by the building ID and sensor ID, for example b1_icm1 is building 1 sensor location 1. For some buildings, we do not have relative sensor locations within the building and identify these as "unknown".

Figure B2 provides examples of the data from select sensor locations from the field studies. The left column shows $\bar{t}_r$, t_a, and operative temperature over time. The right column shows the rolling distribution (i.e., the median, 25th percentile, and 75th percentile) of the difference in between $\bar{t}_r$ and t_a for each 15-minute period from each day for the entire study period; meaning that the median value represents the median difference between $\bar{t}_r$ and t_a at that 15-minute period across all of the days within the study period. As can be seen by comparing sensor b5_icm11, which is at the building perimeter, to b5_icm8, which is in the interior, some sensors are influenced by direct solar radiation and could skew the overall analysis. Although not seen in the field study

dataset, similar observations may occur for sensors located next to windows with cold outdoor conditions.
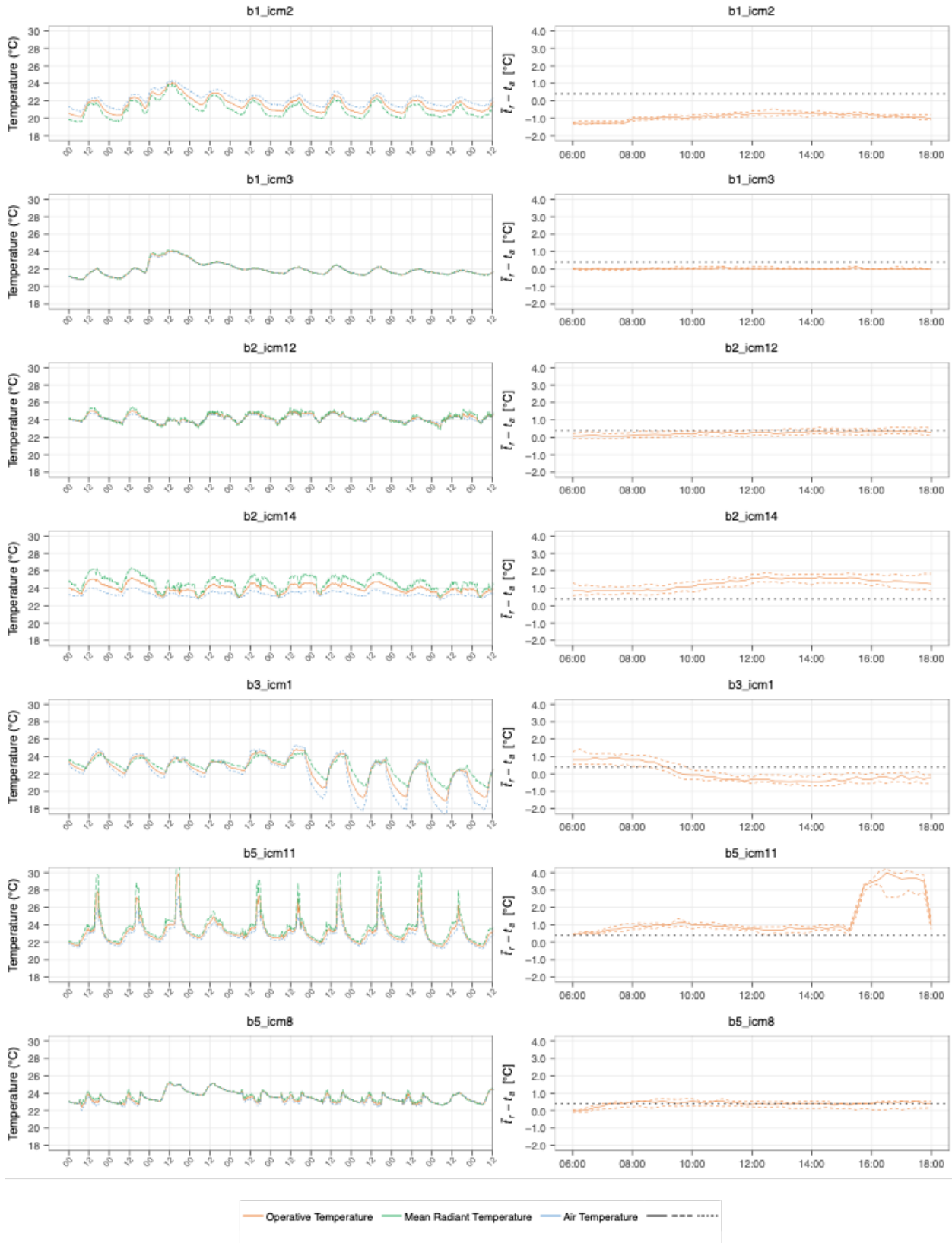
26

C. Temporal and spatial variation of air temperature

Figure C1 shows the daily range (i.e., maximum – minimum) of air temperatures at each interior sensor location from the field studies during typical hours of operation (Monday to Friday from 06:00 to 18:00). Most locations experience a daily distribution below 2.0 °C, which is within typical temperature deadband range. We excluded perimeter sensors that could be influenced by direct solar radiation or cold window surfaces, as seen in the example plots for Figure B2.
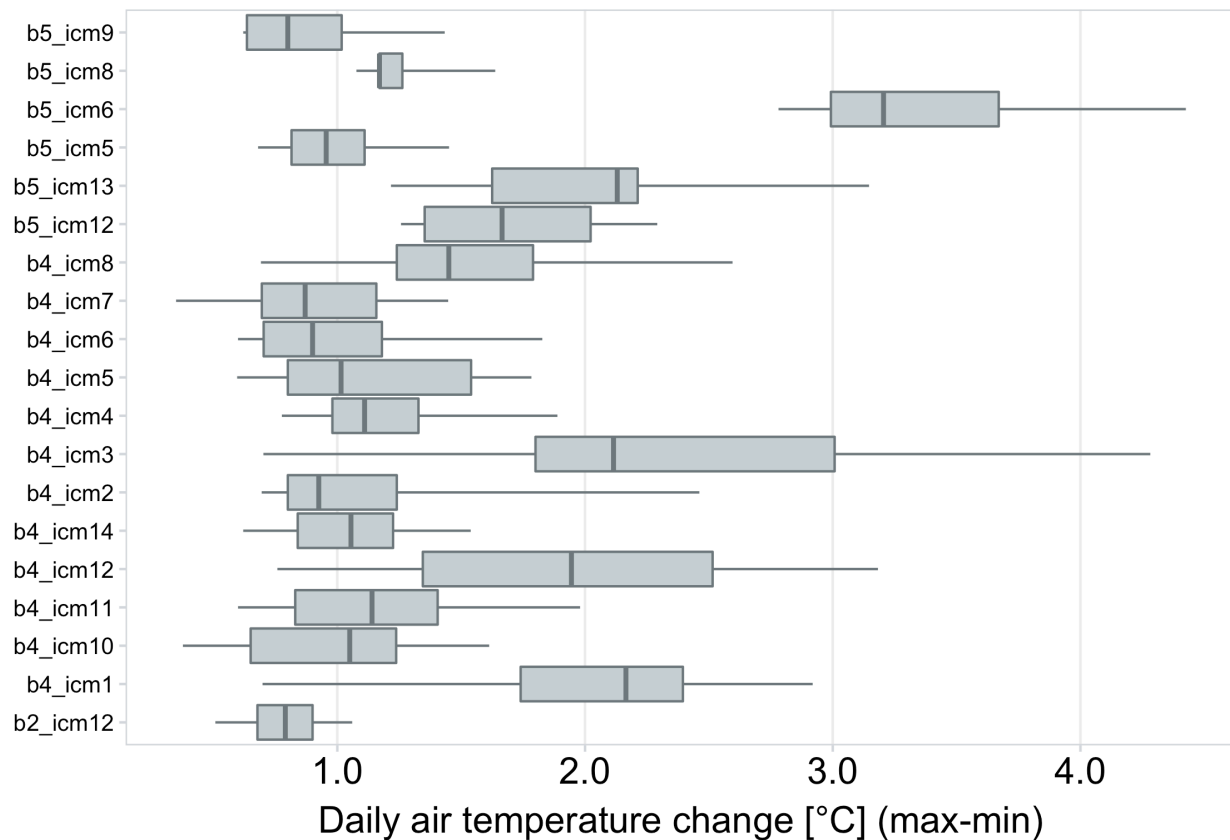

Figure C1. Distribution of daily air temperature range (maximum – minimum) at each interior measurement location during typical occupied hours (06:00 – 18:00) and typical occupied days (Monday – Friday). The range represents the 25th and 75th percentiles, with the whiskers representing the 5th and 9th percentiles. Not all field study buildings are represented because sensor location was not verified for all buildings.

Figure C2 shows the results of spatial variation analysis for the laboratory testbeds with six sensor locations in each testbed. We calculated the difference between each of the three sensors at 0.6 m height and the three sensors at 1.1 m height for each of the five test conditions, omitting the sensors with direct solar radiation to be consistent with the analysis calculating the difference between $\bar{t}_r$ and t_a. The median difference in t_a between any two of the three sensor locations at the same height and at the same time ranged from a minimum of 0.1 °C to a maximum of 0.4 °C

in the all-air testbed and a minimum 0.1 °C to a maximum of 0.3 °C in the radiant testbed. The spatial variation appears to be small, which is likely a result of the highly controlled laboratory experiment, in a zone that did not contain furniture or partitions, and sensor locations omitting direct solar radiation.
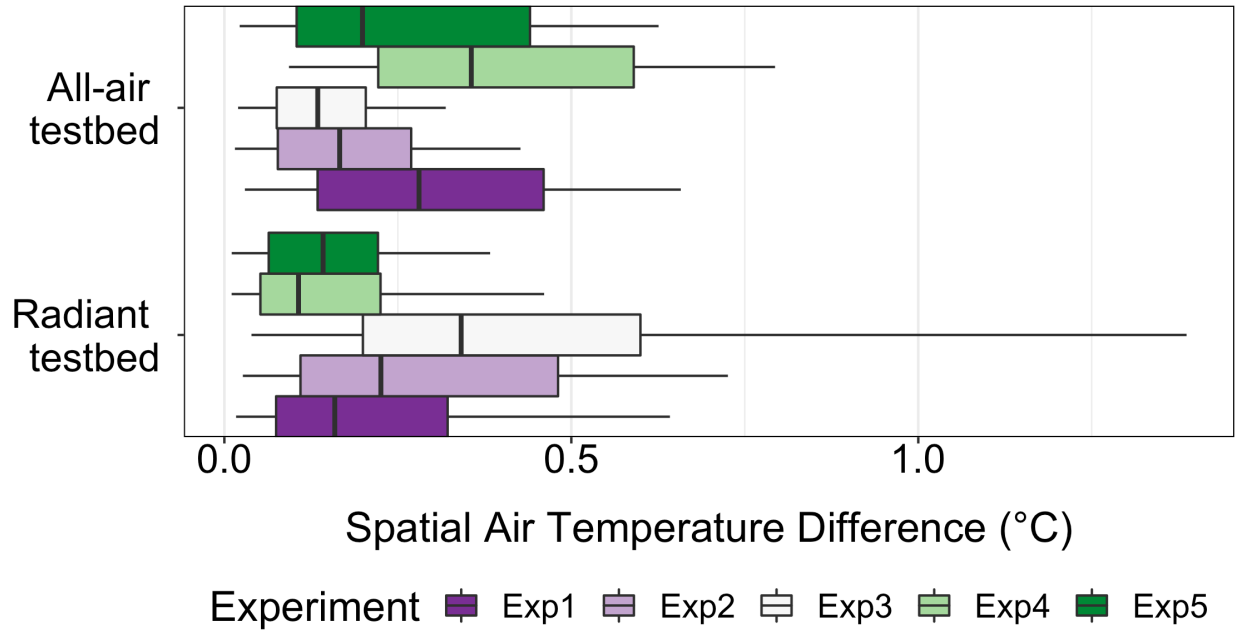

Figure C2. Spatial differences in air temperatures from each laboratory experiment between 08:00 to 18:00 over six days, based on one-minute interval data.