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Integrative Method to Whole-House Energy and Comfort Rating

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Integrative Method to Whole-House Energy and Comfort Rating

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Gaithersburg, MD 20899-8600

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LIST OF ACRONYMS

1-P	One-Parameter
3-P	Three-Parameter
5-P	Five-Parameter
ACCA	Air Conditioning Contractors Association
ACH	Air Changes per Hour
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BA	Bathroom
BR	Bedroom
BSMT	Basement
CBM	Cooling Benchmark
CV-RMSE	Coefficient of Variation of the Root Mean Square Error
DOE	Department of Energy
DR	Dining Room
DST	Daylight Saving Time
EH	Entry Hallway
EIA	Energy Information Administration
HBM	Heating Benchmark
HERS	Home Energy Rating System
HP	Heat Pump
HPWH	Heat Pump Water Heater
HRV	Heat Recovery Ventilator
HVAC	Heating, Ventilating and Air Conditioning
IECC	International Energy Conservation Code
IMT	Inverse Modeling Toolkit
IQR	Interquartile Range
KIT	Kitchen
LR	Living Room
MBA	Master Bathroom
MBR	Master Bedroom
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NZERTF	Net-Zero Energy Residential Test Facility
OA	Outdoor Air
PV	Photovoltaic
RECS	Residential Energy Consumption Survey
RESNET	Residential Energy Services Network
RH	Relative Humidity
R^2	Coefficient of Determination
R-to-T TD	Room-to-Thermostat Temperature Difference
R-to-R DDH	Room-to-Room Discomfort Degree Hours
R-to-R TD	Room-to-Room Temperature Difference

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Ta	Air Temperature
Tg	Globe Temperature
TTD	Thermostat Temperature Differential
WHD	Whole-House Dehumidifier
WD	Washer and Dryer

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EXECUTIVE SUMMARY

Despite broad recognition of the importance of residential energy efficiency and thermal comfort, there were no straightforward methods to accurately measure, compare, and rate whole-house efficiency in terms of both energy use and comfort using a reliable index. Existing methods for residential buildings have placed more emphasis solely on designed energy performance to quantify the home energy efficiency based solely on the inherent components of the house (i.e., home's asset). This is a large shortcoming given that these asset ratings cannot reflect the actual energy use of the house. In addition, for accurate characterization of the actual home energy performance, it is necessary to measure and report the concurrent thermal comfort performance of the house. This is especially critical for low-load homes to make sure they can still deliver high standards of comfort to their residents.

The purpose of this research is to investigate how thermal comfort dynamics are impacted by energy-efficient or thermal comfort improvements in a low-load house and to explore methods or metrics to rate a whole-house performance in an integrative way based on measured energy and comfort performance of the house. This research aims to strike a balance between advancing measurement science of whole-house performance in a holistic manner and developing a next-generation method or metric that is practical and reliable for realistic field applications to the existing residential building stock.

To accomplish this, this research collected, processed, and inspected the high-resolution detailed building and system performance data of the Net-Zero Energy Residential Test Facility (NZERTF) that is located on the campus of the National Institute of Standards and Technology (NIST) in Gaithersburg, MD, USA for its Year 1 and Year 2 operations along with coincident weather data. The quality-controlled 1-min data were then divided into several subgroups to accurately characterize and report the whole-house energy and thermal comfort performance of NZERTF. This includes partitioning long-term energy and thermal comfort data by season based on the heat pump system's actual operation mode under given weather conditions and by three Thermostat's Temperature Differential (TTD) settings that were used to control the heat pump system.

The sub-grouped data were then used to calculate weather-dependent energy models for the whole house and five major end uses (e.g., conditioning, ventilation, lighting, plug loads+ appliances, and domestic hot water). The weather-dependent changing-point regression models for conditioning energy use were then used to estimate the energy performance changes caused by major energy-efficient or thermal comfort improvements applied to NZERTF throughout its Year 1 and Year 2 operations. It was found that the conditioning electricity use would increase with tighter TTD control during the heating season, while the improved control strategy of the backup electric resistance heater during the Year 2 operation to minimize its use would result in high energy savings during the heating season.

In addition, this study calculated several whole-house thermal comfort metrics for each subgroup to reveal the impact of major energy-efficient or thermal comfort improvements applied to NZERTF on its thermal comfort performance. The calculated metrics include temperature deviation from the setpoint temperature (i.e., room-to-thermostat temperature difference) to evaluate the system's fundamental ability to produce and deliver the designed air temperature; room-to-room temperature difference to evaluate spatial thermal uniformity;

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cyclic discomfort to evaluate temporal thermal uniformity; and relative humidity (RH) deviation from the setpoint RH (i.e., room-to-humidistat RH difference) to evaluate dehumidification efficiency in terms of maintaining a setpoint humidity. The calculated metrics for each subgroup were then compared against relevant benchmarks such as the ACCA Manual RS and the ASHRAE Standard 55-2017.

Besides, to fully understand the long-term thermal comfort data, this study performed statistical and advanced characterization of the granular thermal comfort data relative to the outdoor weather and the time of the day not only for the primary rooms but also for the attic and the basement that are thermally important due to possible heat transfer from/to the primary rooms. These analyses revealed weather-dependent characteristics of the thermal comfort metrics and their dynamic interactions with uneven internal heat gains from occupants, lighting, appliances, and miscellaneous electronic devices.

Finally, this study proposed an integrative rating method based on the weather-dependent conditioning energy use of the house and coincident whole-house thermal comfort metrics that were averaged over a particular range of weather conditions. The proposed method was demonstrated using the Year 1 and Year 2 NZERTF performance data, which allowed a weather-normalized comparison of the three different TTD operations in terms of both energy and thermal comfort for a particular weather condition. For both energy and comfort metrics, lower values mean good performance, while higher values mean poor performance.

For example, during the cooling season, the Year 2 operation had the largest temperature deviation from the setpoint in the first-floor rooms but maintained the second-floor temperature closer to the setpoint. The first-floor overcooling during the Year 2 operation was caused by using the average of two temperature sensors (i.e., thermostat sensor in the living room and the remote sensor in the second-floor hallway) to control the heat pump system. It was also found that the use of a thermostat with remote sensing capability during the Year 2 operation did not improve thermal uniformity between the floors.

During the heating season, different results were obtained by the outdoor air temperature. On mild winter days, the Year 2 operation maintained a smaller temperature deviation from the setpoint with comparable room-to-room temperature differences. On colder winter days, the Year 2 operation had the largest room-to-thermostat temperature deviation, which was a comfort penalty due to an improved control strategy to minimize the use of the backup electric resistance heater. As a result, the heat pump system ran constantly to meet the heating setpoint temperature, which was actually helpful to maintain better thermal uniformity with smaller room-to-room temperature differences during the Year 2 operation.

The impact of lowered differential temperatures was also revealed by comparing different TTD settings that had been changed over the Year 1 operation. For example, a larger low-side temperature deviation from the setpoint was observed along with unfavorable non-compliant periods based on the ACCA Manual RS benchmarks when the 1st stage heating differential temperature was set higher. The observed thermal discomfort improved with the lowered TTD setting. However, there was an energy penalty (i.e., increased heating energy use).

In conclusion, the proposed rating method allowed an integrative and rigorous assessment of a whole-house performance in terms of both energy efficiency and comfort of which

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assessments were often made separately in the history of the disciplines. In the absence of high-quality residential datasets, the results of this study can serve as rigorous benchmarks to which other houses and conditioning systems can be compared for respective outdoor weather conditions. The proposed rating method is also expected to be applicable for both short-term and long-term measurements using the data sorted by respective outdoor temperature, although long-term measurements would provide a more accurate characterization.

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1. INTRODUCTION

1.1. BACKGROUND

Project Motivation: Energy use in Residential Buildings

Residential buildings are responsible for one-fifth of the total energy use in the U.S. (EIA 2020a), which is equal to about 55% of the energy use in the U.S. building sector. According to the Annual Energy Outlook 2020 by the U.S. Energy Information Administration (EIA) (EIA 2020b), the number of the U.S. households, which is one of the main drivers of residential energy use, is also projected to grow continuously by an average of 0.6% per year between 2019 and 2050. Not surprisingly, a study by The Rockefeller Foundation and Deutsche Bank Climate Change Advisors (DBCCA) (2012) found that residential buildings have the largest potential for significant energy savings in the building sector by applying appropriate building envelope and HVAC retrofit measures.

However, despite their largest potential impact, the residential energy use historically has gained less attention by professional HVAC&R society such as American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (2014a). Previous efforts largely focused on establishing and complying minimum performance requirements for residential buildings such as International Energy Conservation Code (IECC) (ICC 2018), ASHRAE Standard 90.2 (ASHRAE 2018), and ASHRAE Standard 62.2 (ASHRAE 2019a). Other research efforts examined how to maximize the overall performance of residential buildings, including the concepts of Net-Zero Energy Home (NZEH) or Zero Energy Ready Home (ZERH) by combining state-of-the-art low-energy residential building technology with on-site renewable energy systems (DOE 2020a). However, fewer efforts have been made to quantify the actual performance of these low-load homes after construction in terms of their detailed energy efficiency and comfort performance.

Residential buildings have a wide variety of energy end uses that serve different purposes[1]. In addition, there is a wide variety of the way households use energy (EIA 2018b), which is affected by multiple factors such as geographic location, the physical and structural energy efficiency attributes of housing, envelope, and equipment, as well as widely varying, resident-dependent factors such as residents' comfort preferences, behavioral patterns, and socioeconomic factors. This known variety of residential energy use has partially influenced to a lack of high-quality residential datasets, including complete information on resident-dependent factors that are often hard to measure or control under actual conditions. As a result, there is a need for reliable residential datasets, leading to a better understanding of the actual energy performance of advanced residential building technology and components that also provide comfortable and healthy indoor environments.

[1] According to the 2015 U.S. Residential Energy Consumption Survey (RECS) (EIA 2018a), about 54% of the single-family residential energy is consumed to provide space conditioning, including heating (46%) and air conditioning (8%). Other energy end uses include water heating (17%), refrigerator (3%), and lighting/appliances/equipment (26%).

NIST Net-Zero Energy Residential Test Facility (NZERTF)

One unique effort made by NIST to reliably measure and characterize the long-term operational performance of a net-zero energy home is the Net-Zero Energy Residential Test Facility (NZERTF) on the campus of the NIST (NIST 2020). The NZERTF is a single-family house that serves as a laboratory with simulated occupancy and scheduled internal loads. The house was designed to allow full-scale dynamic testing and analysis of low-energy residential building technology or control strategies under actual conditions. At the NZERTF, measurements from nearly 400 sensors are being continuously collected and stored, typically in increments of one minute. These data are valuable resources for researchers who aim to improve measurement science associated with the low-energy building technology control strategies, which well supports the mission of Engineering Laboratory at NIST.

The overall energy performance data for the first year of NZERTF operation from July 2013 to June 2014 (i.e., Year 1 NZERTF Data) are presented in Fanney et al. (2015), which successfully demonstrated its net-zero operation under harsh winters. A number of lessons were also learned during the Year 1 operation of the NZERTF. As a result, several efficiency-improving adjustments were proposed and applied to the NZERTF for the Year 2 demonstration from February 2015 to January 2016 (i.e., Year 2 NZERTF Data), of which data and a comparison against Year 1 data are presented in Fanney et al. (2017).

As a result, the NZERTF's energy use during the second year of operation was reduced by 9.5%[2] along with mild winter. However, there have been limited discussions and reporting on the impact of the applied energy-efficient improvements on thermal comfort dynamics, although thermal comfort can have a significant impact on residents' overall comfort and well-being. Thermal comfort analysis is essential to verify the measured energy savings while assuring residents' comfort, which is critical for long-term, successful habitation in low-load homes.

Home Performance Rating Systems

In spite of a broad recognition on the importance of residential energy efficiency and thermal comfort, there were no straightforward methods to accurately measure, compare, and rate whole-house efficiency in terms of both energy use and comfort using a reliable index, while some efforts were made for commercial buildings (ASHRAE 2010a; ASHRAE 2014b). Existing methods for residential buildings have placed more emphasis solely on designed energy performance, including:

- The U.S. Department of Energy (DOE) Home Energy Score (DOE 2020b) and
- Residential Energy Services Network (RESNET) Home Energy Rating System (HERS) (RESNET 2020).

Both the U.S. DOE Home Energy Score and the RESNET HERS are designed to quantify the home energy efficiency based solely on the inherent components of the house (i.e., home's asset) such as the physical and structural energy efficiency attributes of housing, envelope, and equipment[3]. As a result, both rating systems assume resident-dependent factors and

[2] 1,241 kWh savings from 13,042 kWh for Year 1 to 11,801 kWh for Year 2.
[3] The U.S. DOE Home Energy Score is based on the calculated home energy use, which is shown on a one-to-ten scale, while the RESNET HERS calculates a relative energy performance score of the house against a standard house of the same size and shape built to comply with the 2004/2006 IECC.

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behaviors (e.g., thermostat settings, appliances, plug loads, and lighting) are fixed and somewhat constant. This is a large shortcoming given that these asset ratings cannot reflect actual energy use of the house and a possible discrepancy between designed performance (i.e., asset rating) and actual performance (i.e., operational rating) of the house, which are often affected by the way how residents use the building/equipment as well as poor construction and maintenance practices. In addition, for an accurate characterization of the actual home energy performance, it is necessary to measure and report the concurrent thermal comfort performance of the house. This is especially critical for low-load homes in order to make sure they can still deliver high standards of comfort to their residents.

Therefore, this study explores new methods or metrics to properly analyze and rate a whole-house performance based on measured energy and thermal comfort performance using the data collected from the NIST NZERTF. The findings from this study are expected to contribute to the existing knowledge and measurement science by developing an improved method or metric enabling an integrative and rigorous assessment of a whole-house performance.

1.2. PURPOSE OF THE RESEARCH

The purpose of this research is to investigate how thermal comfort dynamics are impacted by energy-efficient or thermal comfort improvements in a low-load house and to explore methods or metrics to rate a whole-house performance in an integrative way based on measured energy and comfort performance of the house. This research aims to strike a balance between advancing measurement science of whole-house performance in a holistic manner and developing a next-generation method or metric that is practical and reliable for realistic field applications to the existing residential building stock.

1.3. ORGANIZATION OF THE REPORT

This report is organized into six sections.

Section 1 introduces the background of the study, including the purpose of the research.

Section 2 describes the methodology used to conduct this research, including a description of NIST NZERTF and the HVAC systems; thermal comfort and system performance data collection, processing, and inspection; energy and thermal comfort data analysis methods; and the proposed integrative rating system.

Section 3 presents a detailed analysis of the NZERTF energy and thermal comfort data for the Year 1 and Year 2.

Section 4 presents an analysis of whole-house thermal comfort performance using several whole-house thermal comfort metrics.

Section 5 demonstrates the use of the proposed rating method based on the weather dependent conditioning energy use (i.e., heating, cooling, and dehumidification) of the house and coincident whole-house thermal comfort metrics that were averaged over a particular range of weather condition using the Year 1 and Year 2 NZERTF performance data.

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Section 6 summarizes the key findings from this research and discusses the recommendations for future research, which will contribute to improved design, operation, and measurements of whole-house performance for energy efficiency and thermal comfort.

Appendix A describes the rule that was applied to fill the data gaps identified in the raw data.

Appendix B provides a list of the 49 days that were excluded from the analysis with the reasons for exclusion.

Appendix C presents graphical summaries of the 1-min temperature, humidity, and electricity data for Year 1 and Year 2.

Appendix D graphically present the globe-to-air temperature difference (i.e., ΔT (°C) = $T_g - T_a$) calculated using the 5-min average temperature data collected from the five primary rooms.

Appendix E presents the binned room air temperatures and humidity ratios against outdoor temperatures for the other rooms such as MBR, BR3, ATTIC, MBA and BSMT as supplementary materials to Section 3.4.

Appendix F presents time-of-day colored maps applied to the hourly average room temperatures over the measurement period for the other rooms such as MBR, BR3, BR4, and DR as supplementary materials to Section 3.5.

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2. METHODOLOGY

This section describes the methodology used to conduct this research. This research collected two years of high resolution, 1-min data throughout the NIST NZERTF in Gaithersburg, MD from July 2013 to June 2014 (i.e., Year 1 NZERTF Data) and from February 2015 to January 2016 (i.e., Year 2 NZERTF Data) along with coincident outdoor weather data. During the analysis period, the major energy-efficient or thermal comfort improvements applied to the NZERTF throughout is Year 1 and Year 2 operations include:

- Lowered 2nd stage and 3rd stage differential temperature settings along with shortened delay time to control the same heat pump system;
- Improved control strategy of the backup electric resistance heater of the same heat pump system (i.e., 3rd stage heating) by removing associated delay time to minimize its use;
- Use of a thermostat with an additional remote sensor located in the second-floor hallway in lieu of the combined thermostat/humidistat by the heat pump manufacturer located in the living room of the house;
- Use of a whole-house dehumidifier in lieu of the heat pump's dedicated dehumidification cycle; and
- Lowered outdoor ventilation rate per ASHRAE Standard 62.2-2010 (ASHRAE 2010b), which resulted in a 20% reduced outdoor ventilation compared to Year 1 operation.

Section 2.1 presents a description of the NIST NZERTF.

Section 2.2 presents an overview of the thermal comfort and system performance data collection, processing and inspection.

Section 2.3 describes the data analysis methods.

Section 2.4 describes an integrative rating system proposed to rate a whole-house performance based on measured energy and thermal comfort performance of the house.

2.1. NIST NZERTF

2.1.1. HOUSE DESCRIPTION

The NZERTF is a two-story house shown in Figure 1 that has a basement and attic and is similar in size and aesthetics to homes in the surrounding communities. The occupiable floor area consisting of the first floor (1F) and the second floor (2F) is 242 m^2 (2,605 ft^2). The total floor area of the house, including basement, 1F, 2F, and attic, is 485 m^2 (5,221 ft^2). The house is unoccupied and unfurnished other than permanently installed cabinetry. Despite it being unoccupied, the activities of a family of four (i.e., two adults and two children) were simulated in terms of electrical use (i.e., appliances and lighting), hot water use, and metabolic heat and moisture generation. Details of these control schedules can be found in Omar and Bushby (2013) and Kneifel (2012).

One of the ways the NZERTF achieved its net-zero energy goals was by minimizing heating and cooling loads by installing a well-insulated and tight building envelope. The exterior walls were constructed of wood studs, a fully-adhered membrane applied to plywood

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Figure 1: Front View of the NIST NZERTF (South Façade).

sheathing, two layers of polyisocyanurate foam board, fiber cement lap siding, and blow-in cellulose insulation. The calculated U-factor of the exterior above-grade walls, including framing members, is 0.13 W/m^2-°C. The windows are double-hung units with a rated U-factor of 1.14 W/m^2-°C. A continuous air barrier system was installed to minimize infiltration, and ventilation was provided by a heat recovery ventilator (HRV). Upon completion of the NZERTF, Pettit et al. (2014) reported the results of the airtightness test, which was 0.55 air changes per hour (ACH) at 50 Pa with kitchen and dryer vents sealed; and 0.63 ACH at 50 Pa with kitchen and dryer vents unsealed.

2.1.2. HVAC SYSTEMS

Other ways that the NZERTF achieved its net-zero energy goals were through the 10.2 kW photovoltaic (PV) system, a high-efficiency air-to-air heat pump, and a solar hot water system. During the analysis period, the central air-to-air heat pump system with a two-stage compressor and a variable speed indoor blower provided supply air to all floors except the attic. All ductworks are located within the conditioned space since the fully-adhered membrane air and moisture barrier was applied from the roof down to the foundation. Passive air transfer grilles connect the basement to the first floor and the attic to the second floor of the house. Air is returned to the heat pump via three return air grilles (i.e., one on the first floor and two on the second floor). Table 1 summarizes the characteristics of the heat pump operated at NZERTF during the analysis period, including cooling and heating capacity and efficiency of the system.

The cooling setpoint temperature was 23.8°C (75°F), and the heating setpoint temperature was 21.1°C (70°F) with no setback schedules. The auto HEAT/COOL changeover feature of the thermostat was enabled for both years. The heat pump was operated in the heating mode if the sensed temperature at the thermostat drops below the heating setpoint temperature, while it was in the cooling mode if the sensed temperature goes above the cooling setpoint temperature.

Different thermostats were used between the two years. During the Year 1 operation, the combined thermostat/humidistat provided by the heat pump manufacturer was installed in the living room of the house and used to control the heat pump system, which was replaced by a different thermostat with remote sensing capability during the Year 2 operation. The remote temperature sensor was located in the second-floor hallway. The average of two temperature sensors (i.e., thermostat sensor in the living room and the remote sensor in the second-floor hallway) was used to control the heat pump system.

The compressor speeds were modulated depending on the differential temperature setting on the thermostat, which was the temperature relative to the setpoint temperature. The thermostat used during the Year 1 operation also allows the user to set the stage time delay along with corresponding differential temperatures to initiate the 2nd stage of compressor for both heating and cooling or the 3rd stage electric resistance heating. However, the thermostat used during the Year 2 activates the 2nd stage of compressor or the 3rd stage electric resistance heating only based on the differential temperature setting. Table 2 summarizes these control settings, which had been changed over the analysis period. Since these settings have a direct impact on the maintained thermal comfort and associated heat pump's cooling and heating energy use, this study decided to group the data by Thermostat Temperature Differential (TTD) settings, including:

- Year 1 High TTD (YR1 HTTD) from July 1, 2013 to January 22, 2014;
- Year 1 Low TTD (YR 1 LTTD) from January 24, 2014 to June 30, 2014; and
- Year 2 (YR2) from February 1, 2015 to January 31, 2016.

For example, during the YR1 HTTD operation, the 1st and 2nd stage compressor was set to be activated if the difference between the sensed temperature and setpoint is over 0.6°C (1.0°F) and over 2.8°C (5.0°F), respectively, along with 40 min 2nd stage delay time. The 3rd stage heating (i.e., 5 kW electric resistance heating) was set to be turned on when the sensed temperature dropped lower than 3.3°C (6.0°F) below the setpoint with the 3rd stage delay time of 40 minutes. During the YR1 LTTD operation, only the 2nd stage and 3rd stage differential temperatures were reduced from 2.8°C (5.0°F) to 1.1°C (2.0°F) and from 3.3°C (6.0°F) to 1.7°C (3.0°F), respectively, along with reduced 2nd stage delay time from 40 minutes to 10 minutes. Lastly, during the YR2 operation, the 1st and 2nd stage differential temperatures were lowered to 0.3°C (0.5°F) and 0.6 (1.0°F), while the 3rd stage differential temperature was raised to 2.8°C (5.0°F) compared to YR1 LTTD operation.

During the Year 1 operation, dehumidification was provided by activating the 2-stage dedicated dehumidification cycle of the same heat pump if the relative humidity (RH) at the combined thermostat/humidistat reaches 50% RH. During the 1st stage dehumidification, the indoor fan speed was reduced to reduce the temperature of the indoor coil with the 2nd stage delay time of 15 minutes. The 2nd stage dehumidification activated dedicated dehumidification cycle of the heat pump. During the Year 2 operation, a separate humidistat near the thermostat was used to control the whole-house dehumidifier. The whole-house

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dehumidifier was installed to pull air from the living room and supply the dehumidified air to the supply duct leaving the heat pump system. It uses a damper on the supply which opens only when the whole-house dehumidifier operates. The whole-house dehumidifier installed at the house has a capacity of 63.9 L/day and an energy factor of 1.81 L/kWh at a flow rate of 14 m^3/min (500 CFM) with 26.7°C (80.0°F)/60% RH inlet air conditions.

A balanced, ducted HRV system supplies outdoor air to the first-floor living area and three second-floor bedrooms. It draws return air for heat recovery from one bathroom on the first floor and two bathrooms on the second floor. During the Year 1 operation, the HRV ran continuously at 171 m^3/h (100 CFM), which exceeded the minimum ventilation requirements of the ASHRAE Standard 62.2-2010 (ASHRAE 2010b). During the YR2 operation, the HRV was operated on an intermittent schedule (i.e., approximately 40 minutes on and 20 minutes off with an extra on-time in order to account for the start-up time of the supply fan to reach maximum speed) to provide 137 m^3/h (80 CFM) of outdoor air (i.e., 0.09 ACH based on the entire volume of the house, including basement, first floor, second floor, and attic) per ASHRAE Standard 62.2-2010, which resulted in a 20% reduced outdoor ventilation compared to the Year 1 operation.

Table 1: Summary of the Characteristics of the Heat Pump System at NZERTF.

	CDHP *Two-stage compressor and variable-speed indoor blower*
Cooling Capacity	7.6 kW
Heating Capacity	7.8 kW at 8.3°C
Efficiency	SEER 4.63 W/W HSPF 2.65 W/W
Electric resistance heater	5 kW

Table 2: Summary of the Thermostat Temperature Differential (TTD) Settings.

	Operation Period	**1st Stage**	**2nd Stage**		**3rd Stage**	
		Temperature Differential (°C)	Delay Time (min)	Temperature Differential (°C)	Delay Time (min)	Temperature Differential (°C)
YR1 HTTD	7/1/2013 to 1/22/2014	0.6°C 1)	40 min	2.8°C	40 min	3.3°C
YR1 LTTD	1/24/2014 to 6/30/2014	0.6°C	10 min 2)	1.1°C	40 min	1.7°C
YR2	2/1/2015 to 1/31/2016	0.3°C	Not Used	0.6°C	Not Used	2.8°C

Note:
1) 1.1°C for heating before 11/19/2013.
2) 30 minutes Before 1/28/2014.

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2.2. THERMAL COMFORT AND SYSTEM PERFORMANCE DATA

At the NZERTF, sensors were installed throughout the house to monitor the ambient conditions as well as the performance of each particular subsystem in the house. The instrumentation, data acquisition system, and measurement uncertainty associated with the heat pump system, as well as all other electrical/mechanical subsystems within the NZERTF are described in Davis et al. (2014). The measurements from nearly 400 sensors are continuously collected and stored, typically in increments of one minute, and publicly available (NIST 2020).

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2.2.1. DATA COLLECTION

This study collected detailed building and system performance data of NZERTF during the analysis period, including 1-min whole-house thermal comfort data. The 1-min whole-house thermal comfort data include air temperature (Ta), relative humidity (RH), and globe temperature (Tg) in the center of the selected rooms at approximately 1.4 m (55 in.) above the floor, as shown in Figure 2. Table 3 lists the measurement parameters and instrumentation used for the whole-house thermal comfort measurements.

Figure 3 shows the rooms selected for whole-house thermal comfort data monitoring with specific variables monitored. All three variables were monitored in primary rooms such as living room (LR), kitchen (KIT), master bedroom (MBR), bedroom (BR) 2, and BR3. In the rooms that are not primary habitable but either produce or are near moisture sources such as master bathroom (MBA) and basement (BSMT), two variables (i.e., Ta and RH) were monitored[4]. Lastly, only air temperature was monitored in other rooms, including bathroom (BA) 1, BA2, washer and dryer (WD), dining room (DR), BR4, and entry hallway (EH)[5].

Table 3: Whole-House Thermal Comfort Measurement Parameters and Instrumentation.

Parameter	Instrumentation	Sensor Type	Range	
Air Temperature (Ta)	Omega	Type T thermocouple	13°C to 30°C	±0.2°C
Relative Humidity (RH)	Michell Instruments WM32-3-XX-HX	Capacitive polymer	0% RH to 100% RH	±3% RH
Globe Temperature (Tg)	Omega	Type T thermocouple inside grey ping pong ball	13°C to 30°C	±0.2°C

[4] The attic and basement air temperatures were monitored at four different locations (i.e., in the middle of each quadrant of the room such as northeast, northwest, southeast, and southwest), while room relative humidity in the basement was monitored at one location.
[5] The entry hallway air temperature were monitored at the five different levels: the lowest level at a height of 0.6 m (24 in.); the lower middle level at a height of 1.8 m (71 in.); the middle level at a height of 3.0 m (118 in.); the upper middle level at a height of 4.3 m (169 in.); and the upper level at a height of 5.5 m (217 in.).

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Figure 2: Sensors Mounted on the Metal Stand in the Center of the Room (Davis et al.).

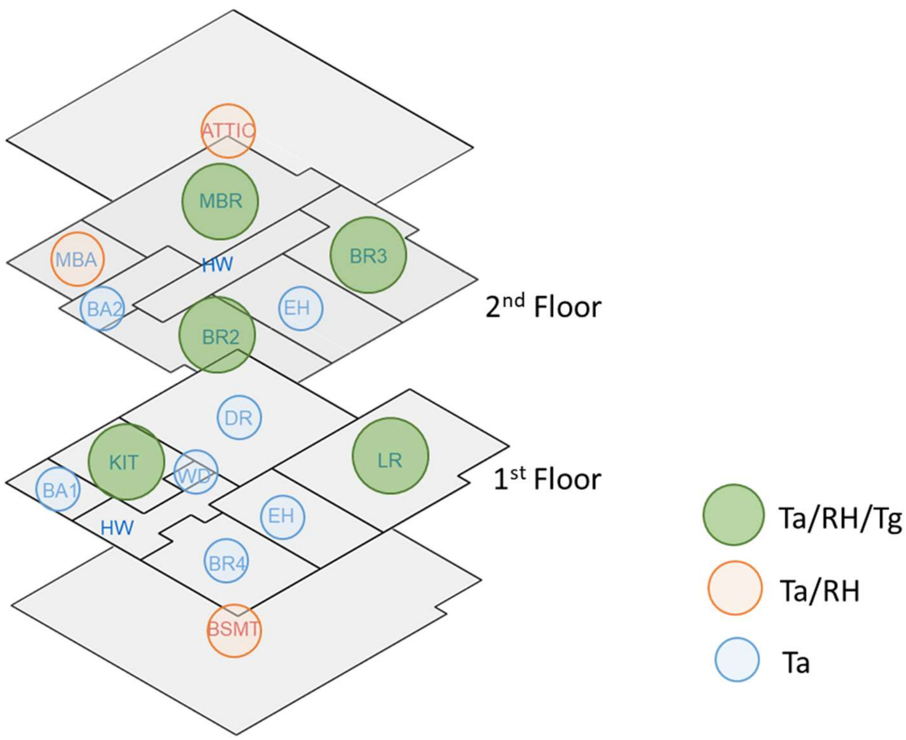

Figure 3: Rooms Selected for Whole-House Thermal Comfort Data Monitoring.

In addition to the thermal comfort data, this study collected:

- 3-sec or 10-sec electric power and performance data for the indoor and outdoor units of the heat pump;
- 1-min outdoor air (OA) temperature and 3-sec or 10-sec OA dew point temperature; and
- Basic building and system characteristics, including as-built architectural and mechanical drawings; and HVAC system operation and event logs.

The collected heat pump power along with supply airflow were used to determine each system's on and off cycling and the season classification as described in Section 3.3.1. The coincident weather data from nearby National Oceanic and Atmospheric Administration (NOAA) weather stations (NOAA 2019), including Washington/Dulles International Airport, VA, were also collected and compared against OA temperature and dew point temperature data collected from NZERTF.

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2.2.2. DATA PROCESSING AND INSPECTION

The collected raw data were processed and inspected using a set of data processing templates that were developed to ensure accuracy and consistency in the collected raw data. The data processing templates are capable of filling in short periods of missing data, replacing bad data with -99, and producing 1-min, 5-min average, and hourly average data based on consistent daylight saving time (DST) timestamp. Appendix A describes the rule that was applied to fill the data gaps identified in the raw data.

The processed data were then inspected along with the collected heat pump system operation and event log in order to identify and document any long-term missing data or abnormal/invalid data that must be excluded from the analysis. As a result, this study identified a total of 25 days (i.e., 15 days in Year 1 and 10 days in Year 2) that should be excluded from the analysis due to operational anomalies of the heat pump system or activities at NZERTF that might affect the collected thermal comfort data. There were additional 24 days (i.e., 15 days in Year 1 and 9 days in Year 2) that were partially excluded from the analysis due to long-term bad data in OA dew point temperature data. Appendix B provides a list of the 49 days that were excluded from the analysis with the reasons for exclusion.

Appendix C presents graphical summaries of the 1-min temperature, humidity, and electricity data for Year 1 and Year 2 for the following data channels:

- 24 room air temperature channels;
- 5 room globe temperature channels;
- 2 outdoor air temperature channels;
- 7 room relative humidity channels;
- 1 outdoor humidity channel; and
- 3 heat pump electricity channels.

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2.3. DATA ANALYSIS

The processed 1-min, 5-min average, and hourly average data based on consistent DST timestamp were analyzed to characterize and evaluate the whole-house energy and thermal comfort performance of NZERTF, with a focus on:

- How thermal comfort dynamics were impacted by energy-efficient improvements at NZERTF; and
- How to adequately normalize the measured energy and comfort performance by the key variables affecting the performance of applied energy-efficient improvements such as weather conditions.

2.3.1. LONG-TERM ENERGY AND THERMAL COMFORT DATA DECOMPOSITION

To accurately characterize and report the energy and thermal comfort performance of the NZERTF under different operation modes and outdoor weather conditions, the two-year granular thermal comfort data were divided into the following subgroups:

- By the heat pump system's TTD settings as summarized in Table 2:
  - YR1 HTTD from July 1, 2013 to January 22, 2014
  - YR1 LTTD from January 24, 2014 to June 30, 2014
  - YR2 from February 1, 2015 to January 31, 2016
- By the heat pump system's on/off cycle:
  - On cycle
  - Off cycle
- By the heat pump system's actual operation mode under given weather conditions:
  - Cooling season
  - Heating season
  - Transitional season

Transitional season was defined to identify and separately group the days when the heat pump systems provided little or no space conditioning, which helped the interpretation process because on these days the unconditioned temperature of the house was floating between the cooling and heating setpoint temperature. For that, this study first calculated the heat pump's actual operation mode based on its measured cooling and heating capacity, and the days with no cooling or heating capacity were then classified into transitional season.

In addition, to identify the days when the heat pump system provided little space conditioning while the house's unconditioned temperature was floating between the cooling and heating setpoint temperature, this study calculated the heat pump energy use models (i.e., five-parameter (5-P) change-point linear models) based on daily data using the ASHRAE Inverse Modeling Toolkit (IMT) (Kissock et al. 2004), as shown in Figure 4. In this classification, the days when the daily average OA temperature was between 7.5°C (45.5°F) and 17.2°C (63.0°F) were classified into transitional season. 7.5°C (45.5°F) was the daily average OA temperature below which the heat pump system at NZERTF was actively running to provide heating based on the model, while 17.2°C (63.0°F) was the daily average OA temperature above which the heat pump system was actively running to provide cooling. Figure 5 presents the final classification of the heating, transitional, and cooling seasons used in this study. This includes:

- YR1 HTTD:

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- 84 days for the cooling season
- 60 days for the heating season
- 52 days for the transitional season

- YR1 LTTD:
  - 48 days for the cooling season
  - 55 days for the heating season
  - 51 days for the transitional season
- YR2:
  - 145 days for the cooling season
  - 97 days for the heating season
  - 113 days for the transitional season

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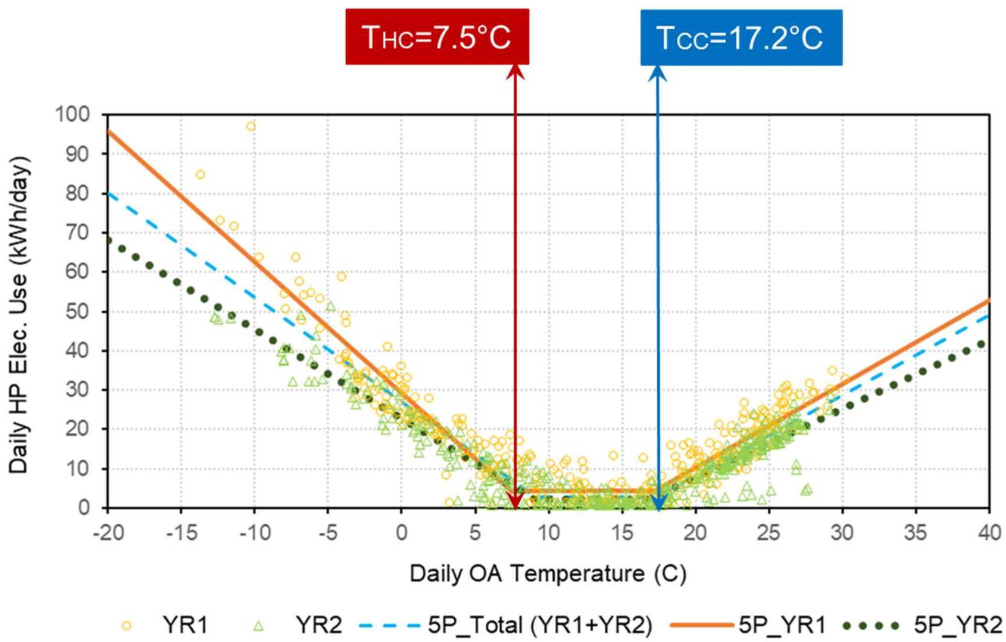
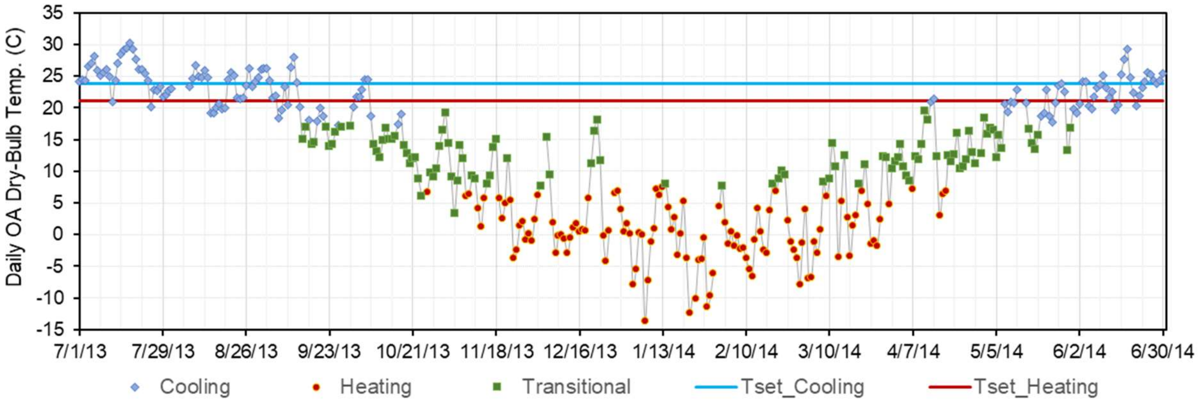
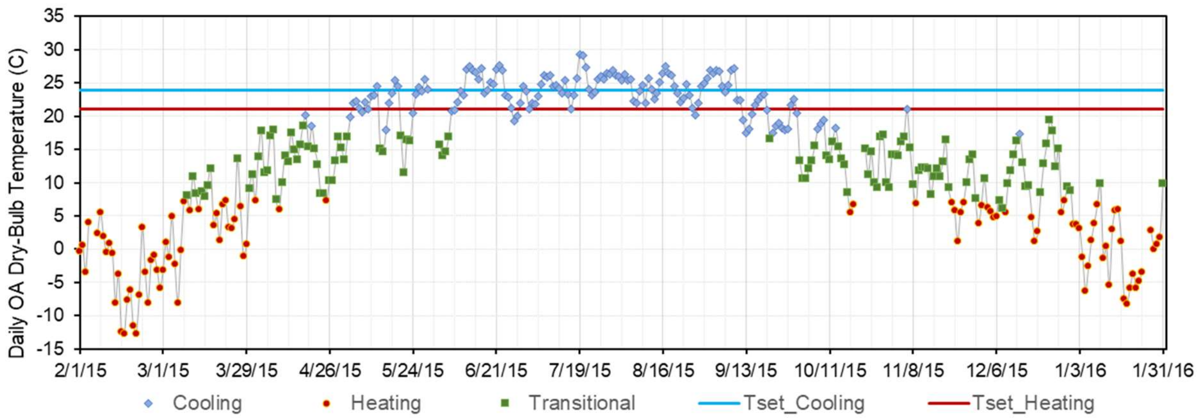


Figure 4: Daily Heat Pump Electricity Use Against the Daily Outdoor Air Temperature with a Five-Parameter (5-P) Change-Point Linear Models, Including the Heating Change-Point Temperature (T_{HC}) and the Cooling Change-Point Temperature (T_{CC}) of the Year 1 Model.



(a) Year 1



(b) Year 2

Figure 5: Classification of the Heating, Transitional, and Cooling Seasons.

2.3.2. ENERGY PERFORMANCE CHARACTERIZATION

To characterize the energy performance of the NZERTF during the analysis period, 43 electric power channels were grouped into five major end uses such as:

- Conditioning (i.e., heat pump (HP) for cooling and heating and whole-house dehumidifier (WHD));
- Ventilation (i.e., HRV);
- Lighting;
- Plug loads + appliances (i.e., refrigerator, dish washer, cooktop, oven, clothes washer, clothes dryer, and microwave); and
- Domestic hot water (i.e., heat pump water heater (HPWH)).

The weather-dependent, change-point linear regression electricity use models were then calculated with daily data for the whole house[6] and major end uses for weekdays and weekends, separately, using the ASHRAE IMT as shown in Figure 6. This method allowed identify key influencing factors about building electricity use to be determined by correlating the electricity use to a potential explanatory variable such as OA temperature. The functional forms of regression models used in this study include a one-parameter (1-P) model (i.e.,

[6] The whole-house electricity use of NZERTF includes the five major end uses and the electricity use by the solar system circulators which was about 3% of the whole-house electricity use on an annual basis.

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mean model when building electricity use does not change with the independent variable), a three-parameter (3-P) change-point linear model, and a five-parameter (5-P) change-point linear model.

When the consumption on the weekdays and weekends were not significantly different, a combined all-day model was developed using data from all days of the week. When the consumption significantly depended on a day-of-week schedule such as lighting and plug loads, multiple day-of-week models were developed. YR1 HTTD (i.e., baseline) data were used to establish a self-reference benchmark for YR1 LTTD and YR2 data with energy-efficient improvements.

The differences in the NZERTF conditioning electricity use (i.e., savings[7]) was then calculated for the YR1 LTTD and YR2 operations against the baseline, YR1 HTTD operation by subtracting the YR1 HTTD consumption from the YR1 LTTD and YR2 consumption, respectively. Two different types of consumption were used in this calculation:

- Measured electricity use; and
- Predicted electricity use.

The measured electricity use is the measured, actual conditioning electricity use, which was available only for the period when the respective TTD operation was applied such as:

- YR1 HTTD from July 1, 2013 to January 22, 2014;
- YR1 LTTD from January 24, 2014 to June 30, 2014; and
- YR2 from February 1, 2015 to January 31, 2016.

The predicted electricity use, which was the consumption that would have been if the corresponding TTD operation was applied, was calculated using the three 5-P change-point linear energy models with the OA temperatures during the period of the Year 1 and Year 2 operations. For example, the YR1 HTTD predicted electricity use could be calculated for the periods of the YR1 LTTD and YR2 operations although the YR1 HTTD operation was not actually applied.

To ensure confidence in the calculated regression model as well as energy performance changes, this study referred to the ASHRAE Guideline 14-2014 (ASHRAE 2014b), including the two statistical indicators such as the coefficient of determination (R^2) and the coefficient of variation of the root mean square error (CV-RMSE). The R^2 was used to quantify the goodness-of-fit of the model, where an R^2 equal to 1.0 means a perfect fit, and an R^2 above 0.8 indicates that the fit is good (ASHRAE 2010a). The CV-RMSE was used to quantify how data were scattered around the model. The Whole-Building Prescriptive Path in Section 4.3.2.1 of the ASHRAE Guideline 14-2014 allows a baseline model to have a maximum CV-RMSE between 20% and 30% depending on the number of months of post-retrofit data available for computing the savings.

[7] In this report, the word "savings" is used to represent the changes in energy use versus the YR1 HTTD operation. Negative savings means increased energy use compared to the YR1 HTTD operation.

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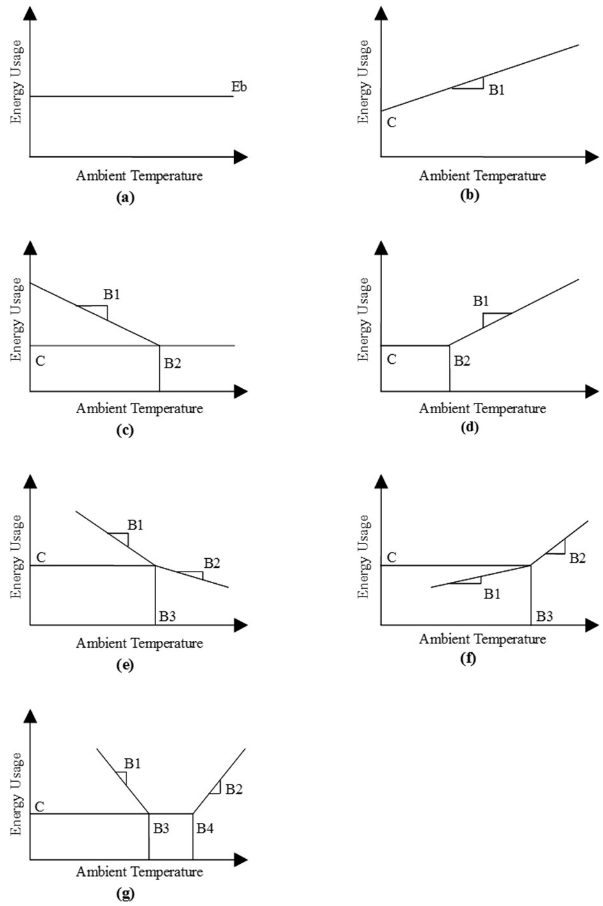

Figure 6: ASHRAE IMT Change-Point Models. (a) Mean or 1-P Model, (b) 2-P Model, (c) 3-P Heating Model, (d) 3-P Cooling Model, (e) 4-P Heating Model, (f) 4-P Cooling Model, and (g) 5-P Model.

2.3.3. THERMAL COMFORT ANALYSIS

This study performed a statistical characterization of the continuously-measured long-term thermal comfort data not only for the primary rooms but also for the attic and the basement that are thermally important due to possible heat transfer from/to the primary rooms. The descriptive statistics of the thermal comfort data were calculated for each subgroup, which was also graphically displayed using the modified box-and-whisker plots proposed by Kim et al. (2019).

The modified box-and-whisker plot displays long-term thermal comfort data using multiple percentile ranks to characterize extreme variations based on ±1.5%, ±2.5%, ±5% and ±10% deviations. For example, the 1.5th and 98.5th percentiles characterize data based on ±1.5% deviation, which corresponds to 3% of the period in total. In the same way, the 2.5th and 97.5th percentiles are based on ±2.5% deviation (i.e., 5% of the period in total), the 5th and 95th percentiles are based on ±5% deviation (i.e., 10% of the period in total), and the 10th and 90th percentiles are based on ±10% deviation (i.e., 20% of the period in total). The 3% and 5% deviations are the recommended criteria for acceptable deviations to evaluate long term performance of buildings provided in the Annex G of the European standard, DIN EN 15251 (CEN 2007).

Although the globe temperatures were measured in the five rooms (i.e., LR, KIT, MBR, BR2, and BR3), this study used room air temperature as the primary index for a thermal uniformity analysis in terms of providing uniform space temperatures across the house since this study primarily focuses on the residential system's fundamental ability to produce and deliver a certain temperature to multiple occupied spaces as installed in the house. In addition, it was found that the globe-to-air temperature differences (i.e., ΔT (°C) = Tg – Ta) calculated using the 5-min average temperature data collected from the five primary rooms were within ±0.5°C, which was more than 98.5% of the period based on 1.5% extreme variation except for the kitchen during the transitional season[8] (Appendix D). This indicates there were no significant radiation sources at NZERTF.

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To better understand the observed temporal variations of the long-term thermal comfort data, which was revealed from a statistical analysis, this study also performed an advanced characterization of the measured thermal comfort data relative to coincident outdoor weather and the time of the day. First, this study characterized variations of the measured thermal comfort data relative to outdoor weather using a 5°C (9°F) binned quartile analysis, which also allowed a weather-normalized characterization and comparison of the impact of the three different TTD operations on thermal comfort. To accomplish this, the 5-min average air temperatures measured in each room were characterized using the modified binned box-and-whisker plots, where the 1.5th, 2.5th, 5th, 10th, 25th, 50th, 75th, 90th, 95th, 97.5th, and 98.5th percentiles, as well as minimum, mean, and maximum values, were arranged against outdoor temperatures binned into 5°C (9°F) bins.

Another characterization was a time-of-day analysis of the hourly average room temperature data using a time-of-day colored map (i.e., heat map). The use of the proposed time-of-day colored map was useful in tracking how the rooms were conditioned over the course of a day and a year separately for YR1 HTTD, YR1 LTTD, and YR2 based on data with an hourly temporal resolution.

2.3.4. WHOLE-HOUSE THERMAL COMFORT METRICS

The whole-house thermal comfort performance was evaluated in terms of:

- Temperature deviation from the setpoint temperature (i.e., room-to-thermostat temperature difference);
- Room-to-room temperature difference to evaluate spatial thermal uniformity;
- Cyclic discomfort to evaluate temporal thermal uniformity; and
- RH deviation from the setpoint RH (i.e., room-to-humidistat RH difference) to evaluate latent cooling performance (i.e., dehumidification efficiency)

The room temperature deviation from the thermostat setpoint temperature was calculated as room-to-thermostat temperature difference (i.e., ΔT (°C) = T_{room} – $T_{setpoint}$) using the 5-min average room temperature data collected from the five primary rooms (i.e., LR, KIT, MBR, BR2, and BR3) and two additional rooms on the first floor (i.e., DR, and BR4). In addition, a whole-house room-to-thermostat temperature difference was calculated using an area-weighted whole-house temperature, which is the temperature weighted by the floor areas of

[8] The globe-to-air temperature differences in the kitchen during the transitional season had a few more occasions exceeding 0.5°C, which was still less than 2.5% of the period.

seven primary rooms (i.e., LR, KIT, DR, BR4, MBR, BR2, and BR3 representing 71% of the total floor area) as shown in Figure 7[9].

The setpoint temperatures used in the calculation are 23.8°C (75°F) for the cooling season and 21.1°C (70°F) for the heating season. For the transitional season, 23.8°C (75°F) was used if the room temperature was above the cooling setpoint temperature (i.e., 23.8°C), while 21.1°C (70°F) was used if the room temperature was below the heating setpoint temperature (i.e., 21.1°C). The percentage distribution of the room-to-thermostat temperature difference was then compared against the Air Conditioning Contractors of America (ACCA) Manual RS benchmarks (ACCA 1997):

- Thermostat setpoint ±1.67°C (±3°F) for the cooling season;
- Thermostat setpoint ±1.11°C (±2°F) for the heating season; and
- Between thermostat setpoint -1.11°C (-2°F) and thermostat setpoint +1.67°C (+3°F) for the transitional season.

To evaluate the spatial thermal uniformity across the house, the room-to-room temperature difference was calculated using the 5-min average room temperature data collected from the five primary rooms (i.e., LR, KIT, MBR, BR2, and BR3) and two additional rooms on the first floor (i.e., DR, and BR4): ΔT (°C) = MAX(T_{room1}, T_{room2}, …) – MIN(T_{room1}, T_{room2}, …). The percentage distribution of the room-to-room temperature difference was then compared against the ACCA Manual RS benchmarks:

- 1.67°C (3°F) average and 3.33°C (6°F) maximum for the cooling and transitional season; and
- 1.11°C (2°F) average and 2.22°C (4°F) maximum for the heating season.

To evaluate the temporal thermal uniformity, the cyclic and drift temperature variations with time were calculated using the 1-min operative temperature for the five primary rooms (i.e., LR, KIT, MBR, BR2, and BR3) and the 1-min area-weighted whole-house operative temperature. The whole-house operative temperature was weighted by the floor areas of five primary rooms (i.e., LR, KIT, MBR, BR2, and BR3 representing 50% of the total floor area) where the globe temperatures were collected. The 1-min operative temperature was calculated in accordance with Appendix A of the ASHRAE Standard 55-2017 (ASHRAE 2017) to be used in this analysis per Section 5.3.5 of the ASHRAE Standard 55-2017. The percentage of failures in cyclic and drift temperature variations was then calculated based on the ASHRAE Standard 55-2017 benchmarks:

- 1.1°C (2.0°F) maximum for any 15-minute period;
- 1.7°C (3.0°F) maximum for any 30-minute period;
- 2.2°C (4.0°F) maximum for any 1-hour period;
- 2.8°C (5.0°F) maximum for any 2-hour period; and
- 3.3°C (6.0°F) maximum for any 4-hour period.

To evaluate the effectiveness of latent cooling performance, the RH deviation from the humidistat setpoint (i.e., 50% RH) was calculated as room-to-humidistat RH difference (i.e., ΔRH (%) = $RH_{room} - RH_{setpoint}$ if $RH_{room} > RH_{setpoint}$; or ΔRH (%) = 0% RH if $RH_{room} < RH_{setpoint}$) using the 5-min average room RH data collected from the five primary rooms (i.e., LR, KIT, MBR, BR2, and BR3) and the MBA and BSMT only for the cooling season. In addition,

[9] Floor area of NZERTF is equivalent to volume of the house because the floor-to-ceiling height was same across the house.

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a whole-house room-to-humidistat RH difference was calculated using an area-weighted whole-house RH, which is the RH weighted by the floor areas of five primary rooms (i.e., LR, KIT, MBR, BR2, and BR3 representing 50% of the total floor area). The percentage distribution of the room-to-humidistat RH difference was then calculated and compared between the three TTD operations.

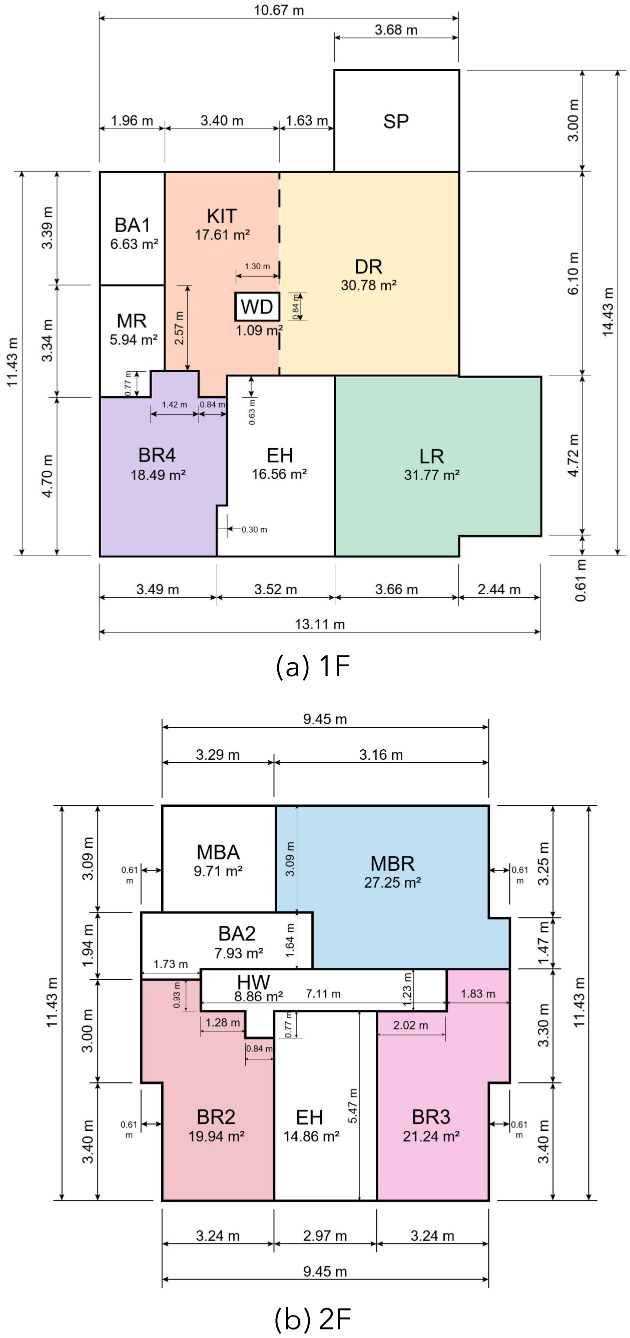

Figure 7: NZERTF Floor Maps Showing the Seven Primary Rooms on the First Floor (Upper Figure) and the Second Floor (Lower Figure) of the NZERTF.

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2.4. INTEGRATIVE METHOD

To assess a whole-house performance in an integrative way based on measured energy and thermal comfort performance of the house, this study proposed a rating method based on the weather dependent conditioning energy use (i.e., heating, cooling, and dehumidification) of the house and coincident whole-house thermal comfort metrics that were averaged over a particular range of weather condition. The proposed method was applied to the collected Year 1 and Year 2 NZERTF performance data to ensure the validity, reliability, and practicality of the proposed assessment method. For example, the daily OA dry-bulb temperature was sorted into 5°C (9°F) temperature bins while the mean coincident values of daily conditioning energy uses and daily room-to-thermostat temperature differences were determined for each bin, which were then paired and plotted using a scatter plot for three different TTD operations. This allowed a weather-normalized comparison of the three different TTD operations in terms of both energy and thermal comfort for a particular weather condition.

The whole-house thermal comfort metrics considered in this study are:

- Room-to-room temperature difference and room-to-room discomfort degree hours
- Room-to-thermostat temperature difference using:
  - Living room temperature
  - Whole-house temperature weighted by the floor areas of seven primary rooms (i.e., LR, KIT, DR, BR4, MBR, BR2, and BR3 representing 71% of the total floor area) as shown in Figure 7.
- Room-to-humidistat RH difference (only for the cooling season) using
  - Living room RH
  - Whole-house RH weighted by the floor areas of five primary rooms (i.e., LR, KIT, MBR, BR2, and BR3 representing 50% of the total floor area) where the humidity data were collected.

The room-to-room temperature difference (R-to-R TD) and room-to-room discomfort degree hours (R-to-R DDH) were calculated as follows:

- Daily average R-to-R TD (°C) = $\sum(\mathrm{MAX}(T_{room1},T_{room2},...) - \mathrm{MIN}(T_{room1},T_{room2},...))$ / N
- Daily total R-to-R DDH (°C·h) = ∑(Hourly average R-to-R TD)

  where,

  Hourly average R-to-R TD (°C) = $\sum(\mathrm{MAX}(T_{room1},T_{room2},...) - \mathrm{MIN}(T_{room1},T_{room2},...))$ / N′

  N = number of data points in a day (i.e., 1440/selected data interval in minutes)

  N′ = number of data points in an hour (i.e., 60/selected data interval in minutes)

Three different metrics were calculated for the room-to-thermostat temperature difference (R-to-T TD) using the living room temperature and the area-weighted whole-house temperature. This includes:

- Daily average R-to-T TD(–) (°C) = $\sum(\Delta T)$ / N
- Daily average R-to-T TD (+) (°C) = $\sum(\Delta T)$ / N
- Daily average R-to-T Total TD (°C) = |R-to-T TD (-)| + |Ro-to-T TD (+)|

  where,

  ΔT (°C) = $T_{room} - T_{setpoint}$

  N = number of data points in a day (i.e., 1440/selected data interval in minutes)

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Daily average R-to-T TD is the sum of absolute differences between the room temperature and the setpoint temperature.

The room-to-humidistat RH difference (R-to H RHD) includes one metric, which was calculated using the living room RH and the area-weighted whole-house RH only for the cooling season:

- Daily average R-to-H RHD (%) $= \sum(\Delta RH\ (\%)) / N$
  where,
  $\Delta RH\ (\%) = RH_{room} - RH_{setpoint}$ (if $RH_{room} > RH_{setpoint}$)
  $= 0\%\ RH$ (if $RH_{room} < RH_{setpoint}$)
  N = number of data points in a day (i.e., 1440/selected data interval in minutes)

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3. NZERTF ENERGY AND THERMAL COMFORT ANALYSIS

This section presents a detailed analysis of the NZERTF energy and thermal comfort data for the Year 1 and Year 2.

Section 3.1 presents a weather-dependent characterization of the NZERTF energy use for the whole house and major end uses.

Section 3.2 presents the results of a weather-normalized comparison of the NZERTF conditioning energy use between the three different TTD operations.

Section 3.3 presents a statistical characterization of the long-term room temperature and humidity data.

Section 3.4 presents an advanced characterization of the room temperature and humidity data relative to the outdoor temperature and humidity.

Section 3.5 presents the time-of-day characterization of the room temperature data using a time-of-day colored map (i.e., heat map).

3.1. ENERGY PERFORMANCE CHARACTERIZATION

3.1.1. WHOLE-HOUSE ELECTRICITY

Figure 8 presents the time series plot of the daily total whole-house electricity use of NZERTF (kWh/day) for both years. Figure 9 presents the same data plotted against the daily average OA temperature with the final 5-P change-point linear models for weekdays and weekends separately because the energy consumption patterns were distinctively different between weekdays and weekends. Figure 10 presents the same data plots by three different TTD operations with all three 5-P models, including an all-day model, a weekday model, and a weekend model.

The results showed that the daily total whole-house electricity use was strongly correlated to the daily average OA temperature. The 5-P change-point linear models appeared to yield the best-fit with:

- (YR1 HTTD) R^2= 0.89 and CV-RMSE = 14.5% for Weekdays; R^2= 0.88 and CV-RMSE = 10.2% for Weekends;
- (YR1 LTTD) R^2= 0.89 and CV-RMSE = 17.9% for Weekdays; R^2= 0.84 and CV-RMSE = 14.2% for Weekends; and
- (YR2) R^2= 0.86 and CV-RMSE = 14.7% for Weekdays; R^2= 0.83 and CV-RMSE = 12.4% for Weekends.

The weekend whole-house electricity use was consistently higher than the weekday electricity use for all three TTD operations due to the higher lighting and plug loads/appliances electrical use simulated for the weekends. Among the three TTD operations, YR2 had the lowest weekday consumption. YR1 HTTD and YR1 LTTD had similar weekday use during the heating months, while there was a slight deviation during the cooling months. Compared to

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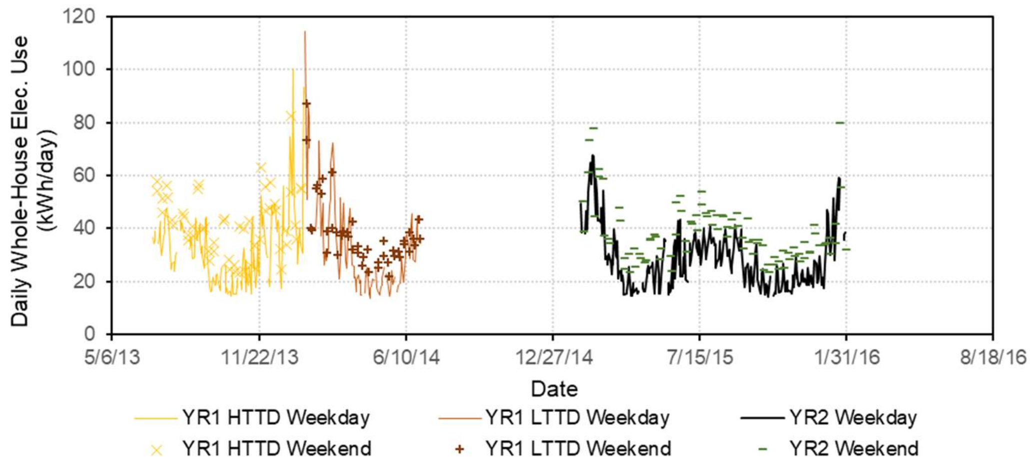
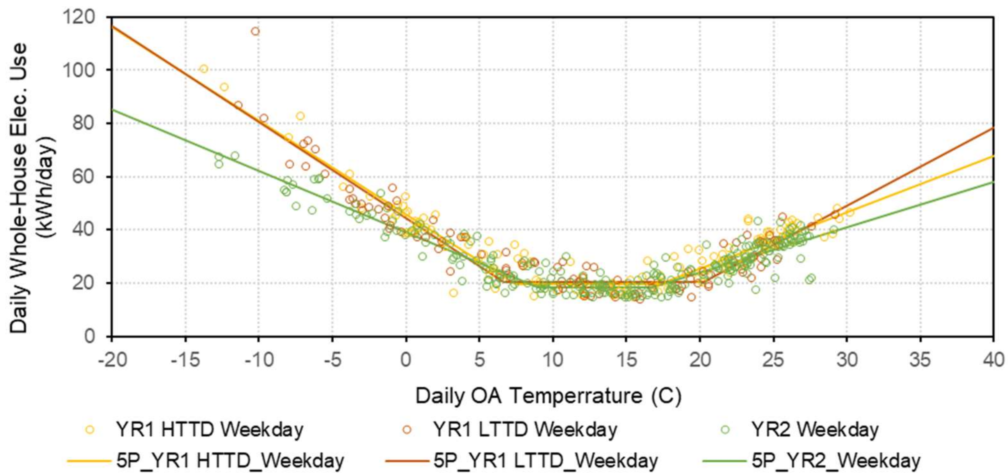
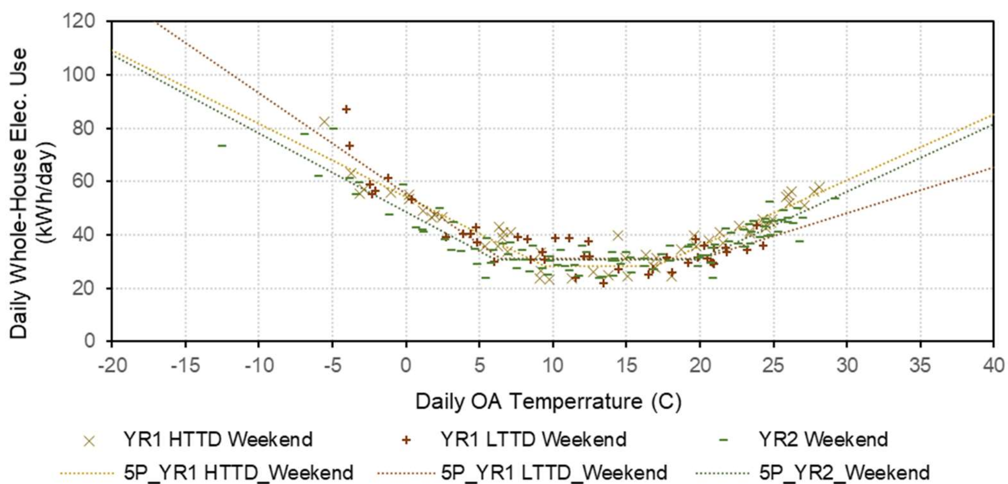


Figure 8: Daily Total Whole-House Electricity Use of the NZERTF.



(a) Weekday Model



(b) Weekend Model

Figure 9: Daily Total Whole-House Electricity Use Models for Weekdays and Weekends.

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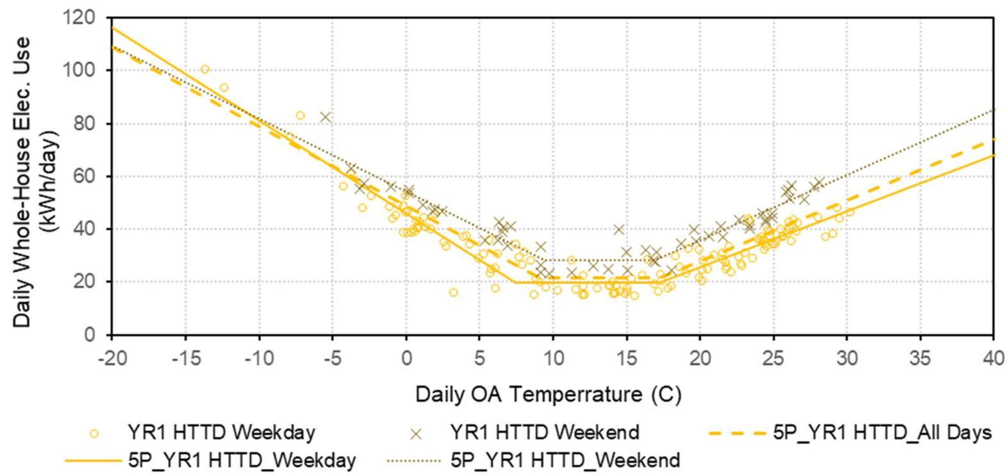
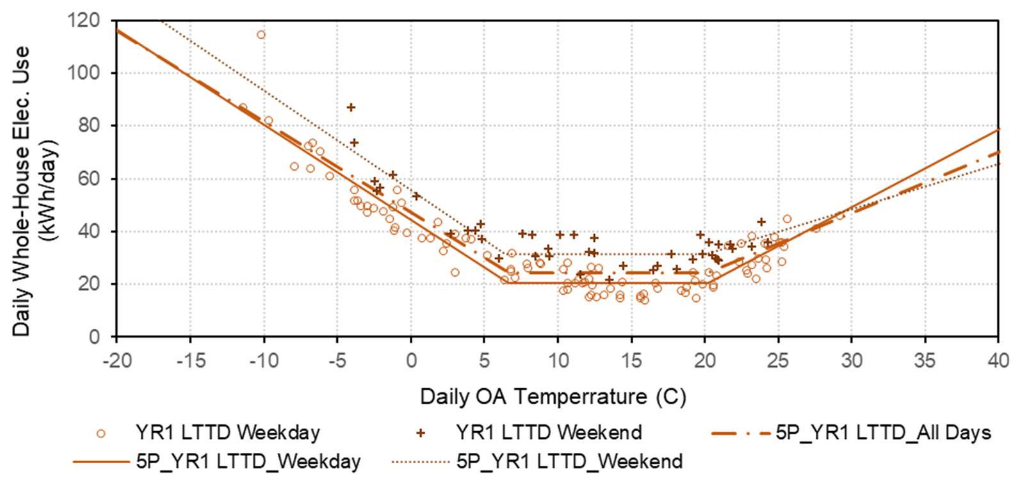
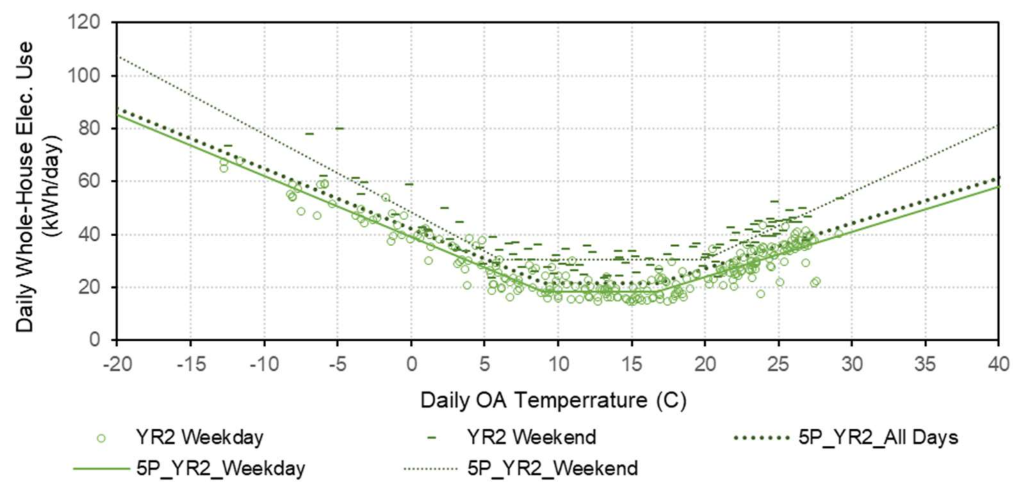


(a) YR1 HTTD



(b) YR1 LTTD



(c) YR2

Figure 10: Daily Total Whole-House Electricity Use Models by TTD Operations.

the weekday electricity use, the difference in the weekend electricity use between the three TTD operations was less obvious.

3.1.2. MAJOR END USES

Figure 11 presents the time series plot of the daily total conditioning electricity use of NZERTF (i.e., HP for cooling and heating and WHD in kWh/day), which was about 49% and 43% of the whole-house electricity use on an annual basis for Year 1 and Year 2, respectively. Figure 12 presents the same data plotted against the daily average OA temperature with the final 5-P change-point linear models. Figure 13 presents the same data plots by three different TTD operations with all three 5-P models, including an all-day model, a weekday model, and a weekend model.

The results showed that the daily total conditioning electricity use was strongly correlated to the daily average OA temperature. The 5-P change-point linear models appeared to yield the best-fit with:

- (YR1 HTTD) R^2= 0.89 and CV-RMSE = 25.6%;
- (YR1 LTTD) R^2= 0.89 and CV-RMSE = 31.6%; and
- (YR2) R^2= 0.86 and CV-RMSE = 30.1%.

There was no clear difference in the conditioning electricity use between the weekdays and weekends for all three TTD operations. Among the three TTD operations, YR2 had the lowest consumption, while YR1 LTTD had the highest consumption at the same OA temperatures.

Figure 14 presents the time series plot of the daily total ventilation electricity use of NZERTF (i.e., HRV in kWh/day), which was about 4% of the whole-house electricity use on an annual basis for both years. Figure 15 presents the same data plotted against the daily average OA temperature with the final 5-P change-point linear models. Figure 16 presents the same data plots by three different TTD operations with all three 5-P models, including an all-day model, a weekday model, and a weekend model.

The results showed that the daily total whole-house electricity use was moderately correlated to the daily average OA temperature. The 5-P change-point linear models appeared to yield the best-fit with:

- (YR1 HTTD) R^2= 0.56 and CV-RMSE = 2.5%;
- (YR1 LTTD) R^2= 0.52 and CV-RMSE = 1.9%; and
- (YR2) R^2= 0.82 and CV-RMSE = 1.6%.

There was no clear difference in the ventilation electricity use between the weekdays and weekends for all three TTD operations. Among the three TTD operations, YR2 had the lowest consumption, while YR1 HTTD and YR1 LTTD had comparable energy consumption patterns. The heating change-point temperature was almost same as the cooling change-point temperature for both YR1 HTTD and YR1 LTTD.

Figure 17 presents the time series plot of the daily total lighting[10] electricity use of NZERTF (kWh/day), which was about 5% of the whole-house electricity use on an annual basis for both

[10] The lighting electricity use in the basement was excluded in this analysis since there were a few occasions the basement lights stayed on due to some activities at NZERTF.

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years. Figure 18 presents the same data plotted against the daily average OA temperature with the final 1-P models for weekdays + Sundays and Saturdays separately because the energy consumption patterns were distinctively different for Saturdays. Figure 19 presents the same data plots by three different TTD operations with all three 1-P models, including an all-day model, a weekday + Sunday model, and a Saturday model.

Not surprisingly, no relationship was observed between the daily total lighting electricity use and the daily average OA temperature, which consequently yielded 1-P models (i.e., mean models). The Saturday lighting electricity use was consistently higher than the weekday + Sunday electricity use for all three TTD operations due to the higher lighting electrical use simulated for the Saturdays. There was no difference in the calculated models between the three TTD operations, which was expected.

Figure 20 presents the time series plot of the daily total plug loads + appliances electricity use of NZERTF (i.e., plug loads, refrigerator, dish washer, cooktop, oven, clothes washer, clothes dryer, and microwave in kWh/day), which was about 31% and 36% of the whole-house electricity use on an annual basis for Year 1 and Year 2, respectively. Figure 21 presents the same data plotted against the daily average OA temperature with the final 1-P models for MTTF (i.e., Mondays, Tuesdays, Thursdays, and Fridays), Wednesdays, Saturdays, and Sundays separately because the energy consumption patterns were distinctively different depending on the day of the week. Figure 22 presents the same data plots by three different TTD operations with all five 1-P models, including an all-day model, a MTTF model, a Wednesday model, a Saturday model, and a Sunday model.

Like lighting electricity use, no relationship was observed between the daily total plug loads + appliances electricity use and the daily average OA temperature, which consequently yielded 1-P models (i.e., mean models). The Saturday plug loads + appliances electricity use was the highest, which was followed by Sundays, Wednesdays, and other days-of-the-week (i.e., MTTF) consumption. There was also a period when the plug loads + appliances consumption was unusually higher than other days, which occurred from November 24, 2015 to December 15, 2015 due to the increased electrical use in the dining room. There was a small difference in the calculated models between the three TTD operations, which might be affected by a few outliers. YR2 had the highest plug loads + appliances electricity use, which was followed by YR1 HTTD and YR1 LTTD.

Figure 23 presents the time series plot of the daily total domestic hot water electricity use of NZERTF (i.e., HPWH in kWh/day), which was about 9% and 10% of the whole-house electricity use on an annual basis for Year 1 and Year 2, respectively. Figure 24 presents the same data plotted against the daily average OA temperature with the final 3-P heating models for weekdays and weekends separately because the energy consumption patterns were distinctively different between weekdays and weekends. Figure 25 presents the same data plots by three different TTD operations with all five 3-P heating models, including an all-day model, a weekday model, and a weekend model.

The daily total domestic hot water electricity use showed meaningful correlation to the daily average OA temperature, although it was not strong. The 3-P heating change-point linear models appeared to yield the best-fit with:

- (YR1 HTTD) R^2= 0.40 and CV-RMSE = 46.9% for Weekdays; R^2= 0.42 and CV-RMSE = 40.0% for Weekends;

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- (YR1 LTTD) R^2= 0.49 and CV-RMSE = 38.6% for Weekdays; R^2= 0.62 and CV-RMSE = 33.2% for Weekends; and
- (YR2) R^2= 0.45 and CV-RMSE = 38.7% for Weekdays; R^2= 0.42 and CV-RMSE = 40.0% for Weekends.

The weekend domestic hot water electricity use was slightly higher than the weekday electricity use for all three TTD operations due to the higher hot water use simulated for the weekends. Between the three TTD operations, a small difference in the calculated models was observed. High CV-RMSE also indicates additional independent variable that might affect hot water electricity use.

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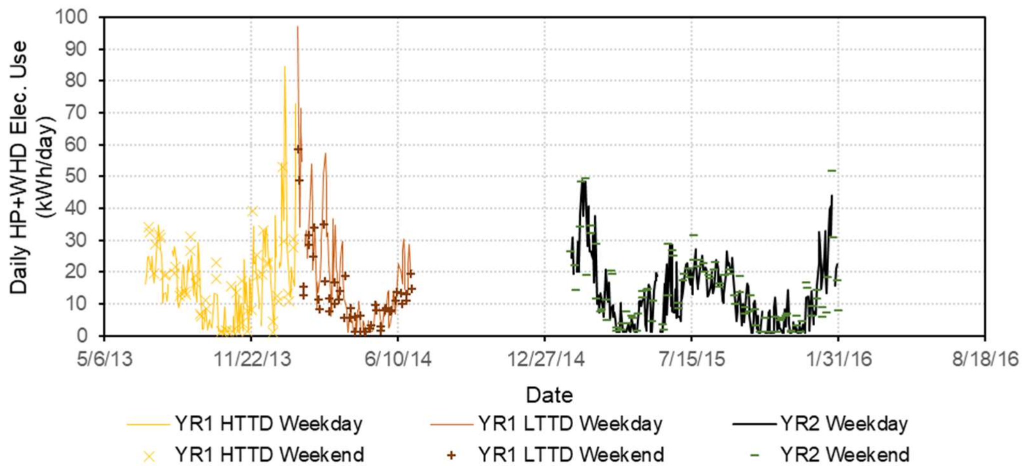


Figure 11: Daily Total Conditioning Electricity Use of the NZERTF.

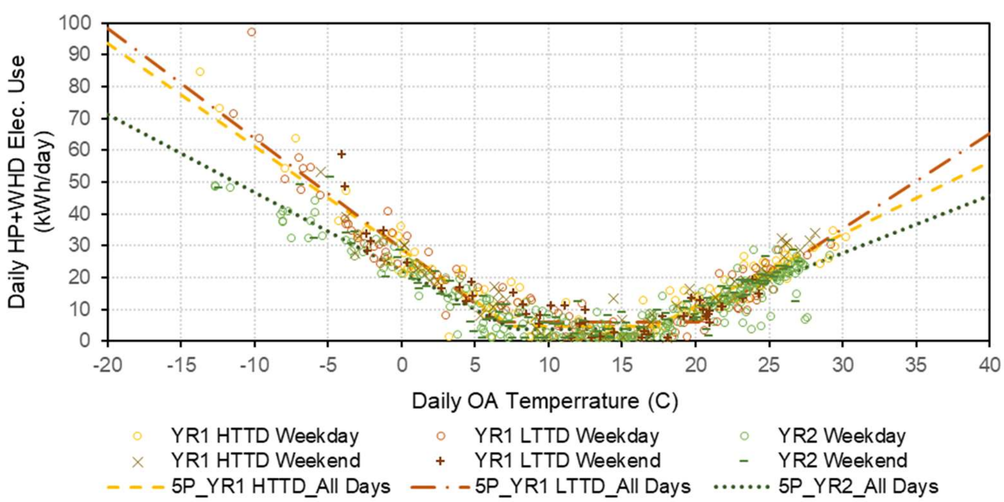
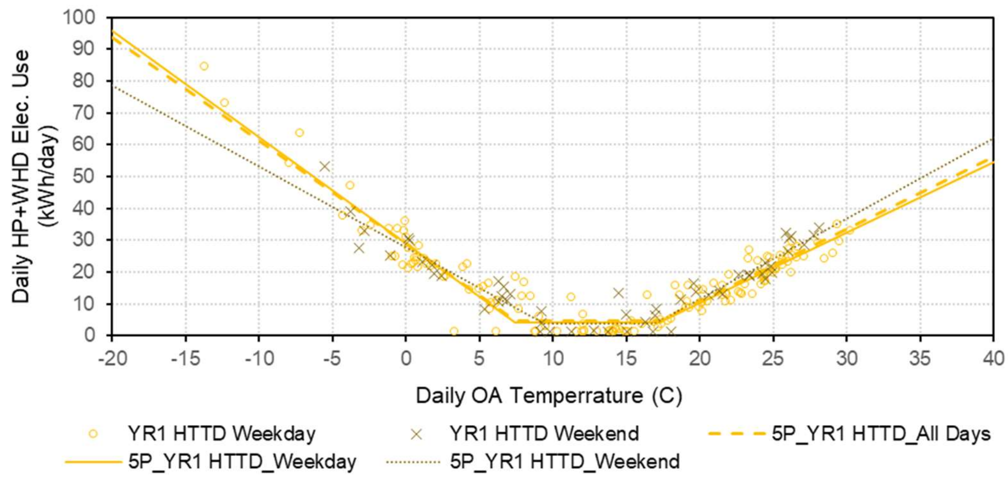
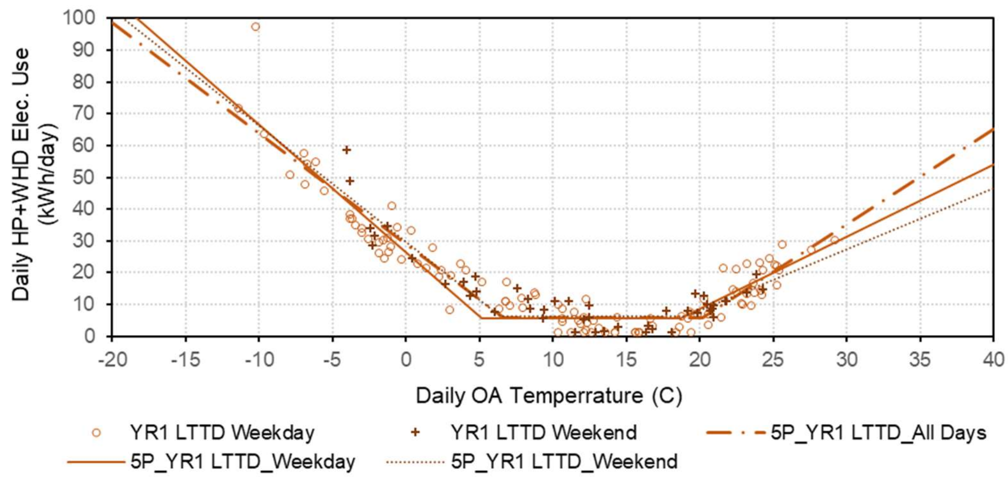


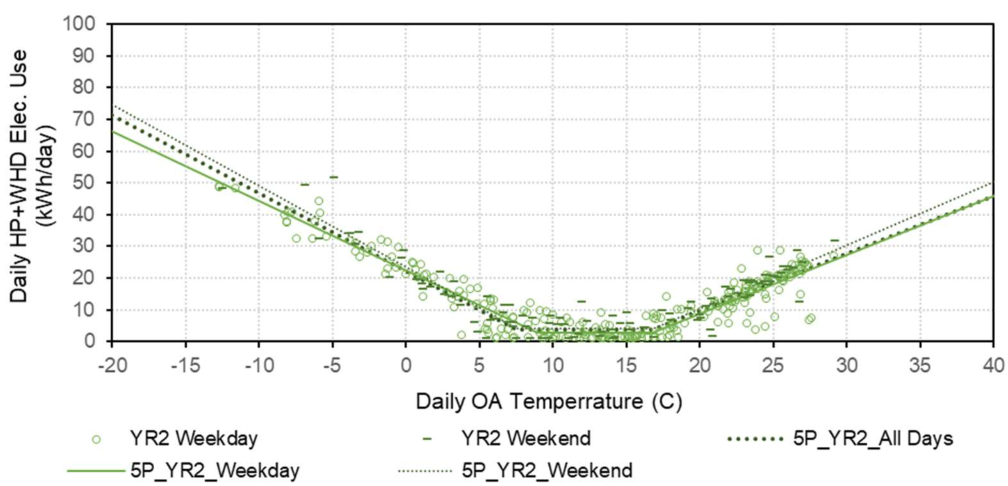
Figure 12: Daily Total Conditioning Electricity Use Models for All Days.



(a) YR1 HTTD



(b) YR1 LTTD



(c) YR2

Figure 13: Daily Total Conditioning Electricity Use Models by TTD Operations.

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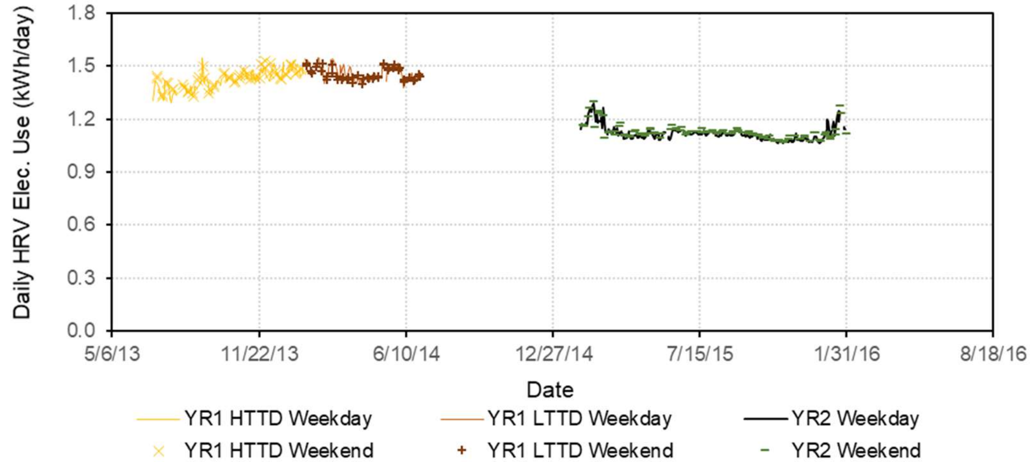


Figure 14: Daily Total Ventilation Electricity Use of the NZERTF.

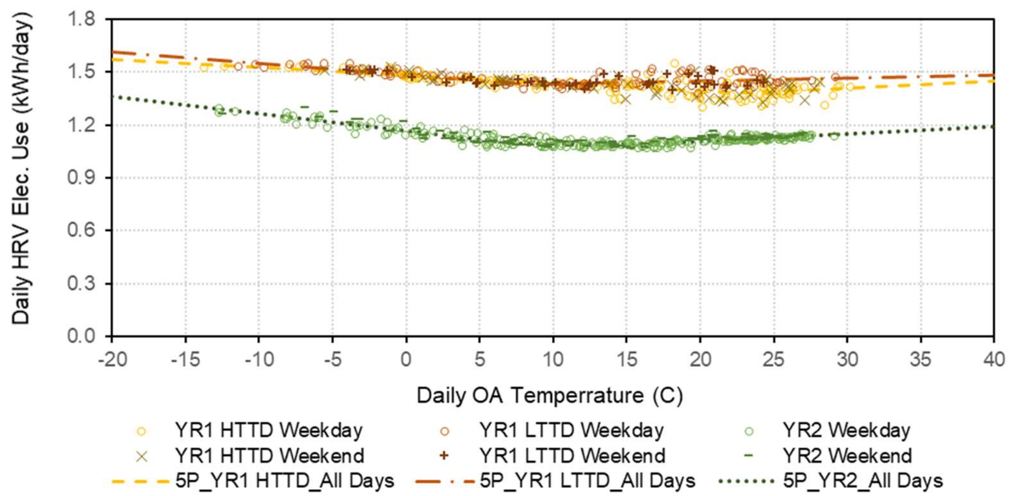
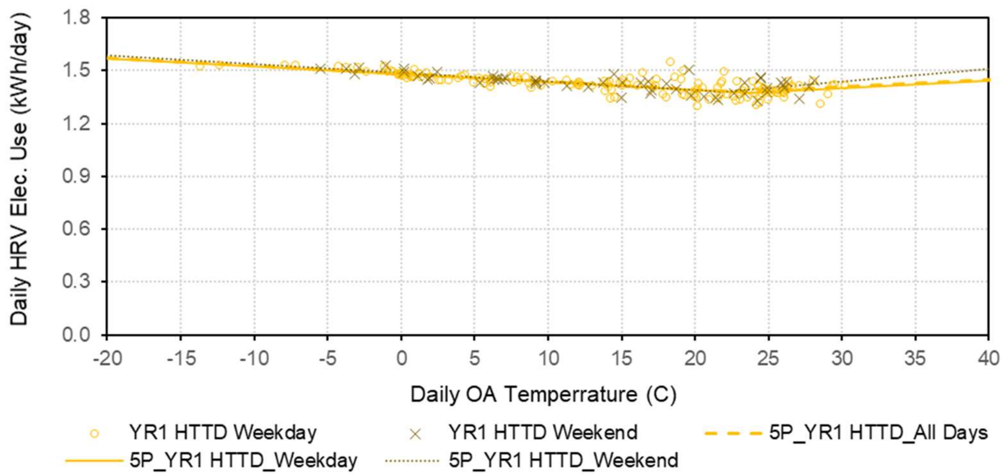
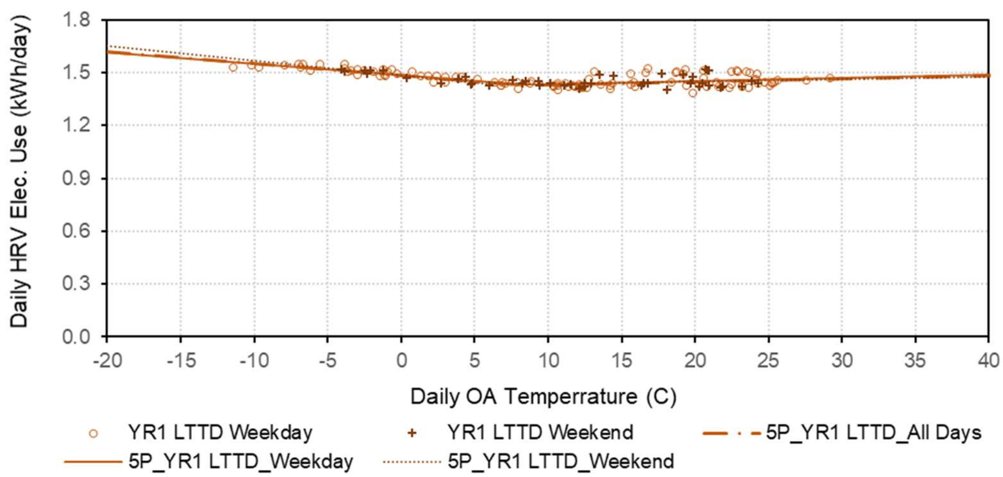


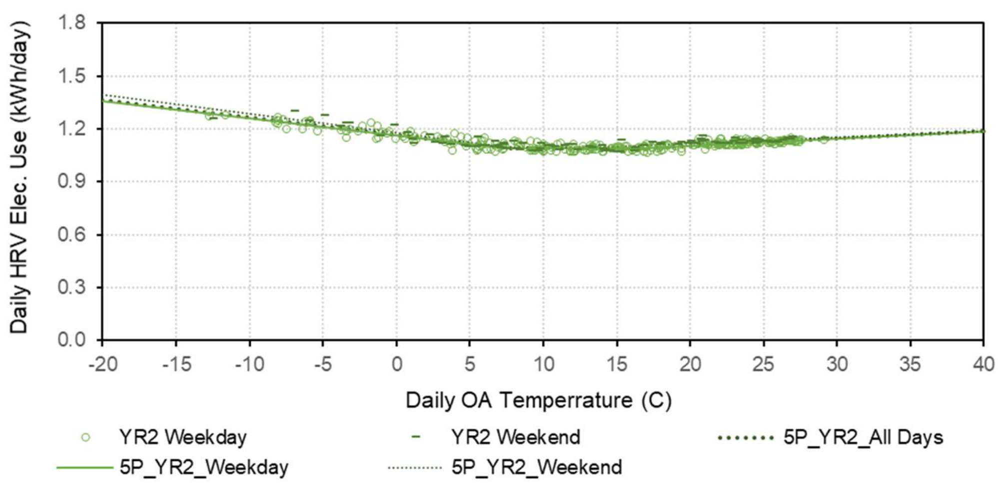
Figure 15: Daily Total Ventilation Electricity Use Models for All Days.



(a) YR1 HTTD



(b) YR1 LTTD



(c) YR2

Figure 16: Daily Total Ventilation Electricity Use Models by TTD Operations.

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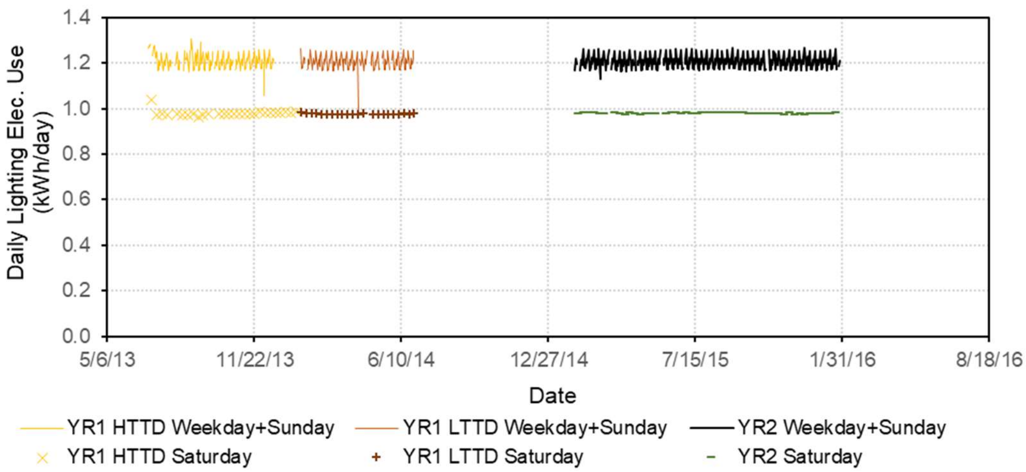
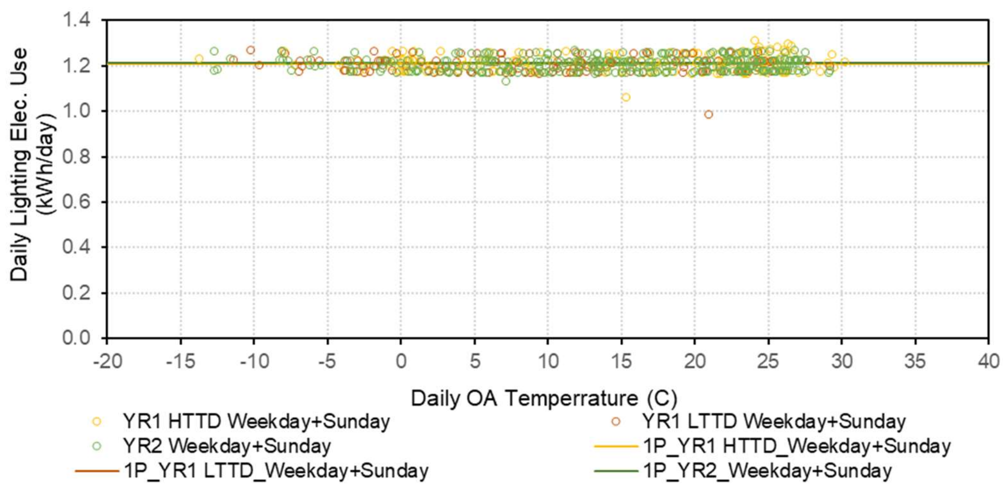
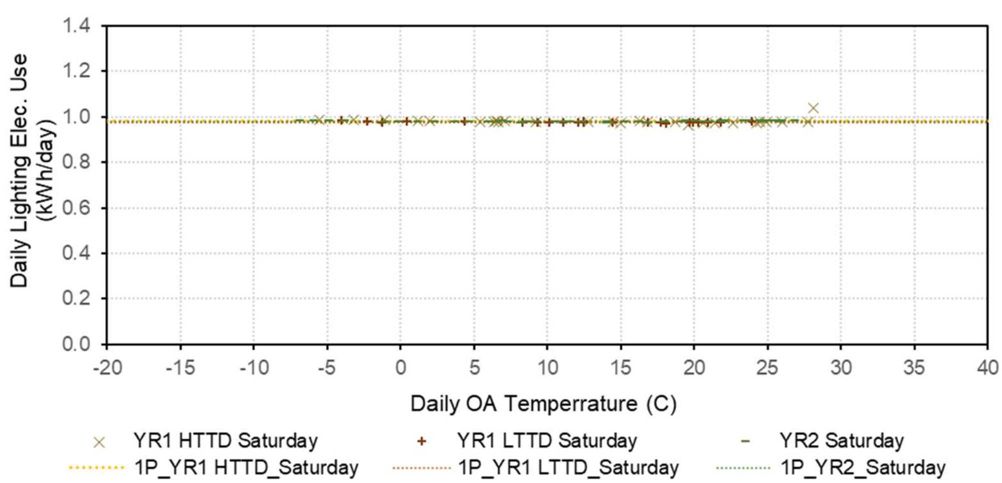


Figure 17: Daily Total Lighting Electricity Use of the NZERTF.



(a) Weekday + Sunday Model



(b) Saturday Model

Figure 18: Daily Total Lighting Electricity Use Models for Weekdays + Sundays and Saturdays.

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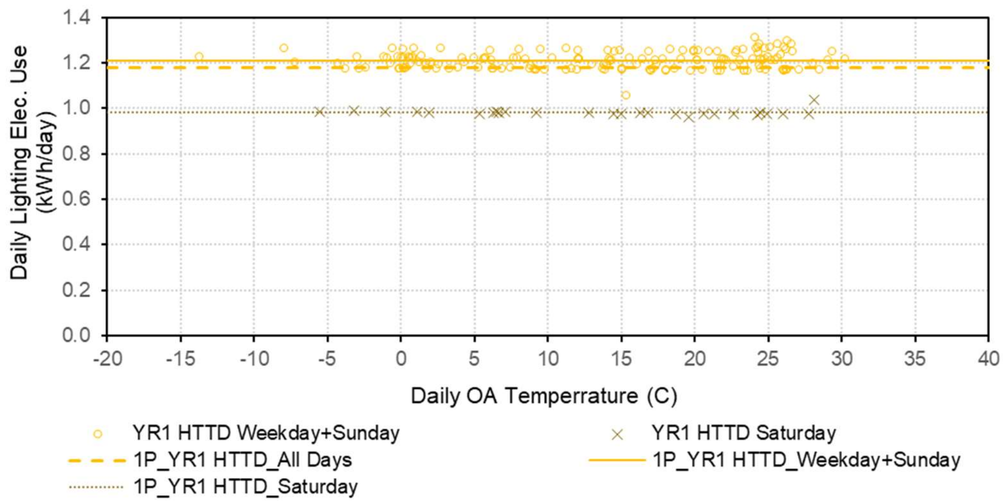
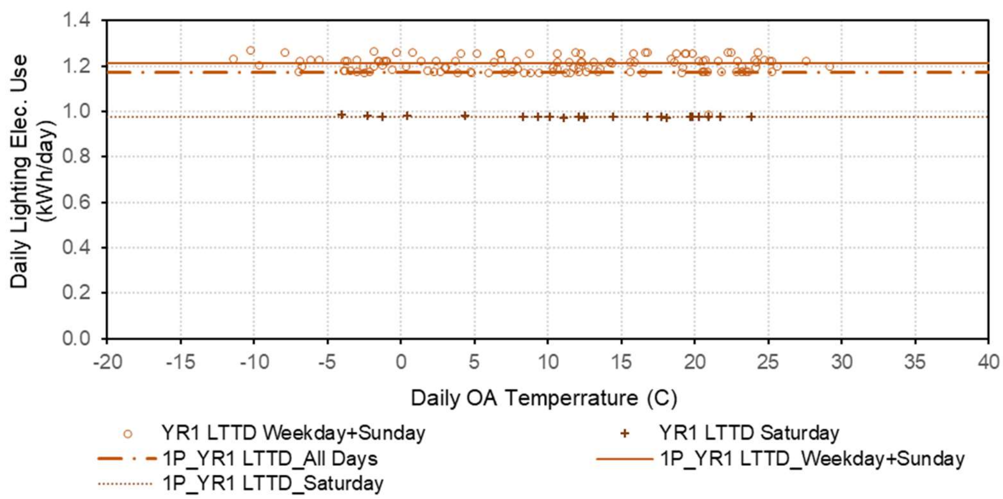
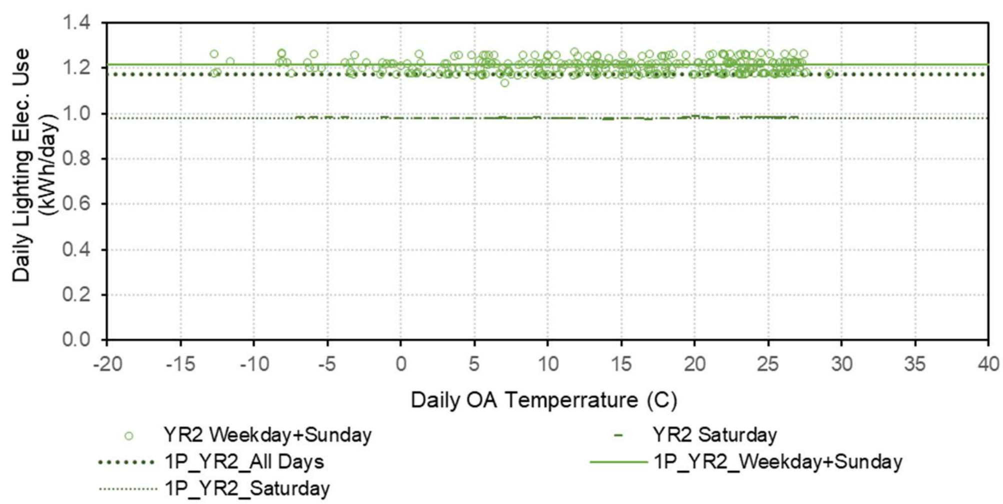


(a) YR1 HTTD



(b) YR1 LTTD



(c) YR2

Figure 19: Daily Total Lighting Electricity Use Models by TTD Operations.

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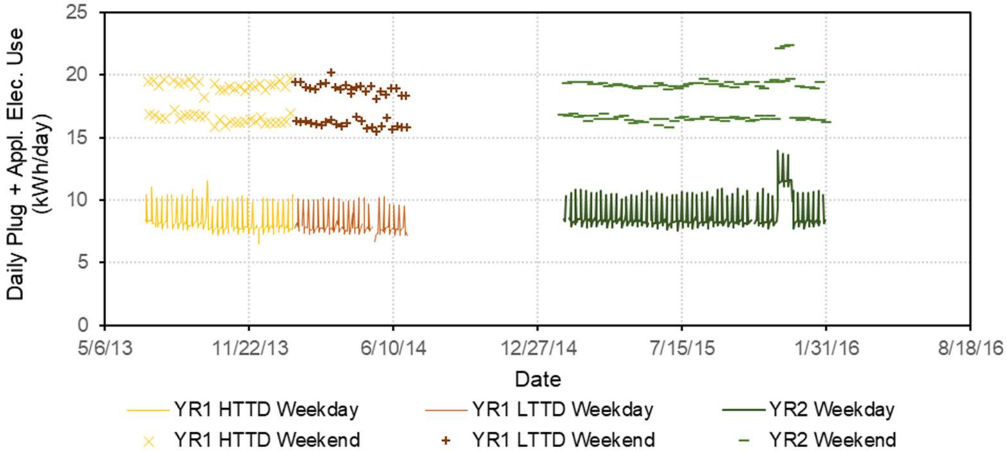
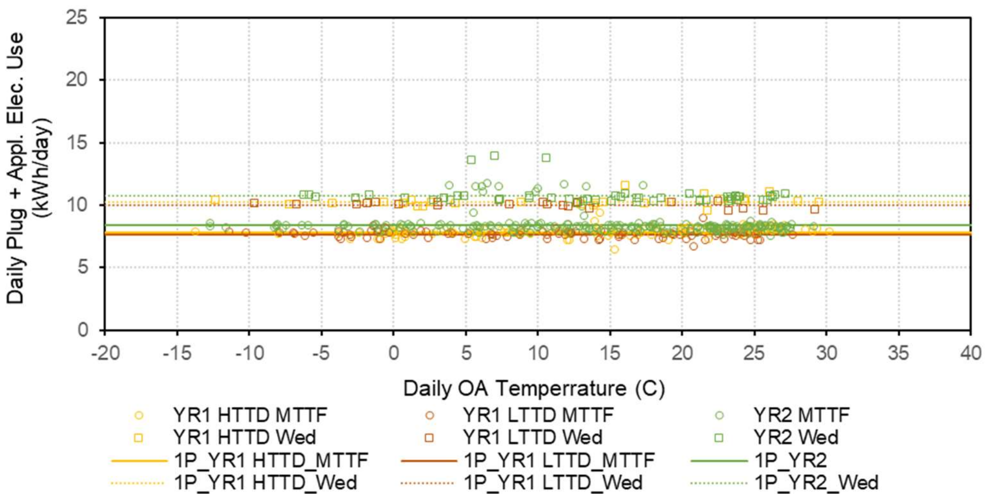
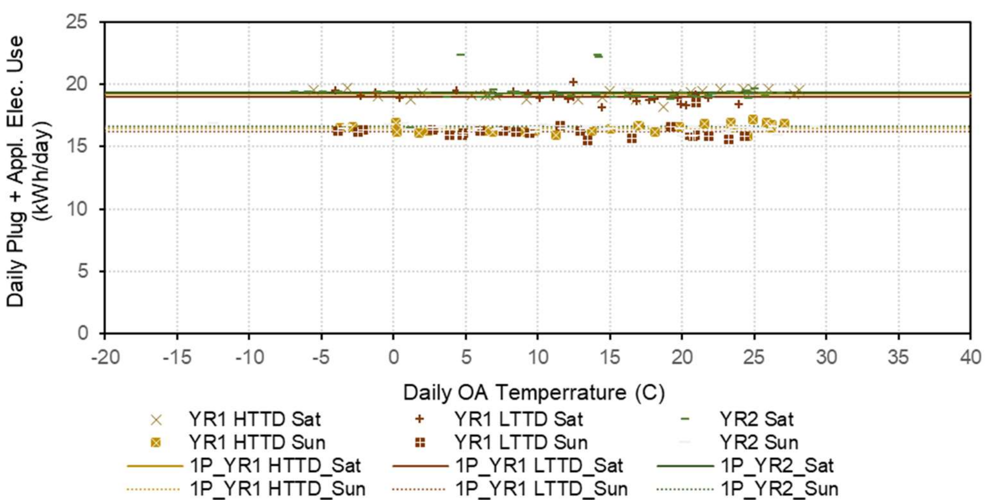


Figure 20: Daily Total Plug Loads + Appliances Electricity Use of the NZERTF.

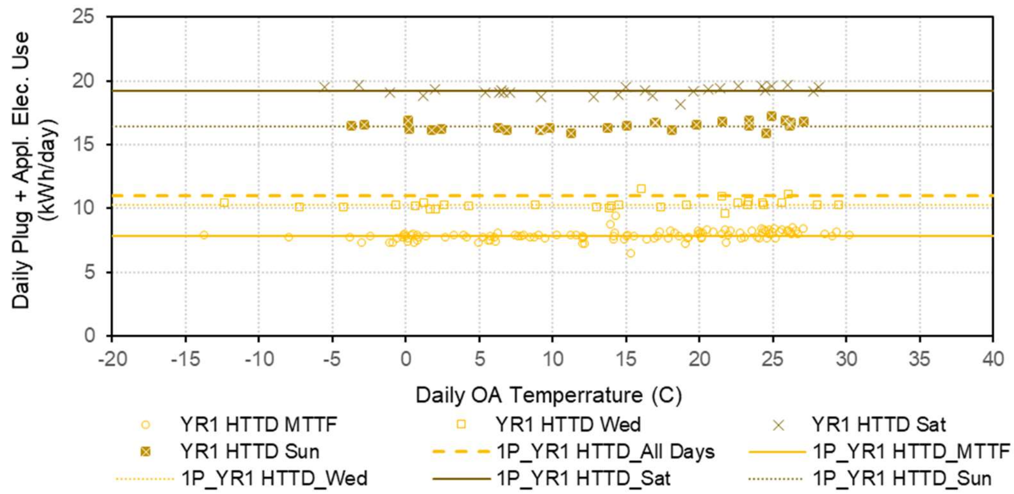


(a) MTTF and Wednesday Model

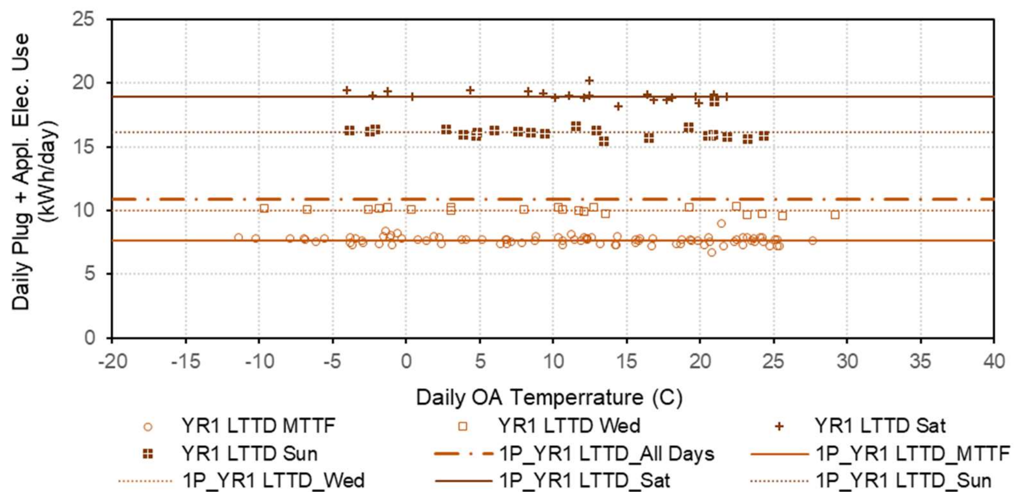


(b) Saturday and Sunday Model

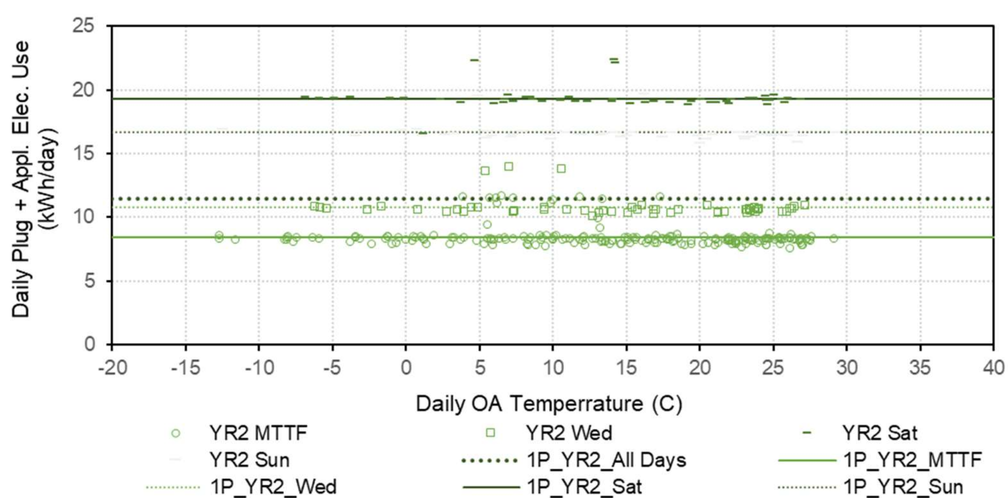
Figure 21: Daily Total Plug Loads + Appliances Electricity Use Models for MTTF (Mondays, Tuesdays, Thursdays, and Fridays), Wednesdays, Saturdays, and Sundays.



(a) YR1 HTTD



(b) YR1 LTTD



(c) YR2

Figure 22: Daily Total Plug Loads + Appliances Electricity Use Models by TTD Operations.

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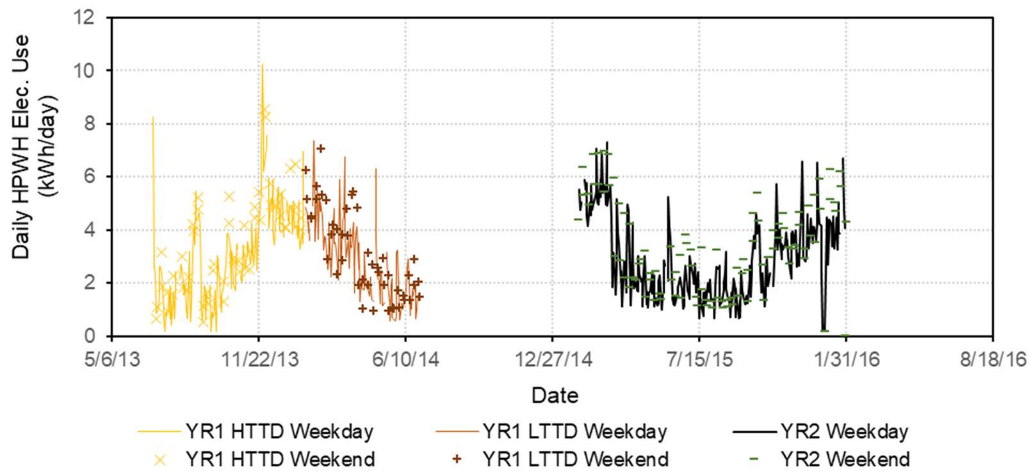
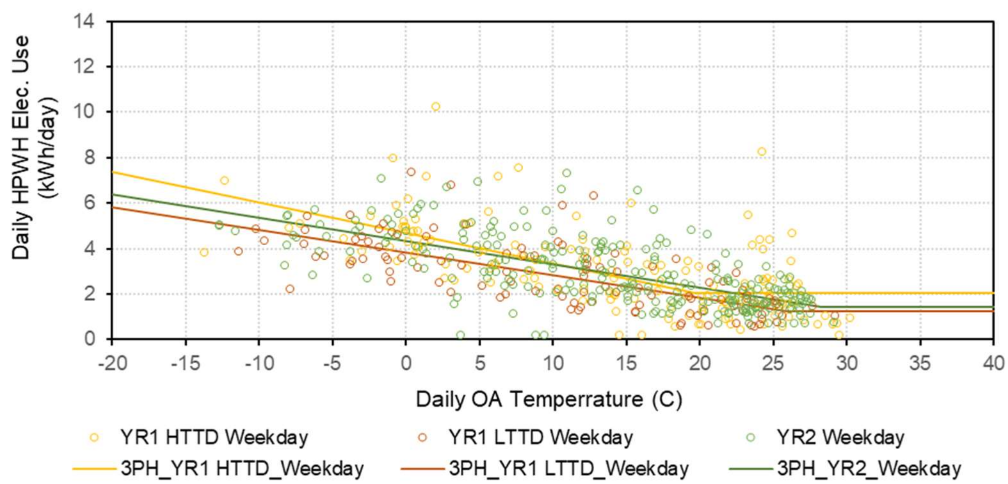
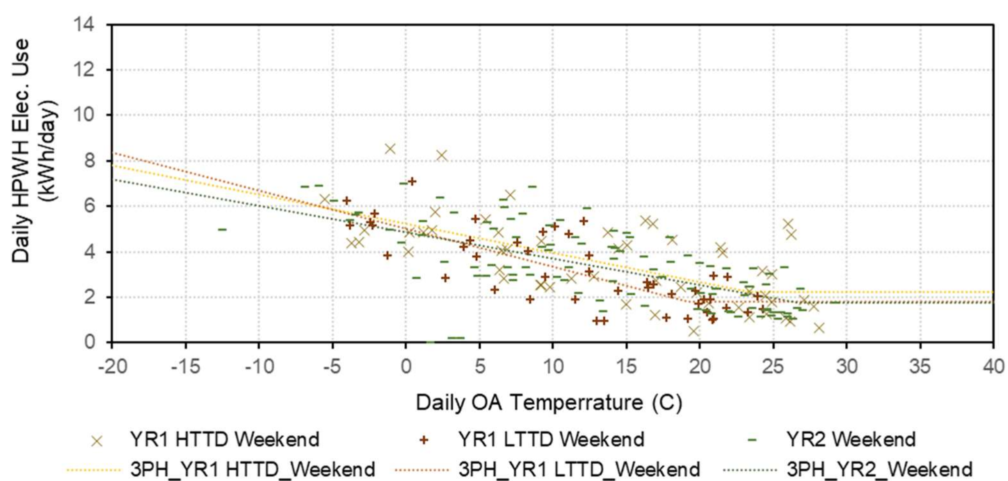


Figure 23: Daily Total Domestic Hot Water Electricity Use of the NZERTF.

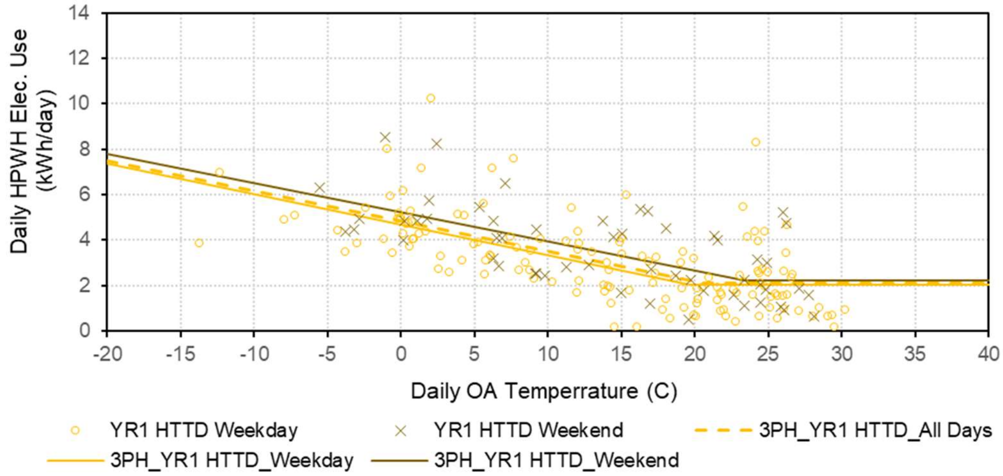


(a) Weekday Model

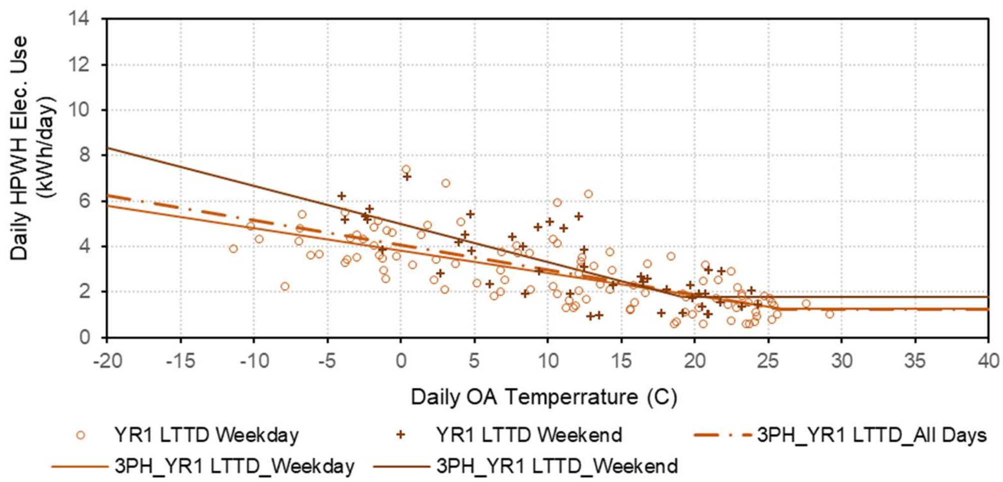


(b) Weekend Model

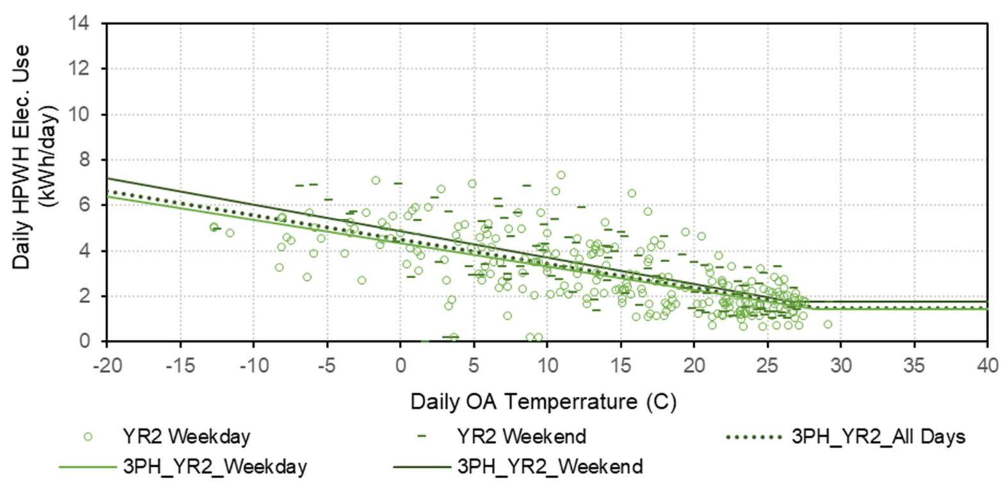
Figure 24: Daily Total Domestic Hot Water Electricity Use Models for Weekdays and Weekends.



(a) YR1 HTTD



(b) YR1 LTTD



(c) YR2

Figure 25: Daily Total Domestic Hot Water Electricity Use Models by TTD Operations.

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3.2. WEATHER-NORMALIZED ENERGY USE COMPARISON

Figures 26 and 27 present the results of the savings calculations for the conditioning electricity use: (a) measured savings and (b) predicted savings during the period of the Year 1 and Year 2 operations, respectively. The measured savings were calculated using the measured electricity use if available, while the predicted savings were calculated only using the predicted electricity use.

The savings percentages calculated on an annual basis were same regardless of the use of either measured or predicted electricity use. The conditioning electricity use would be reduced if the YR1 LTTD operation was applied: 3.2% (204 kWh/year) in the period of the Year 1 operation; and 3.3% (197 kWh/year) in the period of the Year 2 operation. If the YR2 TTD operation was applied, the conditioning electricity use would be further reduced: 19.0% (1,199 kWh/year) in the period of the Year 1 operation; and 18.3% (1,094 kWh/year) in the period of the Year 2 operation. These savings calculated for the Year 2 operation were lower than the whole-house electricity savings reported in Fanney et al. (2017), which was 1,241 kWh savings. This is expected because the savings calculated in this study did not include the savings from ventilation energy.

The monthly savings calculated for the YR1 LTTD operation were negative (i.e., increased electricity use) during the heating months, while positive savings were calculated during the cooling months. The positive savings were calculated for the YR2 TTD operation throughout a year, which tended to increase during the heating months.

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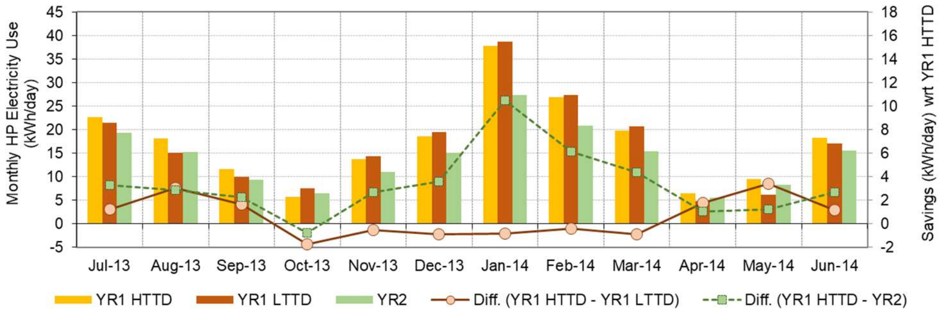
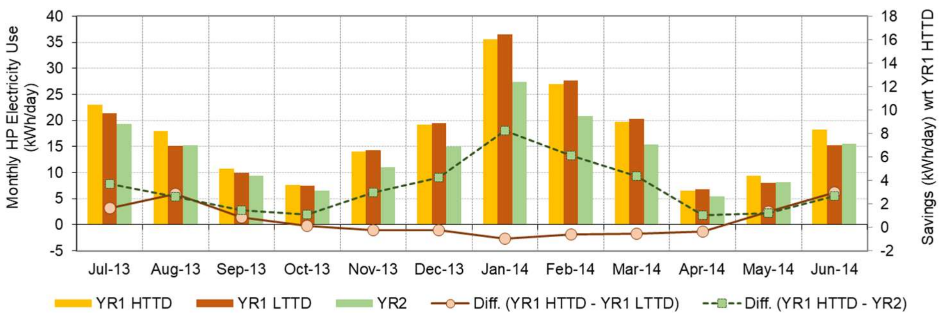
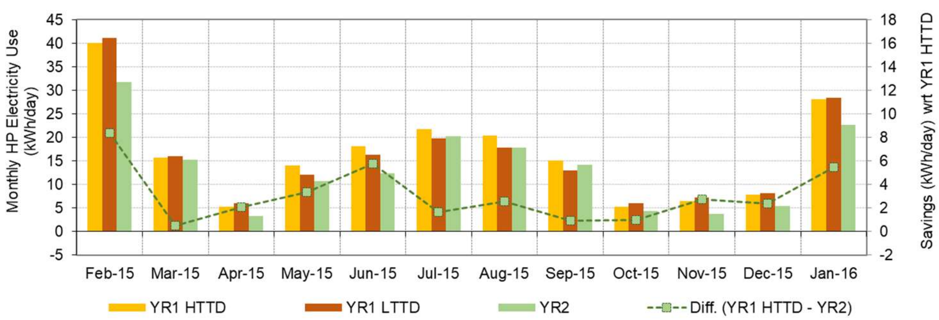


(a) Measured Savings

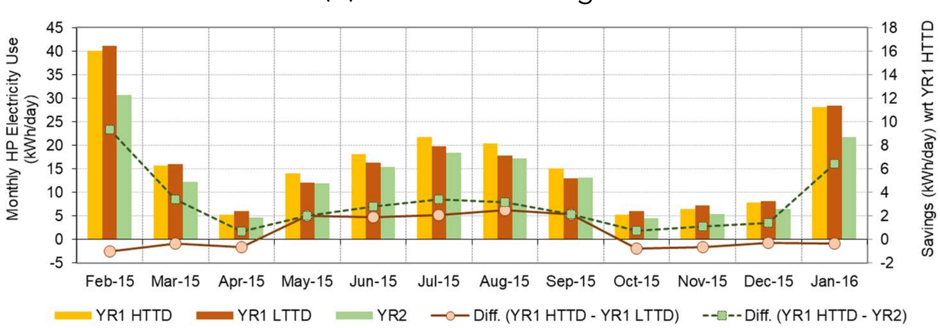


(b) Predicted Savings

Figure 26: Monthly Conditioning Electricity Savings Against the YR1 HTTD Operation during the Period of the Year 1 Operation.



(a) Measured Savings[11]



(b) Predicted Savings

Figure 27: Monthly Conditioning Electricity Savings Against the YR1 HTTD Operation during the Period of the Year 2 Operation.

[11] No measured savings were calculated for the YR1 LTTD operation since both the YR1 HTTD and YR1 LTTD consumptions is predicted electricity use.

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3.3. STATISTICAL CHARACTERIZATION OF LONG-TERM ROOM TEMPERATURE AND HUMIDITY

This study performed a statistical characterization of the continuously-measured long-term temperature and humidity data not only for the primary rooms but also for the attic and the basement that are thermally important due to possible heat transfer from/to the primary rooms. The granular temperature and humidity data were divided into subgroup by the TTD operations and the heat pump on/off cycle in addition to the season (i.e., cooling season, heating season, and transitional season) to understand the impact of different TTD controls on thermal comfort dynamics. Figure 28 presents the modified box and whisker plots used in this analysis. Data were color-coded by TTD operations: yellow for YR1 HTTD, dark orange for YR1 LTTD, and green for YR2.

3.3.1. ROOM TEMPERATURE

Figures 29 to 31 graphically present the statistical characterization of the long-term room temperature data with a superimposed ACCA Manual RS benchmarks (i.e., thermostat setpoint ±1.7°C (±3°F) for a cooling season; and thermostat setpoint ±1.1°C (±2°F) for a heating season). This includes the 10th percentile for the lower whisker and the 90th percentile for the upper whisker, in addition to 1.5th, 2.5th, 5th, 25th, 50th, 75th, 95th, 97.5th, and 98.5th percentiles, as well as minimum, mean, and maximum values for air temperature by season: cooling season in Figure 29, heating season in Figure 30, and transitional season in Figure 31.

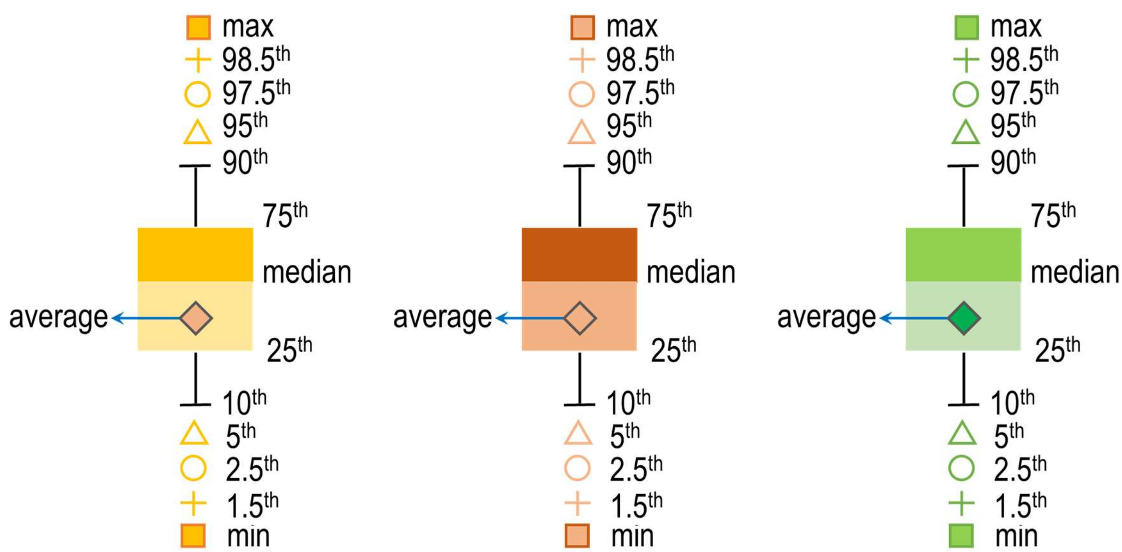

Figure 28: Modified Box and Whisker Plot to Display Continuously-Measured 5-Min Average Thermal Comfort Data for YR1 HTTD (Yellow), YR1 LTTD (Dark Orange), and YR2 (Green).

Important observations on the room temperature during the cooling season (Figure 29) are:

- There was a noticeable difference in the OA temperature when the heat pump was on cycle versus off cycle. When the heat pump cycled on, the OA temperature was higher by 3.0°C (YR1 HTTD), 3.9°C (YR2 LTTD), and 4.6°C (YR2) on average. The system cycled on for about 63% (YR1 HTTD), 55% (YR1 LTTD), and 64% (YR2) of the time.

- Primary rooms on the first floor (i.e., LR and KIT)
  - The rooms on the first floor were colder than the rooms on the second floor, of which temperatures tended to be lower than the setpoint temperature (i.e., 23.9°C (75°F)) for all three TTD operations. This was caused by the natural stratification of warm air.
  - There was a noticeable difference in the measured first-floor room temperatures between the three TTD operations. YR2 maintained the lowest living room temperatures with average temperatures of 22.6°C during the heat pump on cycle. This is a result of overcooling caused by the use of a different thermostat with an additional remote temperature sensor located in the second-floor hallway during the YR2 operation[12].
  - YR1 HTTD had the highest room temperatures with an average living room temperature of 23.6°C during the on cycle. YR1 LTTD with lowered differential temperatures and shortened delay time had an average living room temperature of 23.3°C during the on cycle.
  - YR1 HTTD had the largest temporal variations with the highest interquartile range (i.e., IQR = 75th quartile – 25th quartile) of 0.43°C in the living room during the on cycle. YR1 LTTD and YR2 had similar temporal variations with IQRs of 0.27°C (YR1 LTTD) and 0.28°C (YR2) in the living room.
  - There was no meaningful difference in the room temperatures when the heat pump was on cycle versus off cycle for all three TTD controls.

- Primary rooms on the second floor (i.e., MBR, BR2, and BR3)
  - YR2 maintained the lowest room temperatures, while YR1 HTTD and YR1 LTTD had comparable second-floor room temperatures.
  - YR2 also maintained better temporal variations with the smallest IQRs, which was followed by YR1 LTTD and YR1 HTTD.
  - There was no meaningful difference in the room temperatures when the heat pump was on cycle versus off cycle except for BR2. When the heat pump was on, the BR2 temperature was higher by 0.3°C on average for all three TTD operations.

- Attic and BSMT
  - Like the rooms on the second floor, YR2 maintained the lowest attic temperatures, while YR1 HTTD and YR1 LTTD had comparable attic temperatures.
  - Unlike other primary rooms, there was a meaningful difference in the attic temperature when the heat pump was on cycle versus off cycle by 0.5°C on average (YR1 HTTD), 0.7°C on average (YR1 LTTD), and 0.6°C on average (YR2) (i.e., hotter when the heat pump was on cycle).

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[12] The average of two temperature sensors (i.e., thermostat sensor in the living room and the remote sensor in the second-floor hallway) was used to control the heat pump system.

- Not surprisingly, the basement temperatures were consistently colder than other rooms in the house, which might be also affected by the heat pump water heater located in the basement.

- Comparison to the ACCA Manual RS benchmarks for Primary Rooms (Higher Temperature Side):
  - There were occasions when the room-to-thermostat temperature differences exceeded the ACCA Manual RS cooling benchmark on the high side, which is a comfort penalty in the cooling season. However, the occasions were less than 10% (YR1 HTTD) and 5% (YR1 LTTD) of the period based on 90^{th} and 95^{th} percentiles except for the BR2. BR2 had non-compliances over 25% of the period with the YR1 HTTD operation.
  - A further inspection revealed that this deviation consistently occurred at a specific time of the days when the resistance heating boxes in BR2 were turned on to simulate the scheduled internal loads (i.e., occupancy, plug loads, and lighting). In addition, unlike other bedrooms, constant 20 W base loads remained on in BR2 for both years, which increased the amount of internal heat gains in BR2 compared to other bedrooms.

- Comparison to the ACCA Manual RS benchmarks for Primary Rooms (Lower Temperature Side):
  - There were also occasions when the room-to-thermostat temperature differences exceeded the ACCA Manual RS cooling benchmark on the low side in the first-floor rooms, especially in the kitchen.
  - The KIT had a relatively long period of low-side deviation, which was more frequent with the YR2 operation during the heat pump on cycle.

Important observations on the room temperature during the heating season (Figure 30) are:

- There was a noticeable difference in the OA temperature when the heat pump was on cycle versus off cycle. When the heat pump cycled on, the OA temperature was lower by 6.0°C (YR1 HTTD), 6.5°C (YR2 LTTD), and 7.5°C (YR2) on average. The system cycled on for about 68% (YR1 HTTD), 75% (YR1 LTTD), and 65% (YR2) of the time.

- Primary rooms on the first floor (i.e., LR and KIT)
  - The rooms on the first floor had similar or slightly lower temperatures to the rooms on the second floor, which resulted in a better whole-house temperature uniformity for the heating season.
  - Like the cooling season, the room temperatures were lower than the heating setpoint temperature (i.e., 21.1°C (70°F)) for all three TTD operations. The YR2 operation that controlled the heat pump system based on the average temperature of the living room and second-floor hallway maintained the warmest temperatures, which was nearer to the heating setpoint temperature.
  - YR1 HTTD and YR1 LTTD had tightly-controlled temperature conditions with smaller IQRs compared to the YR2 operation, especially in the LR during the system on cycle.

- Primary rooms on the second floor (i.e., MBR, BR2, and BR3)

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- Similar to the first-floor bedrooms, the second-floor room temperatures tended to be lower than the heating setpoint temperature for all three TTD operations, though to a lesser extent. BR3 maintained the warmest temperature.
- The YR1 HTTD operation had the lowest temperatures among the three TTD operations.
- The three TTD operations had comparable temporal variations although the YR2 operation tended to have slightly higher IQR in MBR.
- Unlike the cooling season, there was a meaningful difference in the room temperatures when the heat pump was on cycle versus off cycle, which was to a greater extent with the YR2 operation especially in BR2. This indicates the system cycled off once it reached the desired temperature, which is expected.

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- Attic and BSMT
  - Like the rooms on the second floor, the YR1 HTTD operation had the lowest attic temperatures among the three TTD operations, and the YR2 operation had the highest temporal variations. The attic temperatures were warmer when the heat pump cycled off.
  - Not surprisingly, the basement temperatures were lower than other rooms' temperatures but to a lesser extent compared to the cooling season.

- Comparison to the ACCA Manual RS benchmarks for Primary Rooms (Higher Temperature Side):
  - There were few occasions when the room-to-thermostat temperature differences exceeded the ACCA Manual RS heating benchmark on the high side, especially in the second-floor bedrooms and attic during the heat pump cycled off. This can be explained by the natural stratification of warm air during the heat pump off cycle.

- Comparison to the ACCA Manual RS benchmarks for Primary Rooms (Lower Temperature Side):
  - There were occasions when the room-to-thermostat temperature differences exceeded the ACCA Manual RS heating benchmark on the low side, which is a comfort penalty in the heating season. The observed low-side deviation was worse during the YR2 operation especially when the heat pump cycled on.

Important observations on the room temperature during the transitional season (Figure 31) are:

- Although the daily average OA temperature during the transitional season was between 7.5°C and 17.2°C[13], the 5-min OA temperatures had a wide temporal variation: from -1.0°C to 24.4°C (YR1 HTTD), from -1.2°C to 26.6°C (YR1 LTTD) and from 0.8°C to 25.4°C (YR2). As a result, the heat pump system occasionally cycled on for about 10% (YR1 HTTD), 12% (YR1 LTTD), and 9% (YR2) of the time. Due to the small sample size of the system on cycle, discussion of transitional season data focuses on the data collected during the heat pump off cycle.

- Primary rooms on the first floor (i.e., LR and KIT)
  - Like other seasons, the rooms on the first floor were colder than the rooms on the second floor due to the natural stratification of warm air.

[13] A detailed explanation of the proposed data decomposition is provided in Section 2.3.1.

- Not surprisingly, the room temperatures varied a lot more than other seasons (i.e., cooling and heating seasons) between the heating setpoint and the cooling setpoint temperatures for all three TTD operations when the system cycled off.
- On average, the three TTD operations had comparable off-cycle room temperatures, although YR1 HTTD had a wider temporal variation compared to other TTD operations.

- Primary rooms on the second floor (i.e., MBR, BR2, and BR3)
  - The second-floor rooms had very similar observations to those of the first-floor rooms as described above.

- Attic and BSMT
  - There was not a noticeable difference in the attic temperatures between the three operations on average, but the observed temporal variations were wider with the YR1 HTTD, which agreed with the observations made for primary rooms.
  - Like other seasons, the basement temperatures were consistently colder than other rooms in the house.

- Comparison to the ACCA Manual RS benchmarks for Primary Rooms (Higher Temperature Side):
  - There were no occasions when the room-to-thermostat temperature differences exceeded the ACCA Manual RS cooling benchmark on the high side for the primary rooms.

- Comparison to the ACCA Manual RS benchmarks for Primary Rooms (Lower Temperature Side):
  - There were occasions when the room-to-thermostat temperature differences exceeded the ACCA Manual RS heating benchmark on the low side especially in the first-floor rooms. The deviation was more obvious with the YR1 HTTD operation, which might be affected by its relaxed differential temperatures.

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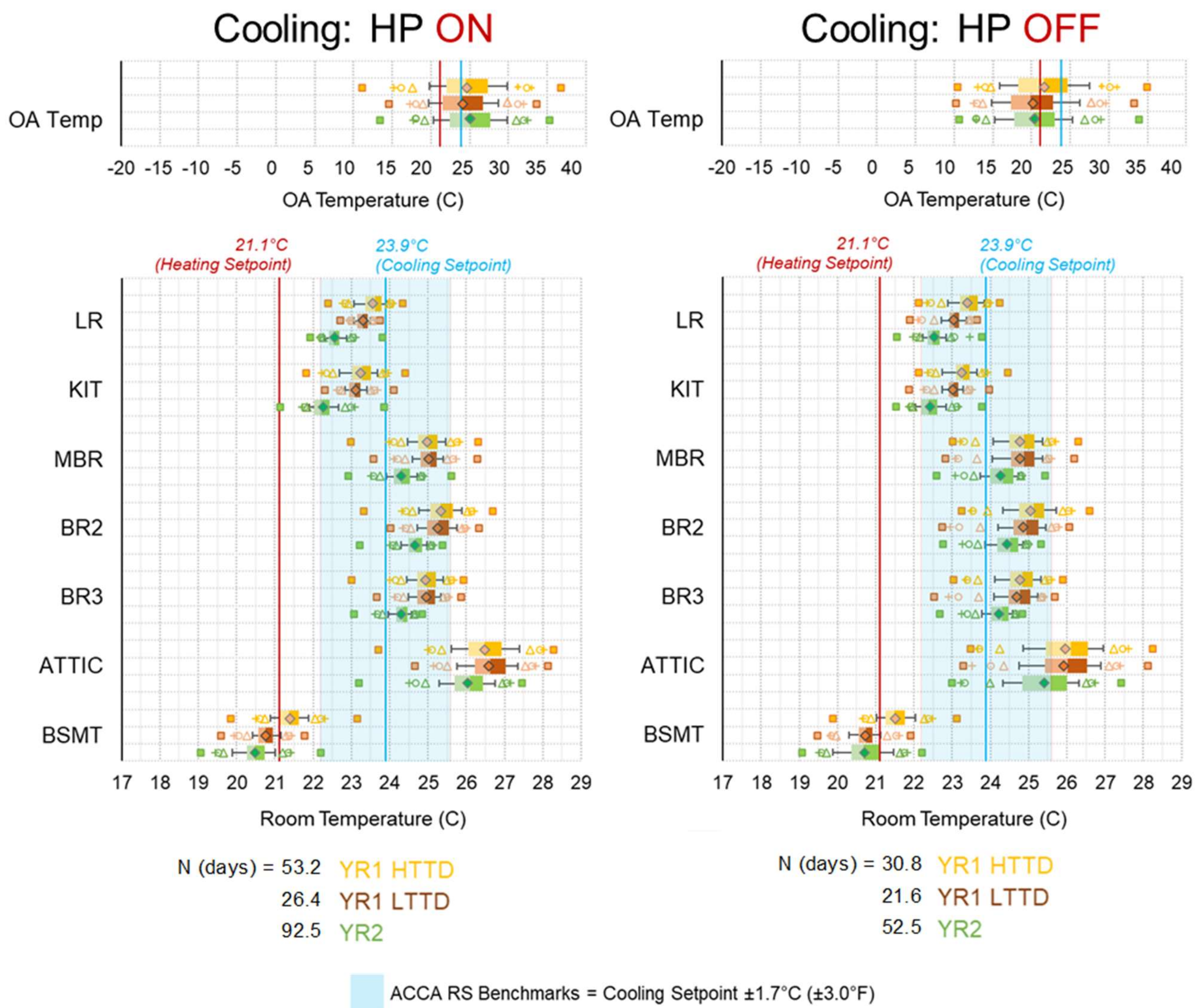

Figure 29: Graphical Summaries of the 5-Min Average Room Temperatures When the Heat Pump Was On (Left Figure) and Off (Right Figure) for the Cooling Season.

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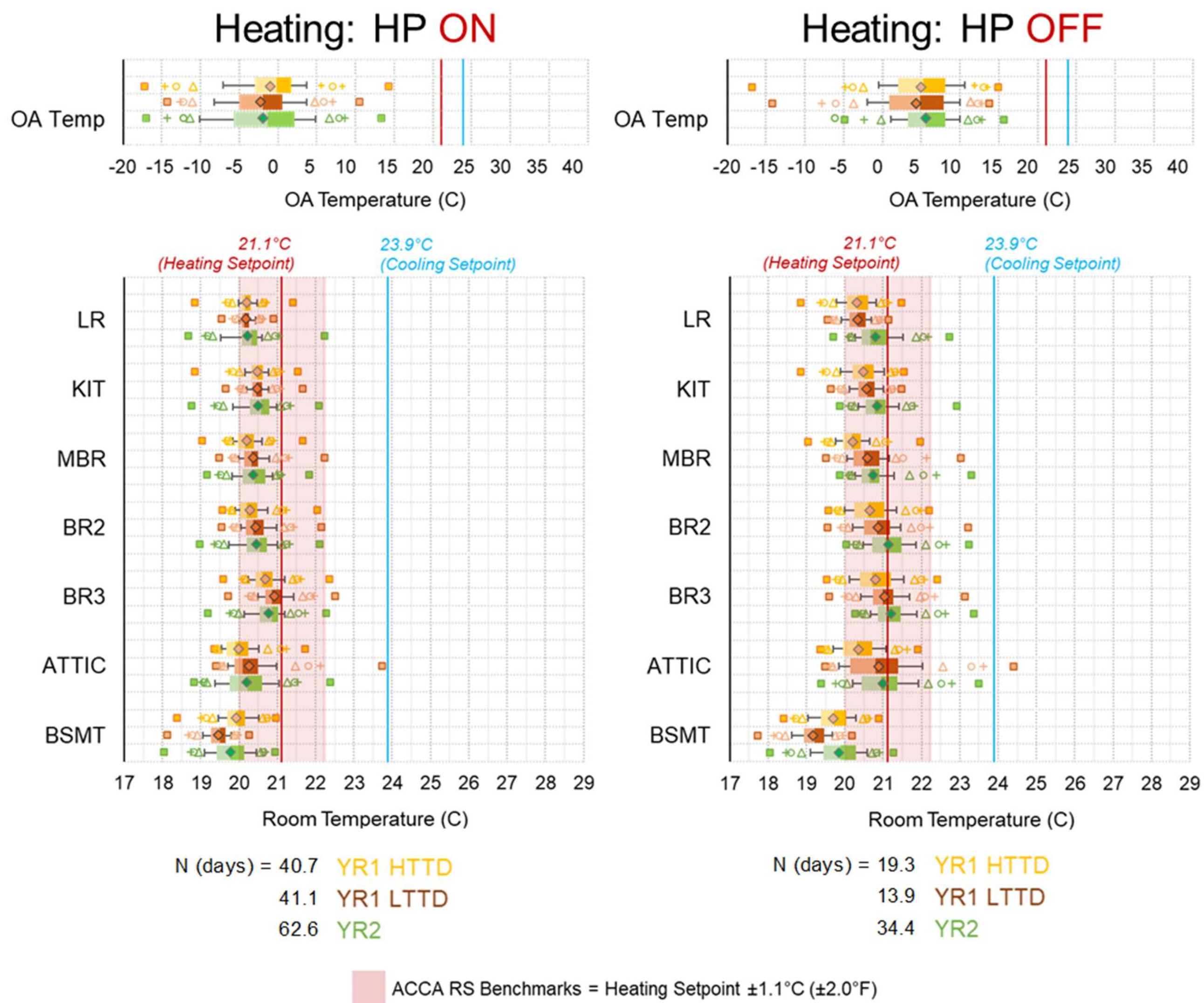

Figure 30: Graphical Summaries of the 5-Min Average Room Temperatures When the Heat Pump Was On Cycle (Left Figure) and Off Cycle (Right Figure) for the Heating Season.

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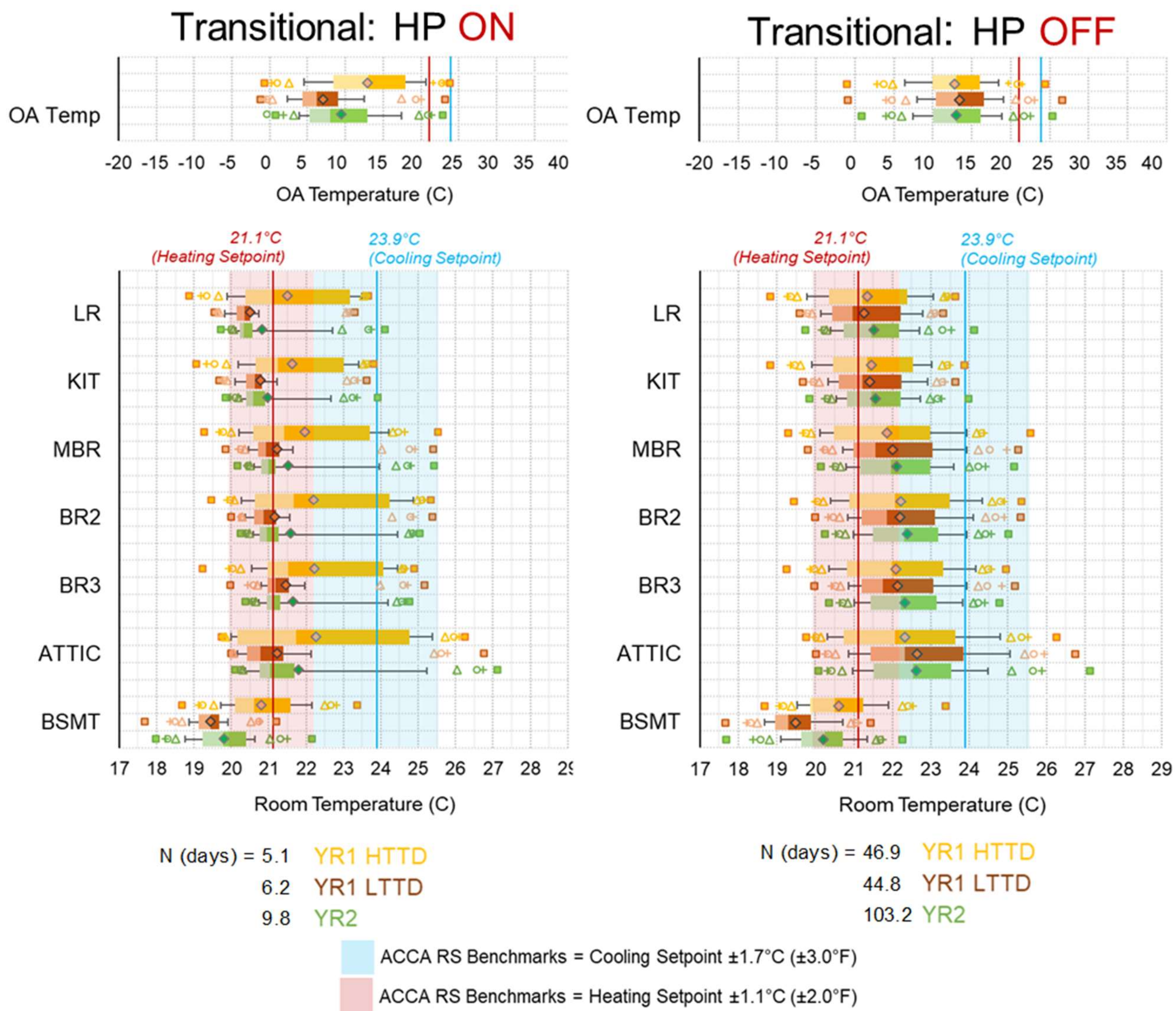

Figure 31: Graphical Summaries of the 5-Min Average Room Temperatures When the Heat Pump Was On Cycle (Left Figure) and Off Cycle (Right Figure) for the Transitional Season.

3.3.2. ROOM HUMIDITY

Figures 32 to 37 graphically present the statistical characterization of the long-term room relative humidity and absolute humidity levels (i.e., humidity ratio in g H_2O/kg dry air). The RH plots include a superimposed dehumidifier setpoint RH (i.e., 50% RH[14]) and other relevant RH benchmark: 30% to 60% RH as reported by Sterling et al. (1985) and more recently by Derby and Pasch (2017)[15]. The humidity ratio plots include a superimposed ASHRAE Standard 55-2017 benchmark: 12 g/kg maximum humidity ratio limit[16] (ASHRAE 2017).

The plots display the 10th percentile for the lower whisker and the 90th percentile for the upper whisker, in addition to 1.5th, 2.5th, 5th, 25th, 50th, 75th, 95th, 97.5th, and 98.5th percentiles, as well as minimum, mean, and maximum values for room humidity ratio by season:

- RH (Figure 32) and humidity ratio (Figure 33) for the cooling season;
- RH (Figure 34) and humidity ratio (Figure 35) for the heating season; and
- RH (Figure 36) and humidity ratio (Figure 37) for the transitional season.

Important observations on the room humidity during the cooling season (Figures 32 and 33) are:

- When the heat pump cycled off, the OA RH was higher by 2.6% RH (YR1 HTTD), 5.9% RH (YR1 LTTD), and 11.7% RH (YR2) on average, which was partially affected by the temperature-dependent nature of the metric (i.e., relative humidity) rather than actual OA moisture levels.

- Room Humidity
  - When the heat pump cycled on, the room RH levels were well within the optimum RH range between 30% and 60% for most of the measurement period except for the KIT. The KIT had a higher percentage of the high-side deviation (i.e., over 60% RH). The KIT RH levels were also higher than other rooms in general.
  - There were few occasions when the humidity ratios exceeded the maximum humidity ratio limit of the ASHRAE Standard 55, which was less than 1.5% of the period except for the kitchen. Kitchen had a few more occasions exceeding the maximum limit, 12 g/kg.
  - The second-floor room RH levels were lower than the first-floor RH levels, which was affected by warmer second-floor room temperatures rather than lower absolute humidity levels. In terms of absolute humidity levels, the second-floor rooms had similar or slightly higher humidity ratios compared to the first-floor rooms.
  - When comparing the three TTD operations, the YR2 operation tended to have higher RH, which was noticeable in the first-floor rooms, including the LR where the humidistats were located. This was partially affected by the lower room temperature during the YR2 operation. However, considering the dehumidifier setpoint based on relative humidity (i.e., 50% RH), the dehumidification

[14] The ASHRAE Standard 62.1-2016 (ASHRAE 2016) limits the relative humidity of occupied spaces to 65% or less at the dehumidification design conditions, which was revised to a maximum dew point of 15°C (60°F) in the 2019 edition of the ASHRAE Standard 62.1-2019 (ASHRAE 2019b).
[15] The ACCA Manual RS (1997) also suggests a 60% RH as the upper limit for human comfort during the cooling season.
[16] The latest version of the ASHRAE Standard 62.1-2019 (ASHRAE 2019b) limits the dew point of occupied spaces to 15°C (60°F) or less in mechanically cooled buildings, which is equivalent to a humidity ratio of 11 g/kg.

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performance during the Year 1 operation were better than that during the Year 2 operation.
  - When the heat pump cycled off, the room RH and humidity ratios tended to have slightly larger interquartile ranges for all three TTD operations. However, the basement that did not directly get the OA ventilation from the HRV maintained similar room RH and humidity ratios regardless of the heat pump on and off cycle with very small IQRs.

Important observations on the room humidity during the heating season (Figures 34 and 35) are:

- When the heat pump cycled on, the OA RH was higher by 11.4% RH (YR1 HTTD), 5.6% RH (YR1 LTTD), and 3.4% RH (YR2) on average, which was partially affected by colder OA temperatures.

- Room Humidity
  - When the heat pump cycled on, the room RH levels were below the lower limit of the optimum RH range (i.e., below 30% RH) for most of the measurement period, except for the BSMT.
  - There was no occasion when the humidity ratio exceeded the maximum humidity ratio limit of the ASHRAE Standard 55 during the heating season.
  - The second-floor room RH and humidity ratios were slightly lower than the first-floor RH and humidity ratios. The BR2 and BR3 had the lowest room humidity, while the basement had the highest RH and humidity ratios.
  - When comparing the three TTD operations, the YR2 operation had higher RH and humidity ratios, which was noticeable during the off cycle. Meanwhile, the YR1 LTTD operation had the lowest RH and humidity ratios across the house, which aligns with the lowest OA RH conditions during the period of the YR1 LTTD operation.
  - When the heat pump cycled off, the room RH and humidity ratios tended to be slightly higher than those during the heat pump on cycle with slightly larger interquartile ranges regardless of the TTD operations.
  - The basement had the highest RH and humidity ratios.

Important observations on the room humidity during the transitional season (Figures 36 and 37) are:

- During the transitional season when the system mostly cycled off[17], there was a noticeable difference in the measured OA RH levels between the three TTD operations, which tended to be higher than the OA RH levels during the heating season but lower than the OA RH levels during the cooling season. The OA RH levels during the YR1 LTTD operation were noticeably lower than those during the other TTD operations.

- Room Humidity
  - Like the OA RH levels, the room RH levels during the transitional season were higher than the room RH levels during the heating season but lower than the room RH levels during the cooling season.

[17] Due to the small sample size of the heat pump on cycle, discussion of transitional season data focuses on the data collected during the system off cycle.

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- There were very few occasions when the humidity ratios exceeded the maximum humidity ratio limit of the ASHRAE Standard 55 only in the kitchen and BR3.
- Like other seasons, the room RH levels of the first-floor rooms were higher than the levels of the second-floor rooms.
- Like the heating season, the YR1 LTTD operation had the lowest RH and humidity ratios across the house, which aligns with the lowest OA RH conditions during the period of the YR1 LTTD operation.

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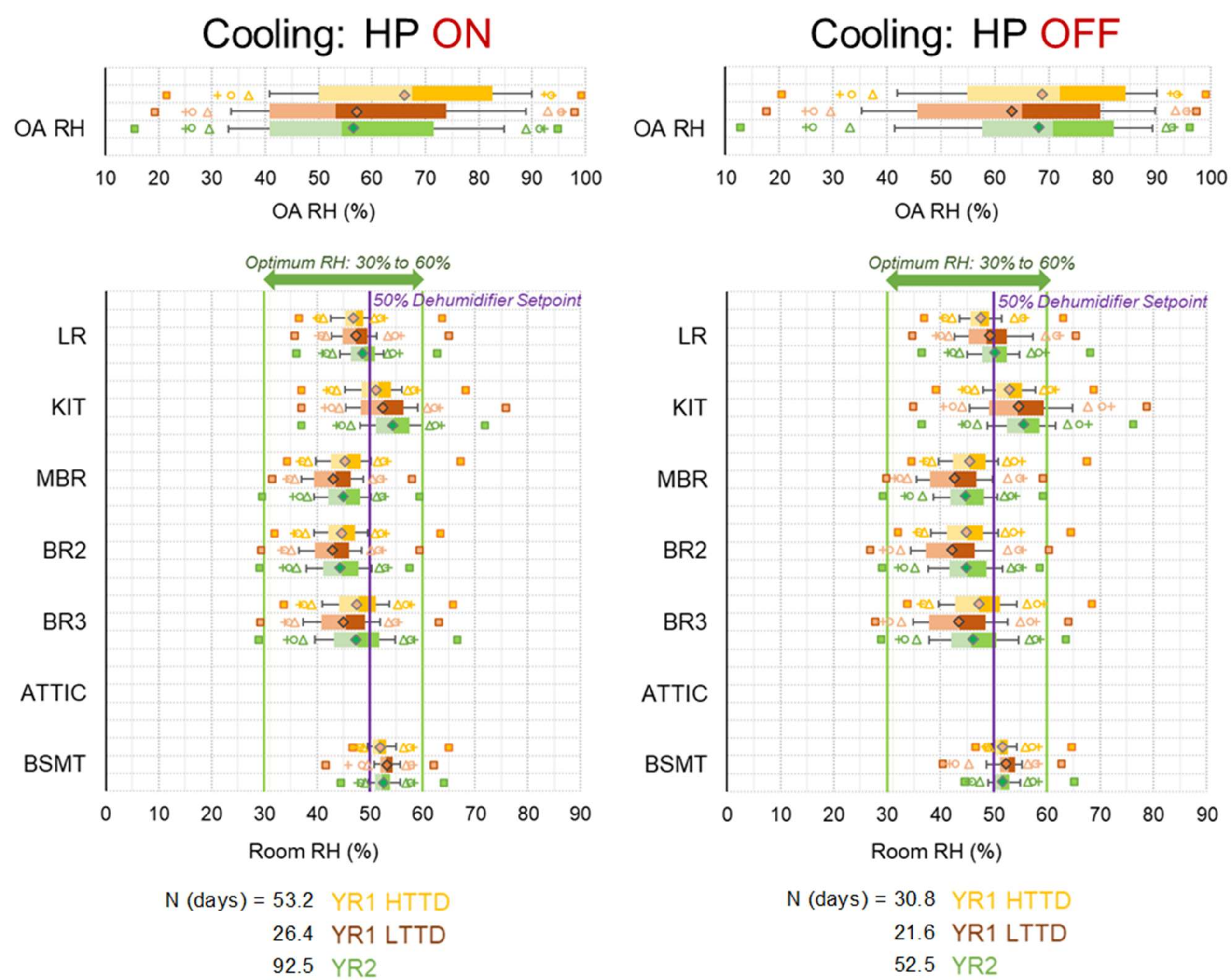

Figure 32: Graphical Summaries of the 5-Min Average Room Relative Humidity When the Heat Pump Was On Cycle (Left Figure) and Off Cycle (Right Figure) for the Cooling.

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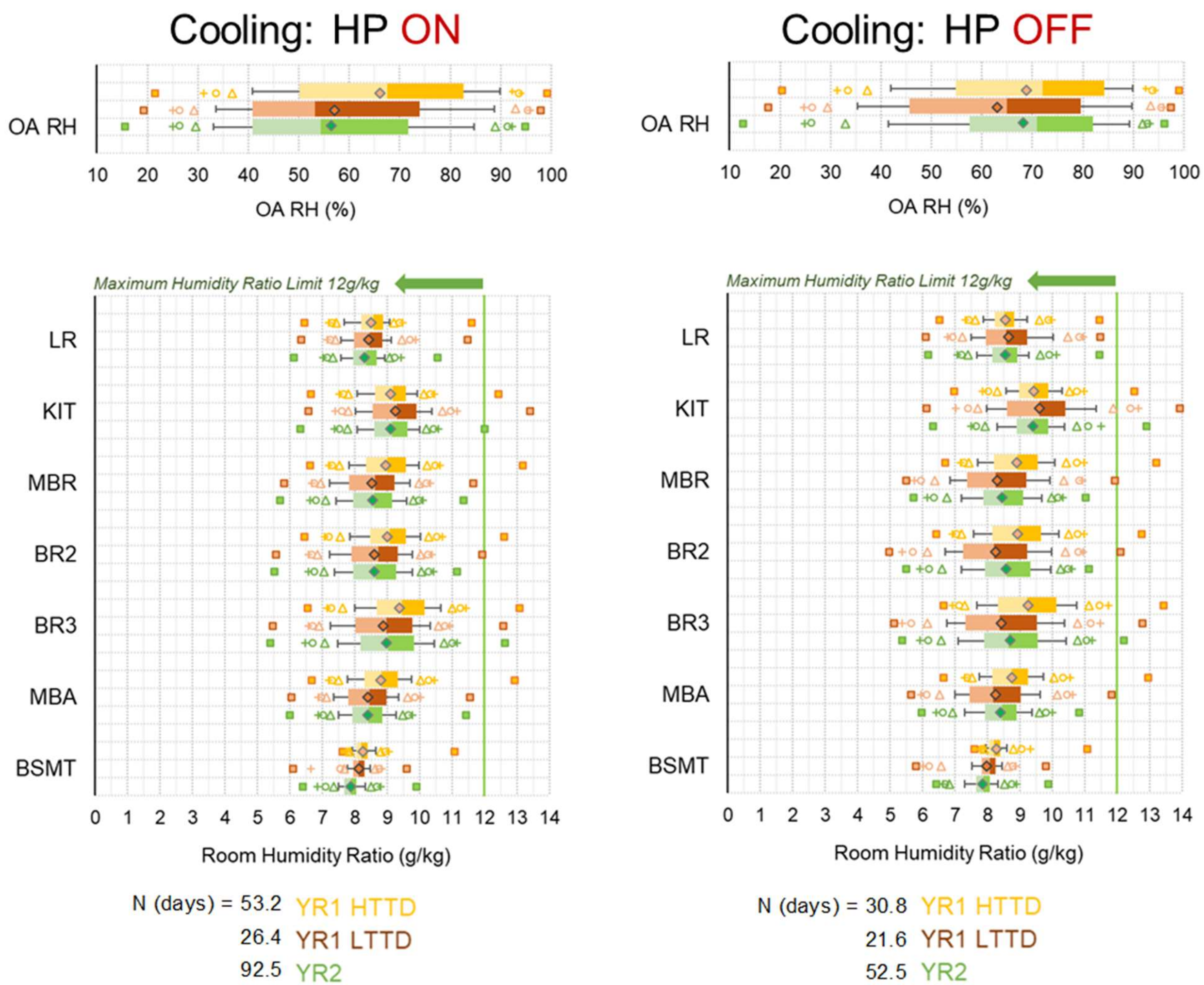

Figure 33: Graphical Summaries of the 5-Min Average Room Humidity Ratio When the Heat Pump Was On Cycle (Left Figure) and Off Cycle (Right Figure) for the Cooling Season.

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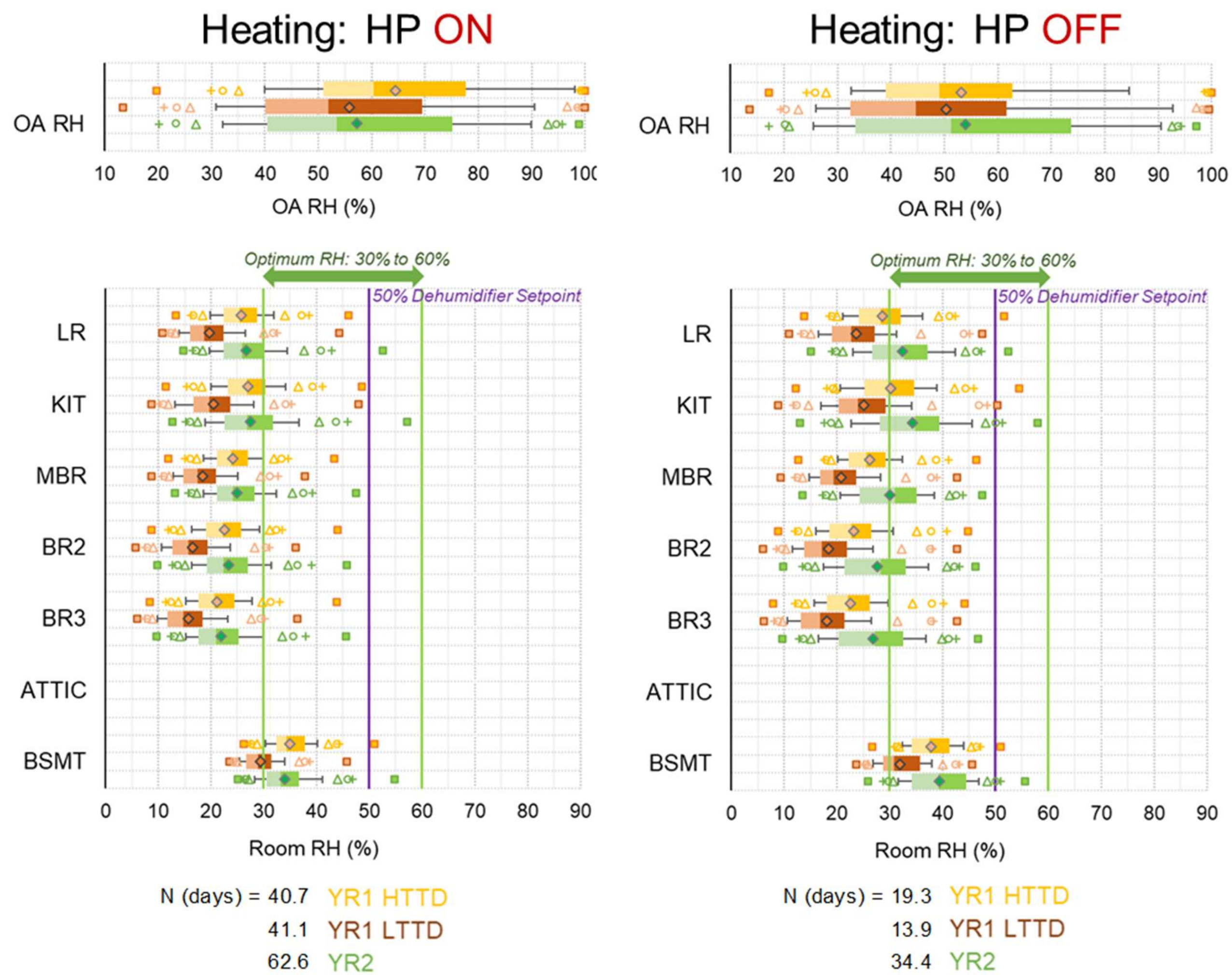

Figure 34: Graphical Summaries of the 5-Min Average Room Relative Humidity When the Heat Pump Was On Cycle (Left Figure) and Off Cycle (Right Figure) for the Heating Season.

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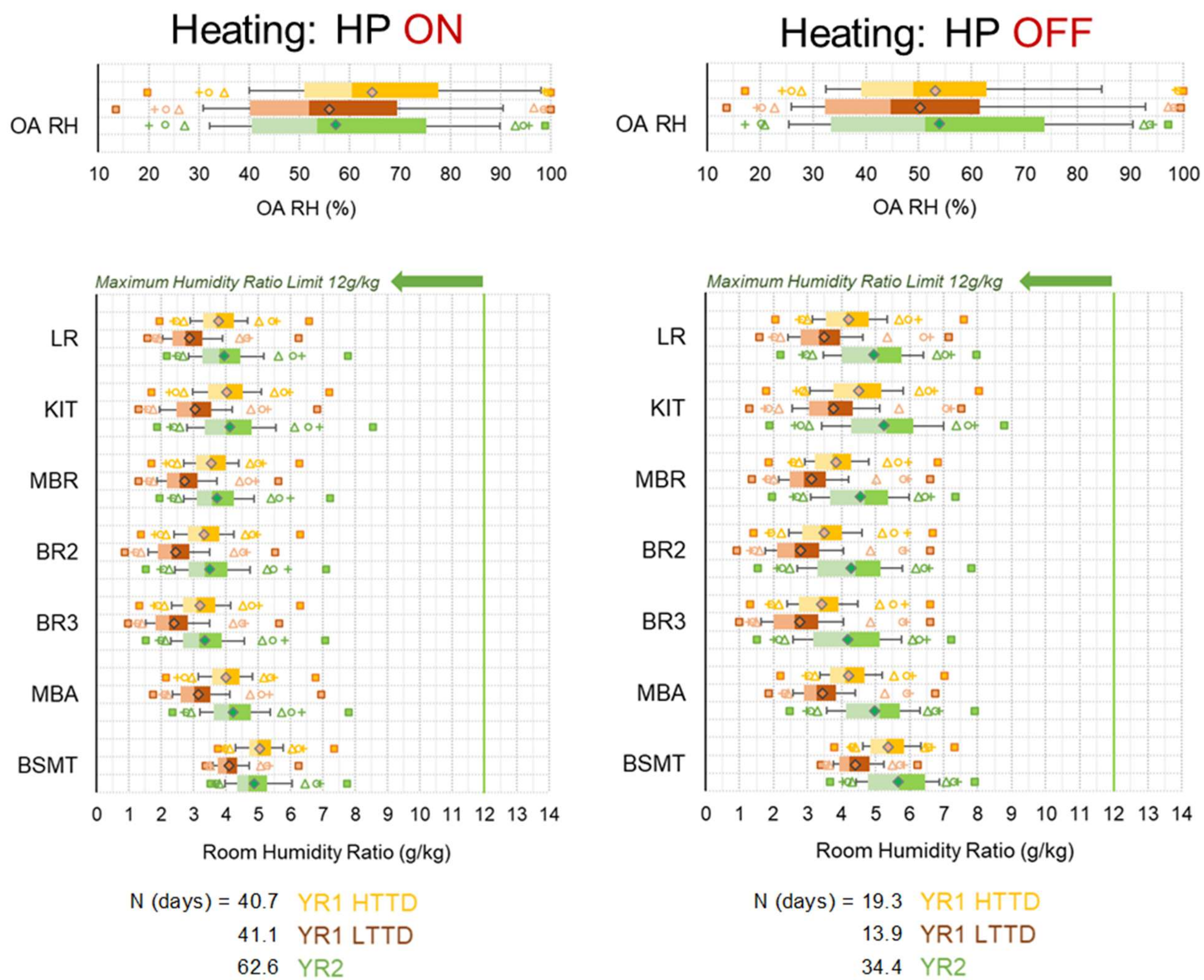

Figure 35: Graphical Summaries of the 5-Min Average Room Humidity Ratio When the Heat Pump Was On Cycle (Left Figure) and Off Cycle (Right Figure) for the Cooling Season.

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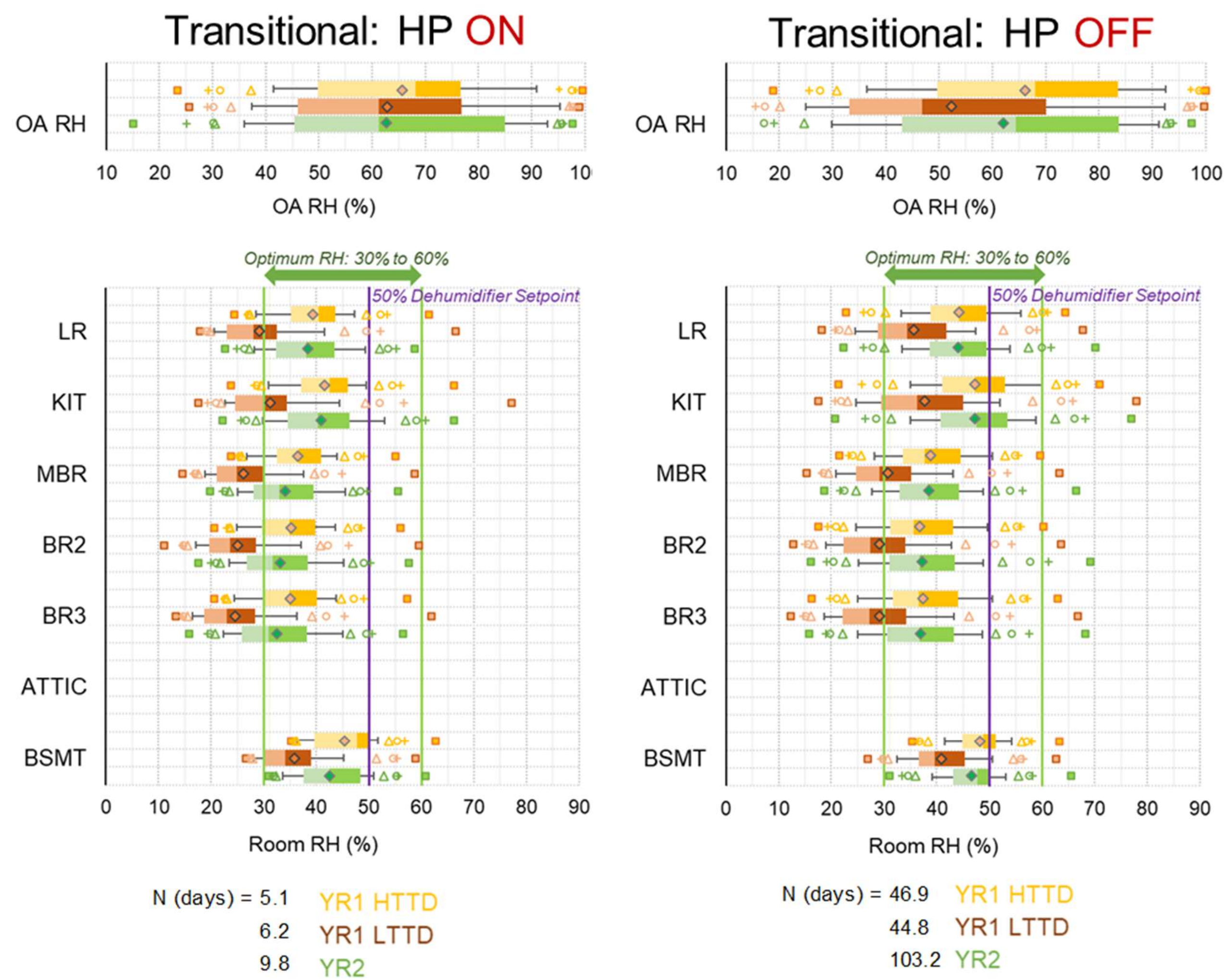

Figure 36: Graphical Summaries of the 5-Min Average Room Relative Humidity When the Heat Pump Was On Cycle (Left Figure) and Off Cycle (Right Figure) for the Transitional Season.

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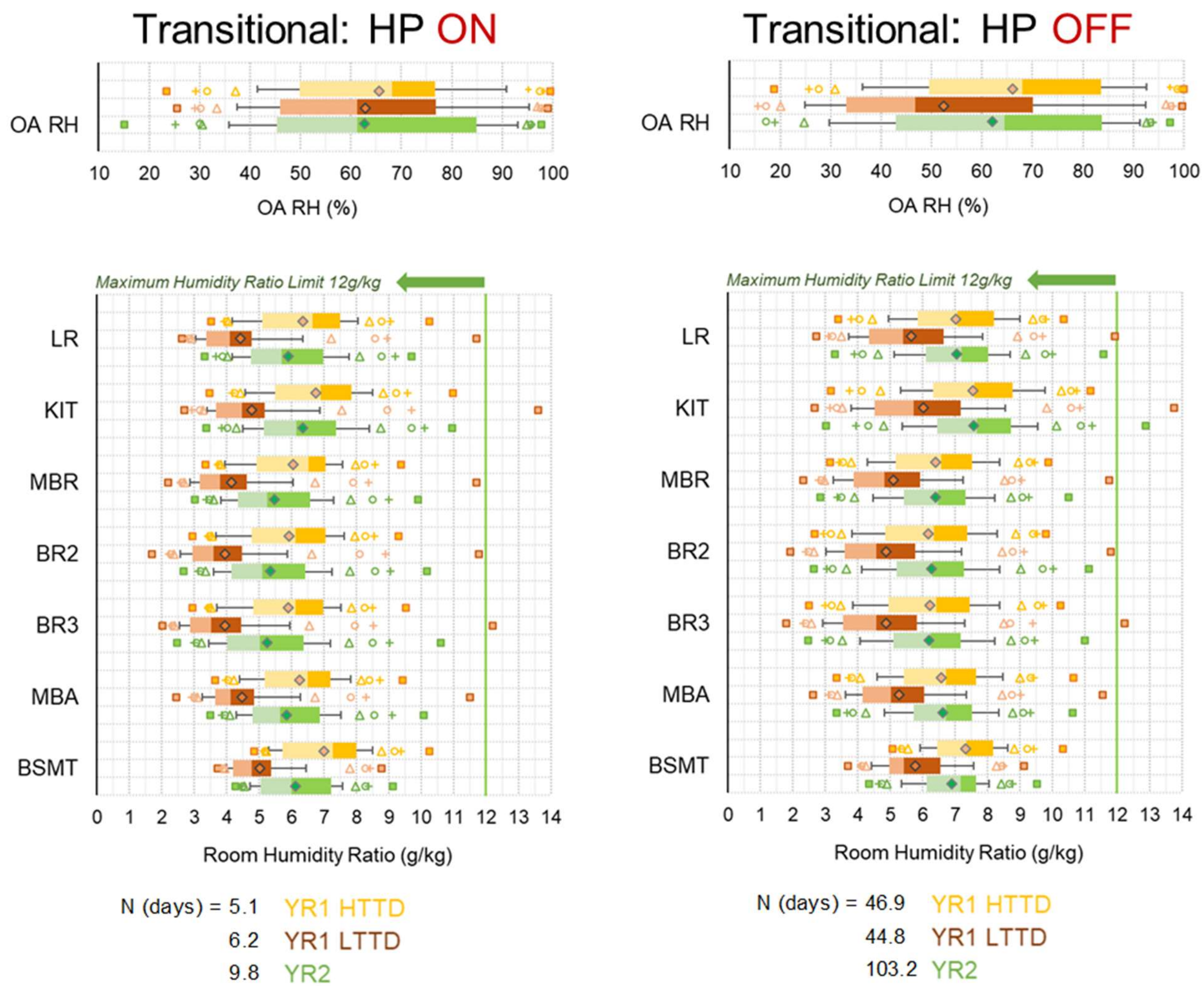

Figure 37: Graphical Summaries of the 5-Min Average Room Humidity Ratio When the Heat Pump Was On Cycle (Left Figure) and Off Cycle (Right Figure) for the Transitional Season.

3.4. ADVANCED CHARACTERIZATION OF TEMPORAL VARIATIONS RELATIVE TO OUTDOOR TEMPERATURE AND HUMIDITY

To better understand the observed temporal variations of the long-term room temperature and humidity data, which was revealed from statistical characterization, this study performed an advanced characterization of the measured room temperature and humidity variations relative to outdoor weather conditions using a 5°C (9°F) interval binned quartile analysis. This allowed a weather-normalized characterization and comparison of the impact of the three TTD operations on thermal comfort dynamics.

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3.4.1. ROOM TEMPERATURE

Figures 38 to 40 present the results of the binned room air temperatures relative to outdoor temperature for the three rooms, including the living room where the thermostat was located and the two rooms representing each floor (i.e., KIT and BR2). Appendix E provides the results for other rooms (i.e., MBR, BR3, ATTIC, and BSMT) as supplementary materials. Each figure consists of the six plots: (a) YR1 HTTD on cycle; (b) YR1 HTTD off cycle; (c) YR1 LTTD on cycle; (d) YR1 LTTD off cycle; (e) YR2 on cycle; and (f) YR2 off cycle.

Important observations are:

- LR during the heat pump on cycle (Figure 38 (a), (c), and (e))
  - The LR temperature where the thermostat was located was consistently lower than the setpoint temperature regardless of outdoor air temperature, which needs a further investigation considering the proximity of the thermostat to the LR measurement stand.
  - The YR1 HTTD operation had a few occasions when the room temperatures approached 19°C at low OA temperature bins (i.e., below 10°C temperature bins). This was caused by the 1st stage heating differential temperature set higher before November 19, 2013, which was reduced from 1.1°C to 0.6°C. In addition, a delayed or no response of the heat pump's 2nd and 3rd stage heating was observed during the YR1 HTTD operation.
  - The YR1 LTTD operation controlled the room temperatures tighter than other TTD operations without extreme outliers regardless of outdoor air temperature with smaller interquartile ranges. This was affected by the lowered differential temperatures for the 2nd and 3rd stage heating along with the associated delay time that was also shortened.
  - The YR2 operation controlled the room temperatures much lower than the cooling setpoint during the cooling season (i.e., 15°C to 35°C OA temperature bins). This is a result of overcooling caused by the use of a different thermostat with an additional remote temperature sensor located in the second-floor hallway during the YR2 operation[18].
  - The YR2 operation also had the coldest room temperature at the very low OA temperatures (i.e., -15°C and -10°C OA temperature bins), while the heat pump system ran constantly. This was affected by an improved control strategy of the backup electric resistance heater (i.e., 3rd stage heating) by removing associated delay time to minimize its use.

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[18] The average of two temperature sensors (i.e., thermostat sensor in the living room and the remote sensor in the second-floor hallway) was used to control the heat pump system.

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- LR during the heat pump off cycle (Figure 38 (b), (d), and (f))
  - Not surprisingly, the LR temperatures during the heat pump off cycle had higher temporal variations, which occurred to a greater extent at the mild OA temperatures (i.e., 10°C and 15°C OA temperature bins).
  - Compared to the conditions during the heat pump on cycle, the room temperatures during the off cycle were slightly warmer at the low OA temperatures and slightly lower or almost identical at the high OA temperature for all three TTD controls. This might be affected by small 1st stage differential temperatures such as 0.6°C for the YR1 operation and 0.3°C for the YR2 operation.

- KIT during the heat pump on cycle (Figure 39 (a), (c), and (e))
  - The KIT had slightly larger temporal variations than the LR.
  - Similar to the LR results, the KIT temperature was consistently lower than the setpoint temperature regardless of OA temperature, and the YR1 LTTD operation tended to have tighter room temperatures than the YR1 HTTD and YR2 operations. The KIT also appeared to have slightly higher room temperatures at the very low OA temperatures (i.e., -15°C and -10°C OA temperature bins).
  - One interesting trend observed in the kitchen with all three TTD operations was the KIT temperatures decreased with increasing OA temperatures during the cooling season (i.e., 30°C and 35°C OA temperature bins).This is the opposite of the trends observed in other primary rooms and indicates a possible overcooling issue in the KIT at the higher OA temperatures, which needs a further investigation.

- KIT during the heat pump off cycle (Figure 39 (b), (d), and (f))
  - Similar to the LR results, the KIT temperatures during the off cycle were slightly warmer at the low OA temperatures and slightly lower or almost identical at the high OA temperature.
  - The observed counter-intuitive trend during the HP on cycle was also observed for the off cycle.

- BR2 during the heat pump on cycle (Figure 40 (a), (c), and (e))
  - Unlike the first-floor rooms, the BR2 appeared to have room temperatures higher than the cooling setpoint during the cooling season for all three TTD operations, which was affected by natural stratification of warm air to higher elevations.
  - The YR2 operation could maintain the lowest BR2 room temperatures which resulted from the use of the average temperature of the living room and the second-floor hallway to control the heat pump system.

- BR2 during the heat pump off cycle (Figure 40 (b), (d), and (f))
  - Like the other rooms, the BR2 temperatures during the heat pump off cycle had higher temporal variations, which occurred to a greater extent at the mild OA temperatures (i.e., 10°C and 15°C OA temperature bins).

Figure 41 displays the median values of the binned room temperatures of all seven rooms (i.e., LR, KIT, MBR, BR2, BR3, ATTIC, and BSMT) for a comparison between rooms: (a) 1F rooms and ATTIC HP on cycle; (b) 1F rooms and ATTIC HP off cycle; (c) 2F rooms and BSMT HP on cycle; and (d) 2F rooms and BSMT HP off cycle. The rooms on each floor had similar indoor-outdoor temperature relationship to some extent within each TTD operation except for the kitchen[19]. As a result, Figure 42 displays the median values of the binned room temperatures averaged by floor (i.e., 1F and 2F) for simplicity: (a) HP on cycle and (b) HP off cycle. Lastly, Figure 43 presents the binned room-to-room temperature differences (i.e., ΔT (°C) = MAX(T_{room1}, T_{room2}, …) – MIN(T_{room1}, T_{room2}, …)) relative to outdoor temperature with a superimposed ACCA Manual RS benchmarks (i.e., 1.67°C (3°F) average and 3.33°C (6°F) maximum for a cooling season; and 1.11°C (2°F) average and 2.22°C (4°F) maximum for a heating season).

During the cooling months, there was an obvious difference in the maintained room temperatures by floor between the three TTD operations under the same OA temperatures. The YR2 operation maintained the second-floor bedrooms and the attic colder at the high OA temperatures, which was nearer to the cooling setpoint temperature. However, the first-floor bedroom were overcooled during the YR2 operation, which resulted in the largest temperature deviation from the cooling setpoint temperature.

During the heating months, the YR2 maintained warmer temperature at the 0°C OA temperature bins. However, at the very low OA temperatures, the YR2 operation had lower room temperatures, which was affected by an improved control strategy to minimize the use of backup electric resistance heater.

In terms of the room-to-room temperature differences, all three TTD operations had stronger association with the OA temperature during the cooling season (i.e., at the high OA temperature bins). Among the three TTD operations, YR1 HTTD maintained better thermal uniformity with lower room-to-room temperature differences at the OA temperatures between 15°C and 30°C, while the YR2 operation had the highest room-to-room temperature differences. However, during the heating season, YR2 had slightly better temperature uniformity across the house with lower room-to-room temperature differences especially at the very low OA temperatures (i.e., -15°C and -10°C OA temperature bins). This might be affected by the heat pump running constantly to meet the heating setpoint temperature at this low OA temperatures without activating the backup electric resistance heater during the YR2 operation.

[19] The kitchen had decreasing room temperatures with increasing OA temperatures when the CDHP was in operation during the cooling season.

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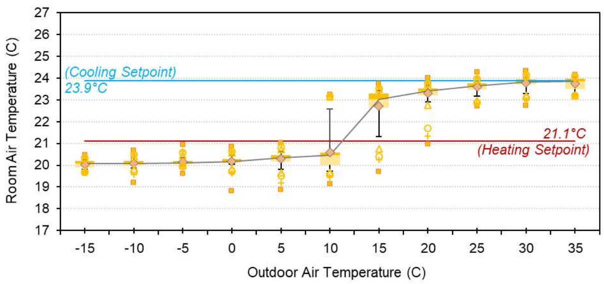
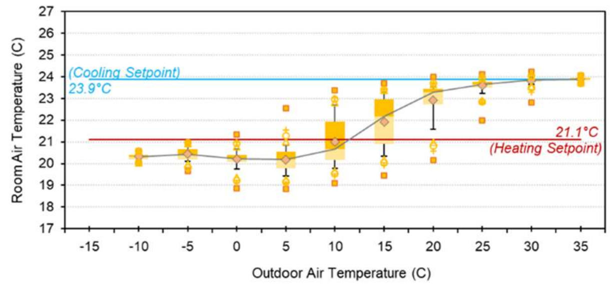
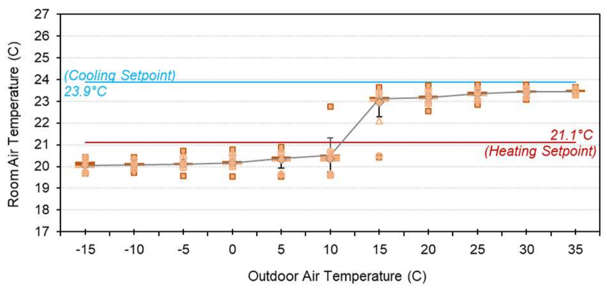


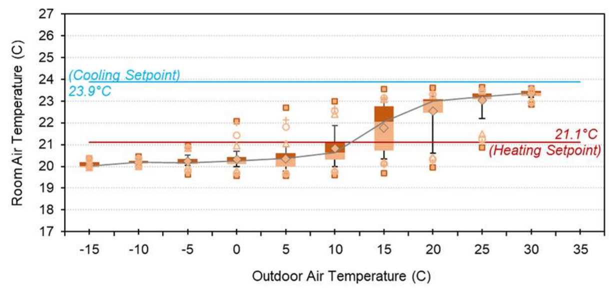
(a) YR1 HTTD HP On



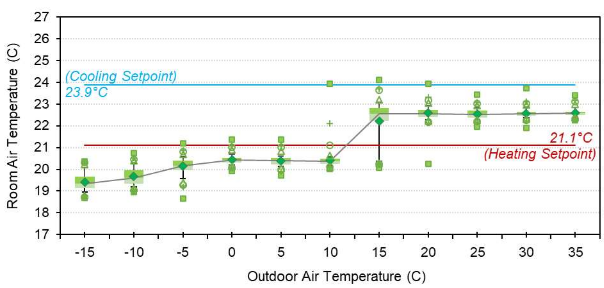
(b) YR1 HTTD HP Off



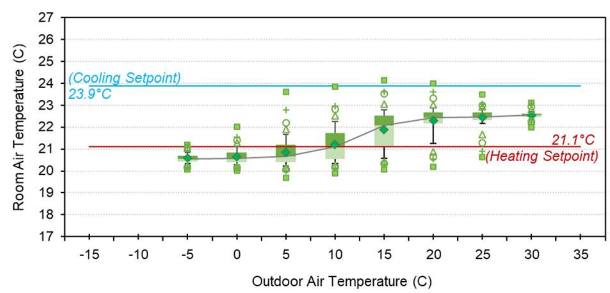
(c) YR1 LTTD HP On



(d) YR1 LTTD HP Off



(e) YR2 HP On



(f) YR2 HP Off

Figure 38: Binned LR Room Air Temperatures Against Outdoor Temperatures.

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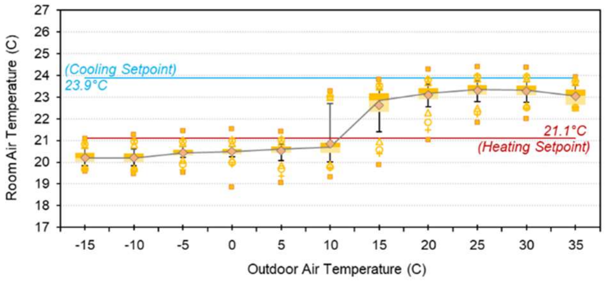
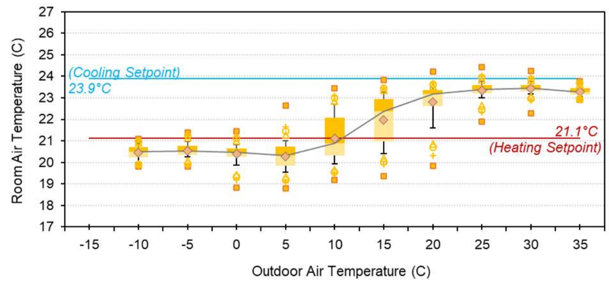
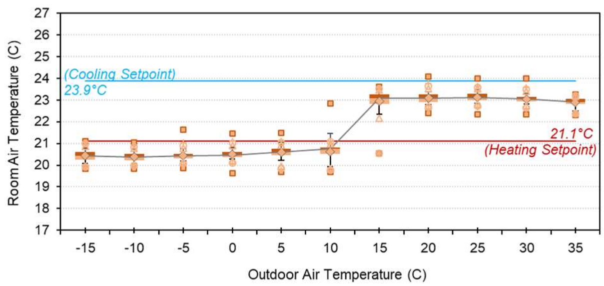


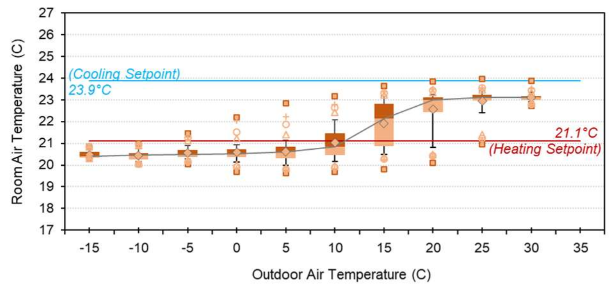
(a) YR1 HTTD HP On



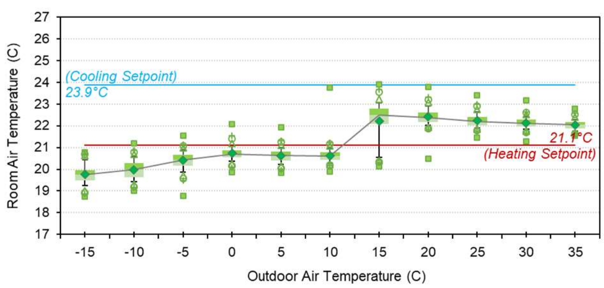
(b) YR1 HTTD HP Off



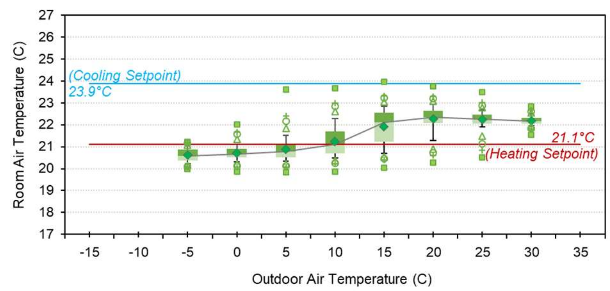
(c) YR1 LTTD HP On



(d) YR1 LTTD HP Off

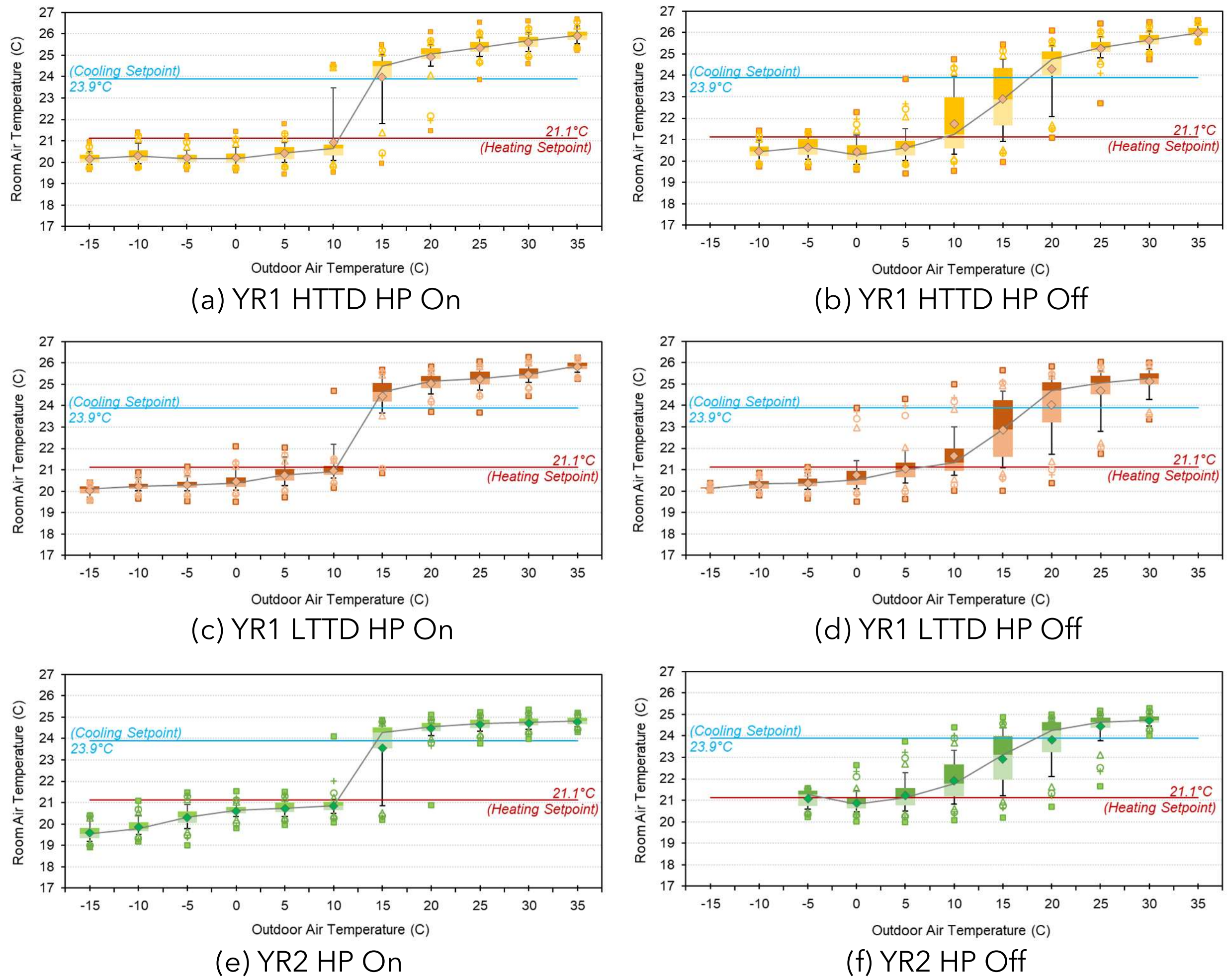


(e) YR2 HP On



(f) YR2 HP Off

Figure 39: Binned KIT Room Air Temperatures Against Outdoor Temperatures.



(a) YR1 HTTD HP On
(b) YR1 HTTD HP Off
(c) YR1 LTTD HP On
(d) YR1 LTTD HP Off
(e) YR2 HP On
(f) YR2 HP Off

Figure 40: Binned BR2 Room Air Temperatures Against Outdoor Temperatures.

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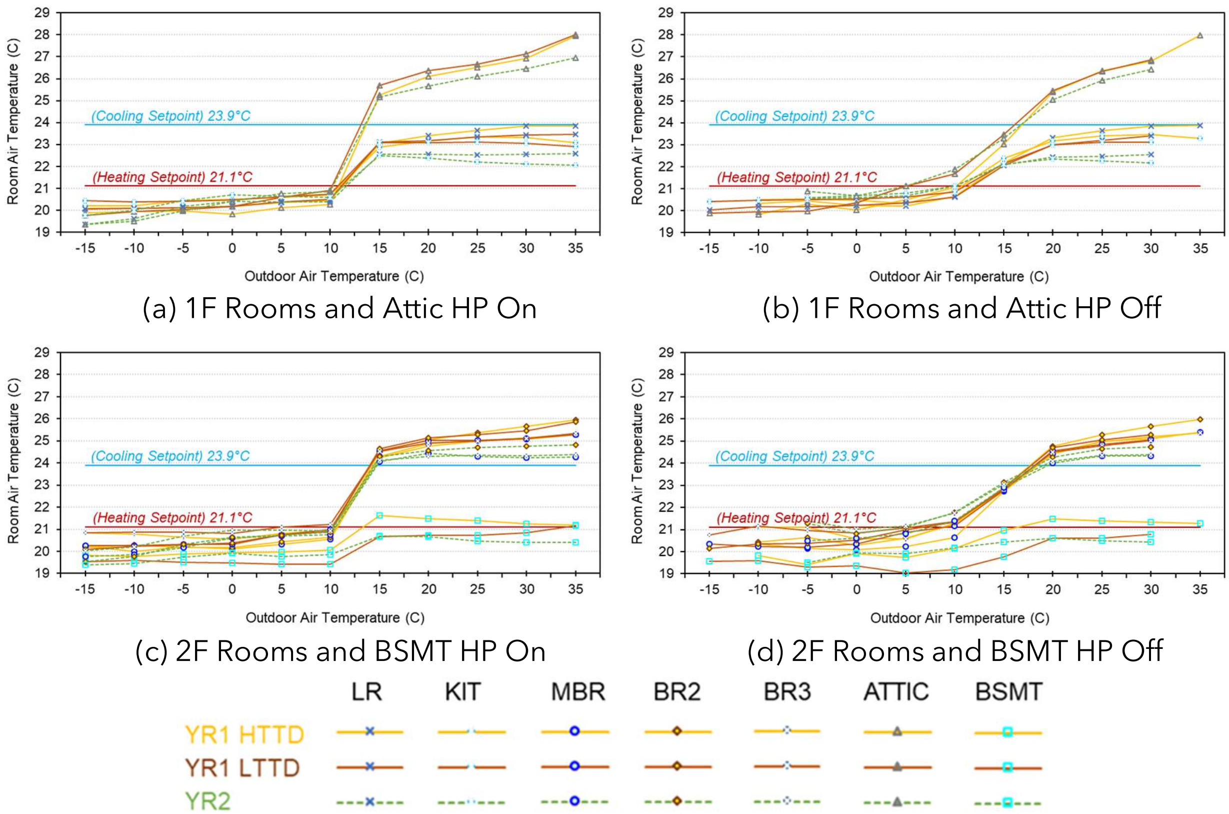

Figure 41: Comparison of Median Values of Binned Room Temperatures of the Seven Rooms Against Outdoor Temperatures.

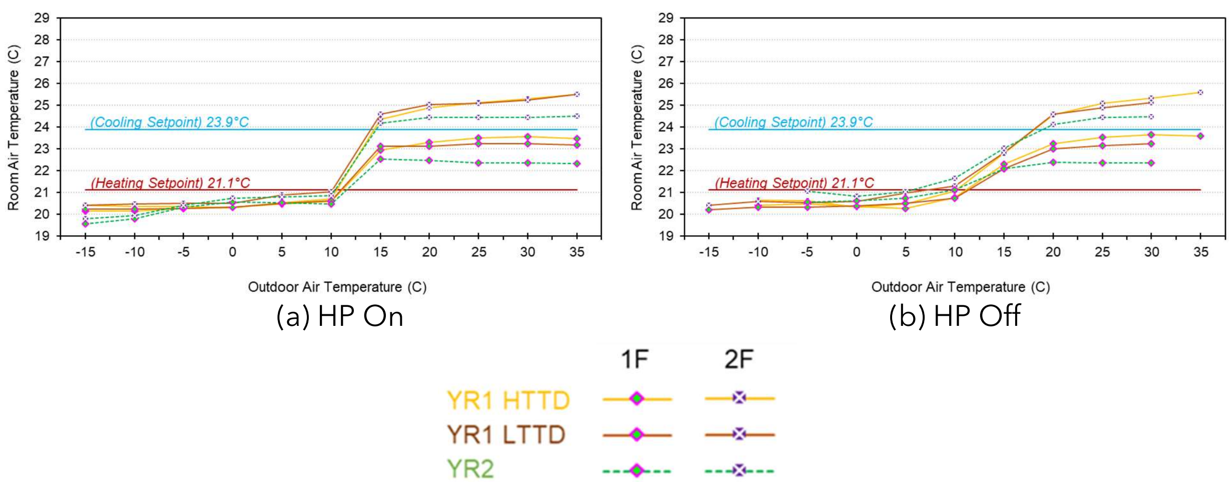

Figure 42: Comparison of Median Values of Binned Room Temperatures Averaged by Floor Against Outdoor Temperatures.

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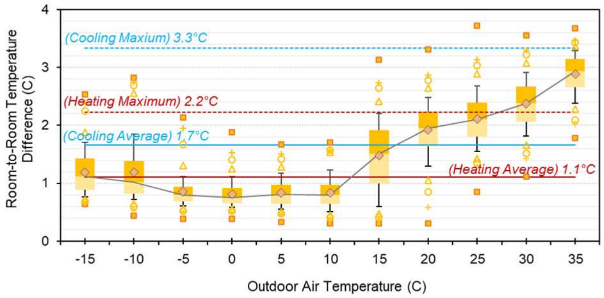
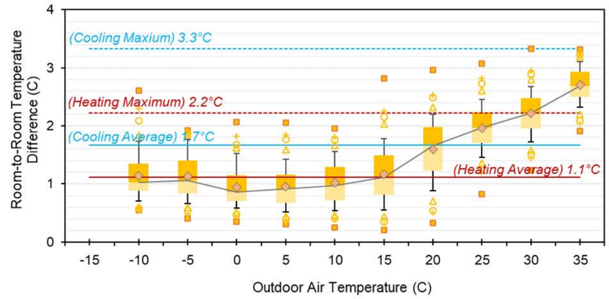
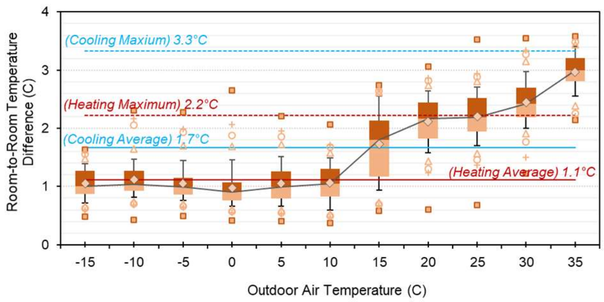


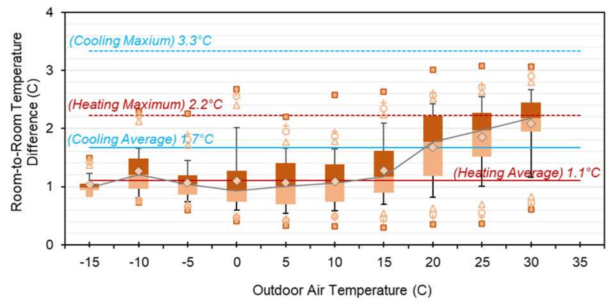
(a) YR1 HTTD HP On



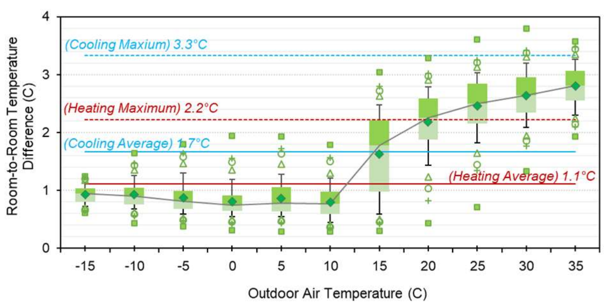
(b) YR1 HTTD HP Off



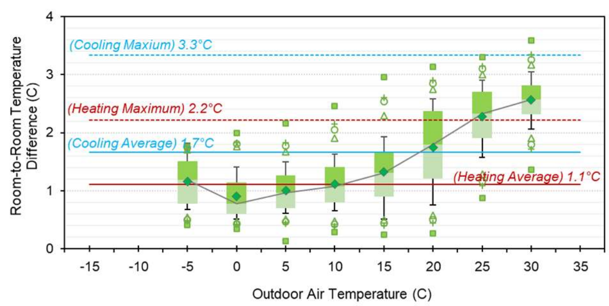
(c) YR1 LTTD HP On



(d) YR1 LTTD HP Off



(e) YR2 HP On



(f) YR2 HP Off

Figure 43: Binned Room-To-Room Temperature Differences Against Outdoor Temperatures.

3.4.2. ROOM HUMIDITY

Figures 44 to 46 present the results of the binned room absolute humidity levels (i.e., humidity ratio in g H_2O/kg dry air) relative to outdoor dew point temperatures for the three rooms, including the living room where the thermostat was located and the two rooms representing each floor (i.e., KIT and BR2). Appendix E provides the results for other rooms (i.e., MBR, BR3, MBA, and BSMT) as supplementary materials. Each figure consists of the six plots: (a) YR1 HTTD on cycle; (b) YR1 HTTD off cycle; (c) YR1 LTTD on cycle; (d) YR1 LTTD off cycle; (e) YR2 on cycle; and (f) YR2 off cycle.

Important observations are:

- All primary rooms appeared to have an association between the outdoor and indoor absolute humidity levels to some extent regardless of the type of TTD operations. The observed relationship was not linear and was less clear at the lower or the higher outdoor dew point temperatures.
- At the high outdoor dew point temperatures (i.e., cooling season), the dehumidification controls applied to the Year1 and Year 2 operations effectively removed moisture from the air and maintained humidity ratios in the rooms below the upper recommended humidity limit of the ASHRAE Standard 55-2017 (i.e., 12 g/kg, which is equivalent to 17.2°C (63°F) dew point temperature) for most of the measurement period.
- There were a few incidences when the maximum humidity ratios exceeded 0.012 kg/kg, which occurred in the KIT during the YR1 LTTD operation and in all second-floor bedrooms during the YR1 HTTD operation.

Figure 47 displays the median values of the binned room absolute humidity ratio of all six rooms (i.e., LR, KIT, MBR, BR2, BR3, and BSMT) for a comparison between rooms: (a) 1F rooms and BSMT HP on cycle; (b) 1F rooms and BSMT HP off cycle; (c) 2F rooms HP on cycle; and (d) 2F rooms HP off cycle. Figure 48 displays the median values of the binned room humidity ratios averaged by floor (i.e., 1F and 2F) for simplicity: (a) HP on cycle and (b) HP off cycle. Lastly, Figure 49 presents the binned room-to-room humidity ratio difference (i.e., ΔW (g/kg) = $MAX(W_{room1}, W_{room2}, \ldots) - MIN(W_{room1}, W_{room2}, \ldots)$) relative to outdoor dew point temperature.

During the cooling months, there was no noticeable difference in the maintained room humidity ratios between the three TTD operations under the same OA dew point temperatures. During the heating months, there was an obvious difference in the maintained room humidity ratios between the three TTD operations. The YR1 LTTD operation had the lowest humidity ratios (i.e., driest) under the same OA dew point temperatures, while the YR2 operation had the highest humidity ratios. In addition, the first-floor rooms appeared to have higher humidity ratios than the ratios of the second-floor rooms.

In terms of the room-to-room humidity ratio differences, their relationship with the OA dew point temperature was less stronger compared to the room-to-room temperature differences, although they tended to increase at the high OA dew point temperatures. Among the three TTD operations, YR1 HTTD maintained better thermal uniformity with slightly lower room-to-room humidity ratio differences at the OA dew point temperatures above 15°C. The YR2 operation tended to have larger temporal variations.

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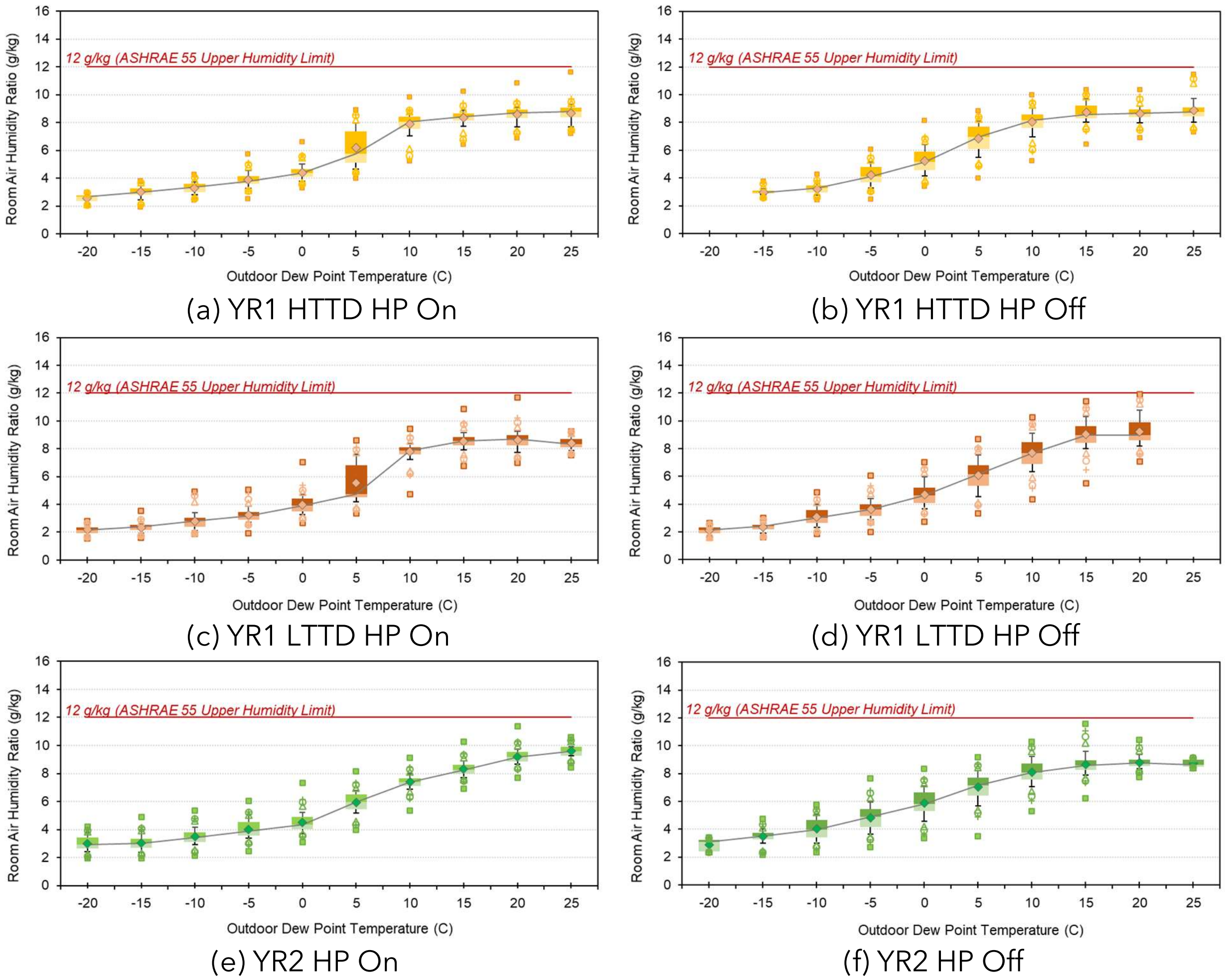

(a) YR1 HTTD HP On

(b) YR1 HTTD HP Off

(c) YR1 LTTD HP On

(d) YR1 LTTD HP Off

(e) YR2 HP On

(f) YR2 HP Off

Figure 44: Binned LR Room Air Humidity Ratios Against Outdoor Dew Point Temperatures.

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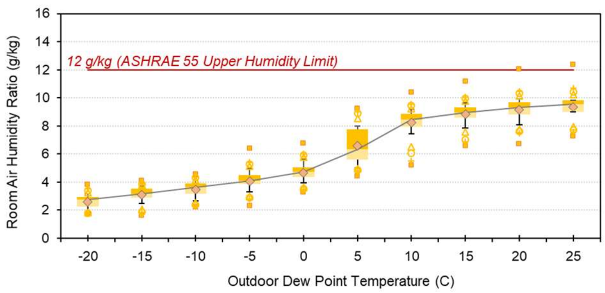
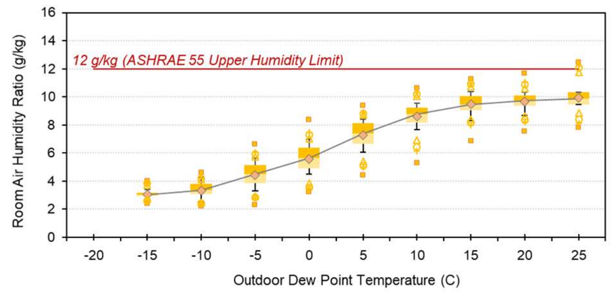
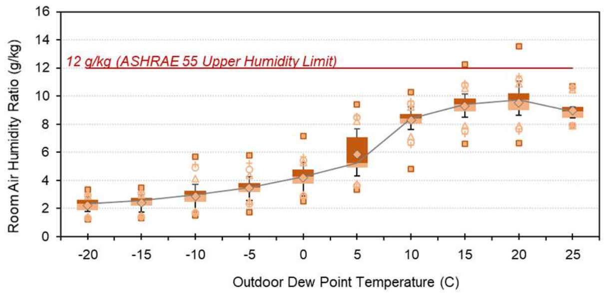


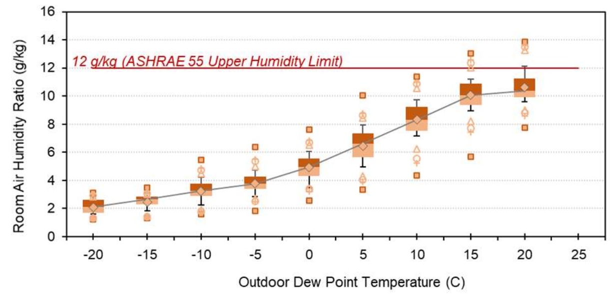
(a) YR1 HTTD HP On



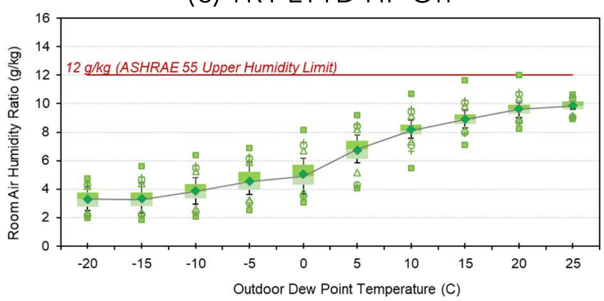
(b) YR1 HTTD HP Off



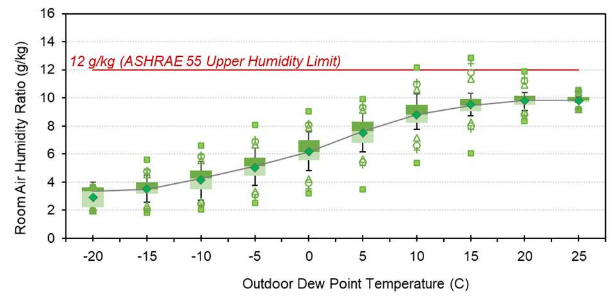
(c) YR1 LTTD HP On



(d) YR1 LTTD HP Off



(e) YR2 HP On



(f) YR2 HP Off

Figure 45: Binned KIT Room Air Humidity Ratios Against Outdoor Dew Point Temperatures.

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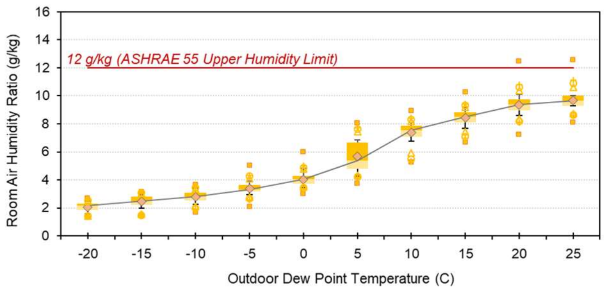
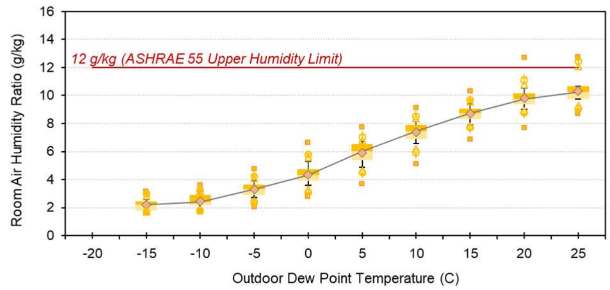
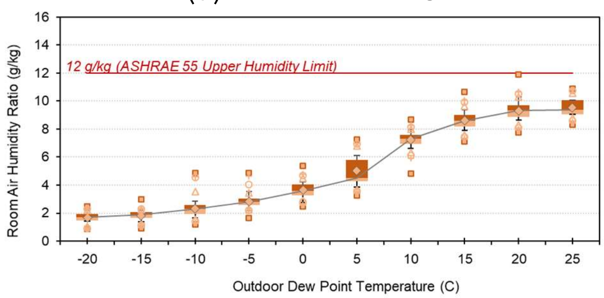


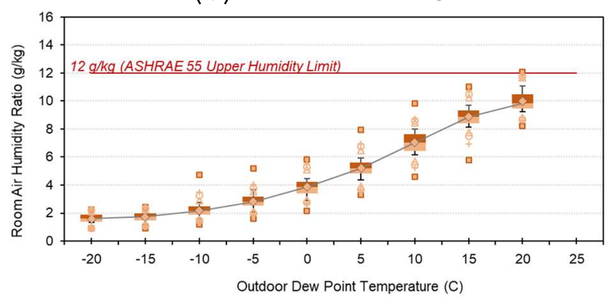
(a) YR1 HTTD HP On



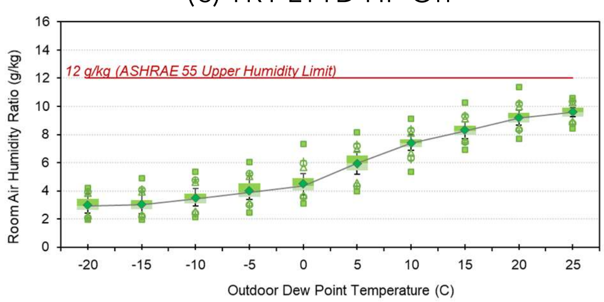
(b) YR1 HTTD HP Off



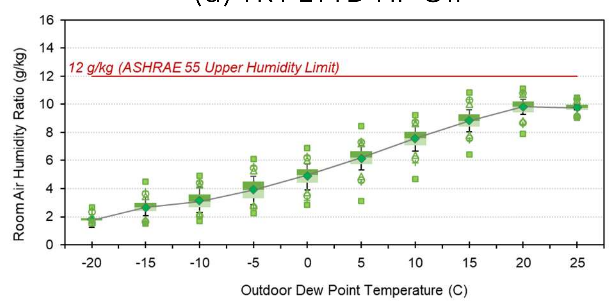
(c) YR1 LTTD HP On



(d) YR1 LTTD HP Off



(e) YR2 HP On



(f) YR2 HP Off

Figure 46: Binned BR2 Room Air Humidity Ratios Against Outdoor Dew Point Temperatures.

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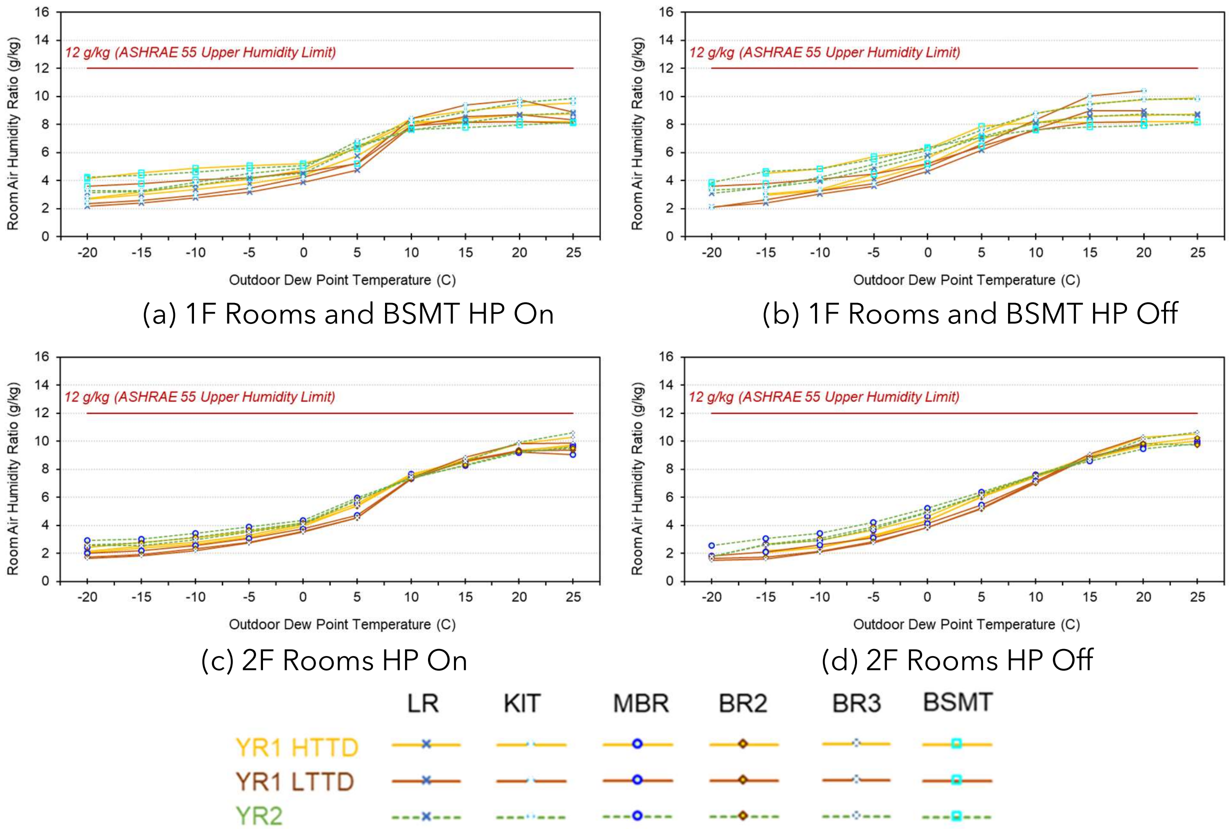


Figure 47: Comparison of Median Values of Binned Room Air Humidity Ratios of the Six Rooms Against Outdoor Dew Point Temperatures.

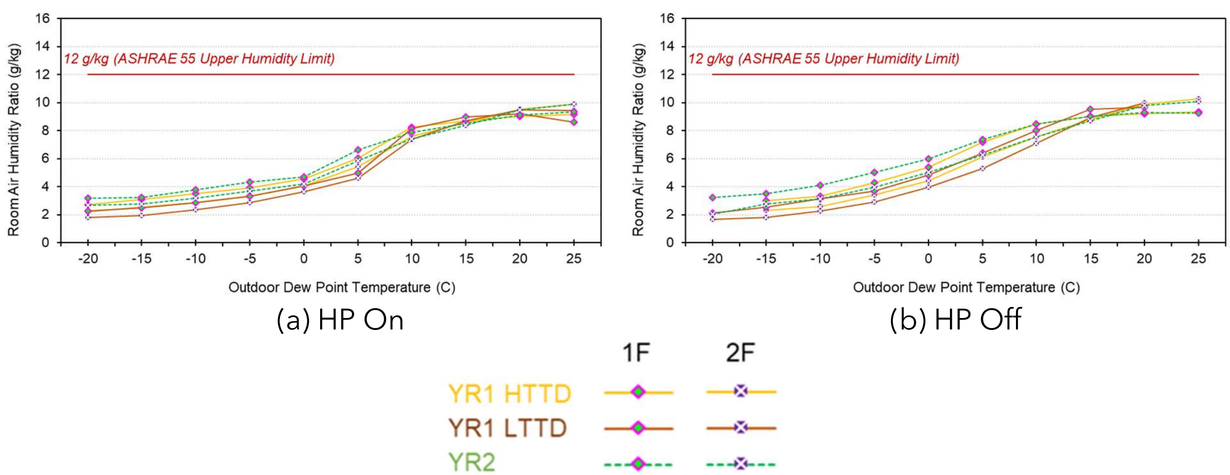
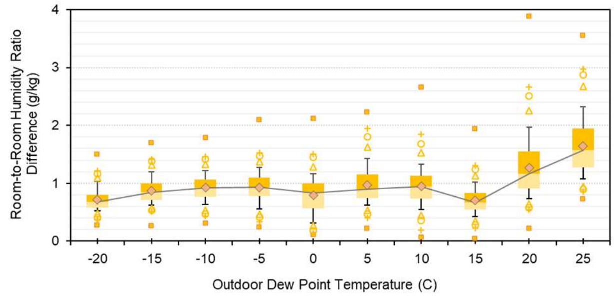
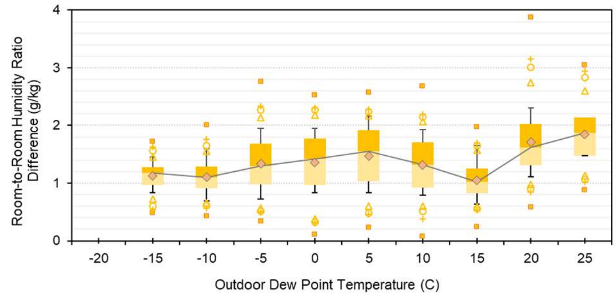


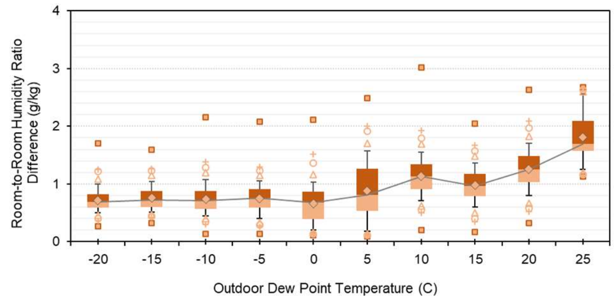
Figure 48: Comparison of Median Values of Binned Room Air Humidity Ratios Averaged By Floor Against Outdoor Dew Point Temperatures.



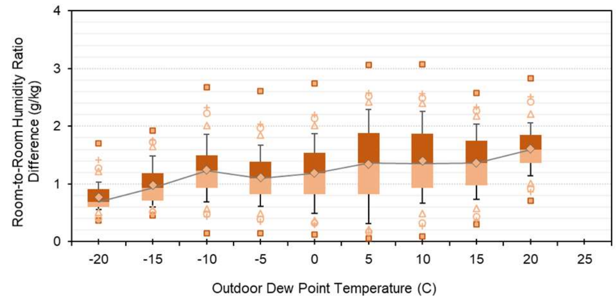
(a) YR1 HTTD HP On



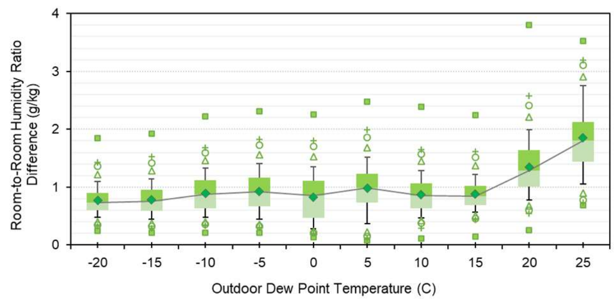
(b) YR1 HTTD HP Off



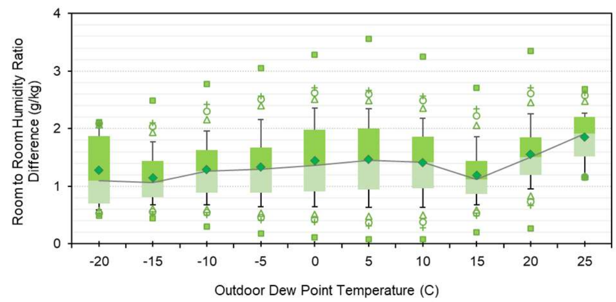
(c) YR1 LTTD HP On



(d) YR1 LTTD HP Off



(e) YR2 HP On



(f) YR2 HP Off

Figure 49: Binned Room-To-Room Humidity Ratio Differences Against Outdoor Dew Point Temperatures.

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3.5. TIME-OF-DAY CHARACTERIZATION

Another characterization performed in this study to better understand the observed temporal variations of the long-term temperature data at NZERTF was a time-of-day analysis of hourly average room temperature data using a time-of-day colored map (i.e., heat map). At NZERTF, the activities of a family of four (i.e., two adults and two children) were simulated in terms of electrical use (i.e., appliances and lighting), hot water use, and metabolic heat and moisture generation based on a consistent schedule. This provides a unique opportunity to understand the dynamic interactions between uneven internal heat gains from occupants, lighting, appliances, and miscellaneous electronic devices and the measured thermal conditions since they can have significant localized impacts on indoor climates even in low-load houses (Stecher et al. 2012).

Figures 50 to 52 present the results for the three rooms, including the living room where the thermostat was located and the two rooms representing each floor (i.e., KIT and BR2). Appendix F provides the results for other rooms (i.e., MBR, BR3, BR4, and DR) as supplementary materials. Each figure consists of the six plots: (a) YR1 HTTD on cycle; (b) YR1 HTTD off cycle; (c) YR1 LTTD on cycle; (d) YR1 LTTD off cycle; (e) YR2 on cycle; and (f) YR2 off cycle.

In the figures, the heat pump thermostat's TTD operations was color-coded (i.e., yellow for YR1 HTTD, dark orange for YR1 LTTD, and green for YR2) and displayed in the first row named TTD Operation. The season classification was also color-coded (i.e., blue for the cooling season, dark red for the heating season, and grey for the transitional season) and displayed in the second row. The non-colored cells represent the data collected during the 25 days that were excluded from the analysis, as described in Appendix B.

Each room consists of the following three plots with the corresponding color key on the left side of each plot:

- (a) hourly average room temperatures with a continuous scale from 17°C to 27°C;
- (b) hourly average room-to-thermostat temperature difference (i.e., ΔT (°C) = $T_{room} - T_{setpoint}$) with a discrete scale to represent the following seven value ranges; and
  - >1.67: ΔT above 1.67°C (3°F)
  - +1.67: ΔT from 1.11°C to 1.67°C (2°F to 3°F)
  - +1.11: ΔT from 0.56°C to 1.11°C (1°F to 2°F)
  - ±0.56: ΔT from -0.56°C to 0.56°C (-1°F to 1°F)
  - -1.11: ΔT from -1.11°C to -0.56°C (-2°F to -1°F)
  - -1.67: ΔT from -1.67°C to -1.11°C (-3°F to -2°F)
  - <-1.67: ΔT below -1.67°C (-3°F))
- (c) ACCA Manual RS compliance based on an hourly average room-to-thermostat temperature difference while the favorable temperature differences (i.e., ΔT below 0°C in the cooling season and ΔT above 0°C in the heating season) were intentionally color-coded using green[20].
  - >±1.67 (red): ΔT above 1.67°C (cooling season) and ΔT below -1.67°C (heating season)

[20] The color-coding system of the transitional season followed the cooling season if the corresponding room temperature was above the cooling setpoint temperature (i.e., 23.8°C) or the heating season if the corresponding room temperature was below the heating setpoint temperature (i.e., 21.1°C).

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- ±1.67 (peach): ΔT from 1.11°C to 1.67°C (cooling season) and ΔT from -1.67°C to -1.11°C (heating season)
- ±1.11 (light green): ΔT from 0.56°C to 1.11°C (cooling season) and ΔT from -1.11°C to -0.56°C (heating season)
- ±0.56 (green): ΔT below 0.56°C (cooling season) and ΔT above -0.56°C (heating season)

In this way, the red cells represent only the hours when the room temperatures unfavorably exceeded the ACCA benchmarks (i.e., ΔT above 1.67°C in the cooling season and ΔT below 1.67°C in the heating season). Due to the more stringent ACCA benchmark for a heating season (i.e., thermostat setpoint ±1.11°C (±2°F)), the peach cells in the heating season also represent a non-compliant period.

Different temporal patterns were observed, which was mostly affected by the schedule of internal loads simulated in each room. For example, the LR temperature was always lower during the nighttime before the sun rises, which was affected by no presence of the simulated occupancy/plug loads in the LR at night. However, the opposite pattern (i.e., lower BR2 temperatures during the daytime due to no presence of the simulated occupancy) was observed in the BR2.

These maps also allowed the identification of non-compliant periods based on the ACCA Manual RS benchmarks and the resulting thermal discomfort. For example, during the Year 1 operation, the unfavorable non-compliant period (i.e., red and peach in a heating season; red in a cooling season in Figure 48 (c) and (f)) in the LR mainly occurred during the heating days before November 19, 2013 when the1st stage heating differential temperature was set higher. In addition, delayed or no responses of the heat pump's 2nd and 3rd stage heating were occasionally observed during the YR1 HTTD operation. In addition, non-compliance in the LR mostly occurred at nighttime when there were no internal heat gains.

Like the Year 1 operation, the unfavorable non-compliant period in the LR during the Year 2 operation occurred when the heat pump was in the heating mode. They mainly occurred on cold winter days of which nighttime OA temperatures were below 0°C. The observed temporal patterns of the unfavorable non-compliant period for the KIT resembled those for the LR, though to a lesser extent.

In the BR2, the unfavorable non-compliance occurred through a year during the Year 1 operation. During the year 2 operation, the unfavorable non-compliant period in the BR2 occurred only when the heat pump was in the heating mode. It should be noted that the BR2 had a lot more non-compliances when the heat pump was in the cooling mode compared to other second-floor bedrooms (Appendix F). This occurred at a specific time of the days due to the combined effect of the scheduled internal loads (i.e., occupancy, plug loads, and lighting) and the constant 20 W base loads remained on in BR2.

As explained above, the heating non-compliance includes both red (ΔT below -1.67°C) and peach (ΔT from -1.67°C to -1.11°C). Unlike the Year 1 operation, a few extreme incidences of the heating non-compliance (i.e., red) were observed during the Year 2 operation. This was due to extreme weather conditions on these four days on February 2015 of which daily average OA temperatures were below -10°C (i.e., February 15, 16, 19, and 20, 2015). This

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was a comfort penalty caused by an improved control strategy of the backup electric resistance heater (i.e., 3rd stage heating) to minimize its use.

In addition to the room-to-thermostat temperature compliance with the ACCA Manual RS, the room-to-room temperature differences and the resultant compliance with the ACCA Manual RS were also graphically displayed using a time-of-day colored map, as shown in Figure 53. The hourly average room-to-room temperature difference (i.e., ΔT (°C) = MAX(T_{room1}, T_{room2}, …) – MIN(T_{room1}, T_{room2}, …)) was color-coded with a discrete scale to represent the following seven value ranges:

- ΔT above 3.33°C (6°F);
- ΔT from 2.78°C to 3.33°C (5°F to 6°F);
- ΔT from 2.22°C to 2.78°C (4°F to 5°F);
- ΔT from 1.67°C to 2.22°C (3°F to 4°F);
- ΔT from 1.11°C to 1.67°C (2°F to 3°F);
- ΔT from 0.56°C to 1.11°C (1°F to 2°F); and
- ΔT from 0°C to 0.56°C (0°F to 1°F).

The ACCA Manual RS compliance based on hourly average room-to-room temperature difference was color-coded using three different colors:

- Not compliant (red): ΔT above 3.33°C (cooling and transitional season) and ΔT above 2.22°C (heating season);
- Compliant with the maximum benchmarks (orange): ΔT from 1.67°C to 3.33°C (cooling and transitional season) and ΔT from 1.11°C to 2.22°C (heating season); and
- Compliant with the average benchmarks (green): ΔT below 1.67°C (cooling and transitional season) and ΔT below 1.11°C (heating season).

As a result, the use of the proposed time-of-day colored map was useful to find out when the non-compliance period occurred and the level of discomfort. For both years, the room-to-room temperature differences exceeded the ACCA average cooling benchmark (i.e., orange) for most of the measurement period when the heat pump was in the cooling mode, although the YR1 HTTD operation had more occasions of which room-to-room temperature differences were below the average cooling benchmark (i.e., green) than the other two TTD operations. When the heat pump was in the heating mode, both years had several occasions exceeding the ACCA average heating benchmark (i.e., orange), which mostly occurred during the daytime.

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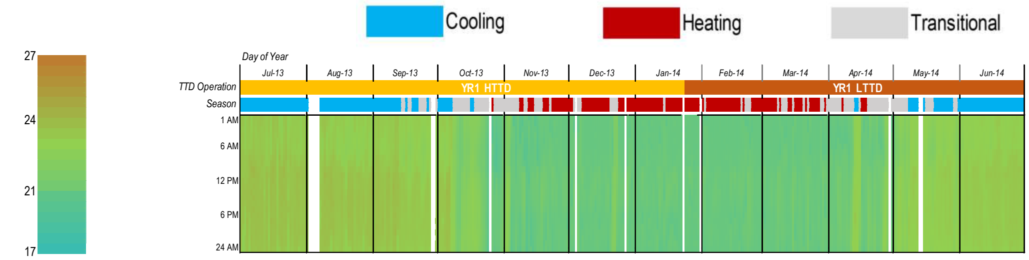
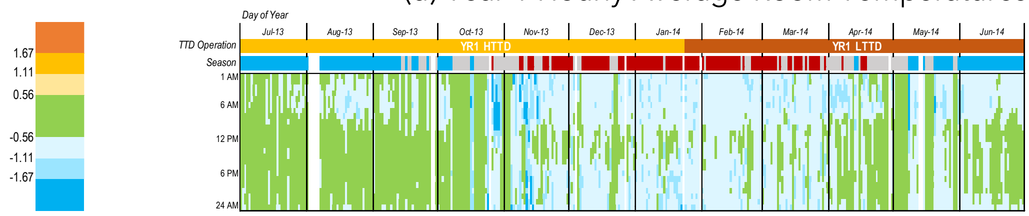
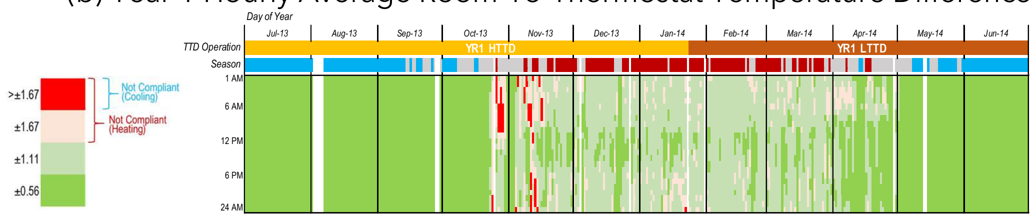


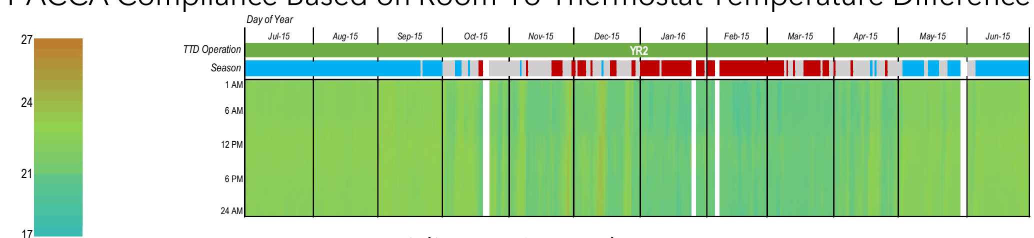
(a) Year 1 Hourly Average Room Temperatures



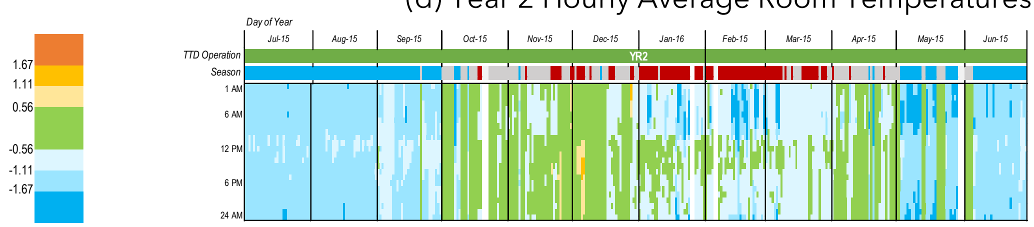
(b) Year 1 Hourly Average Room-To-Thermostat Temperature Difference



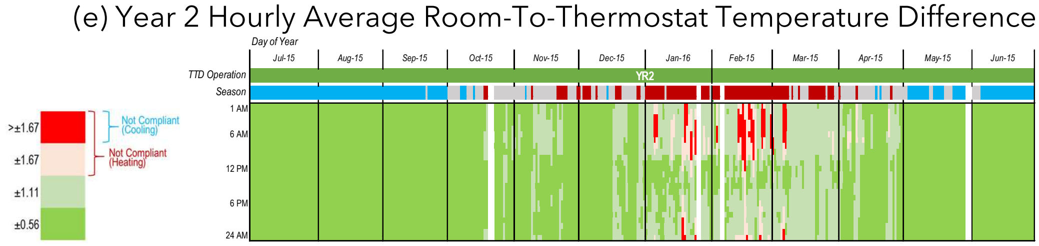
(c) Year 1 ACCA Compliance Based on Room-To-Thermostat Temperature Difference



(d) Year 2 Hourly Average Room Temperatures



(e) Year 2 Hourly Average Room-To-Thermostat Temperature Difference



(f) Year 2 ACCA Compliance Based on Room-To-Thermostat Temperature Difference

Figure 50: Time-of-Day Colored Map of LR Temperature.

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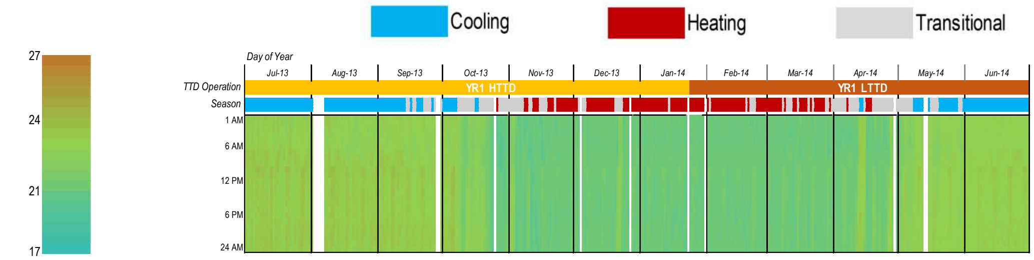
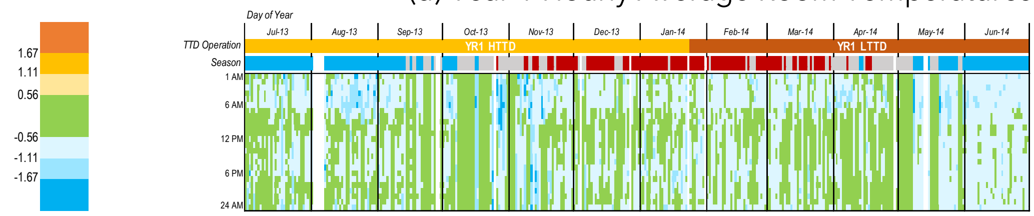
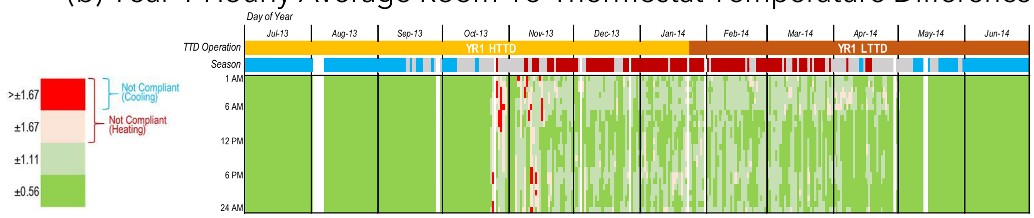


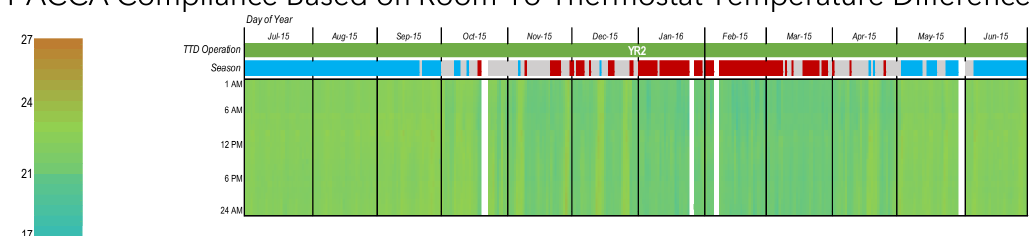
(a) Year 1 Hourly Average Room Temperatures



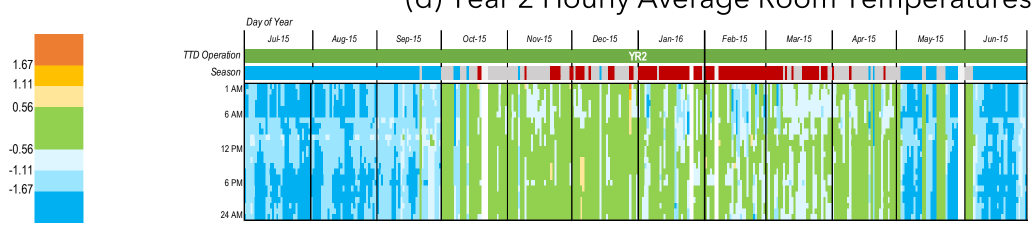
(b) Year 1 Hourly Average Room-To-Thermostat Temperature Difference



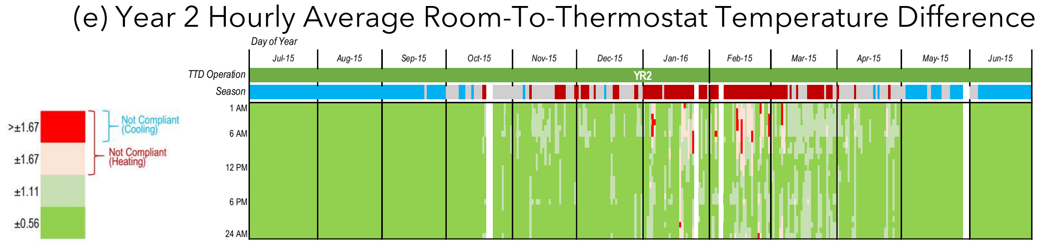
(c) Year 1 ACCA Compliance Based on Room-To-Thermostat Temperature Difference



(d) Year 2 Hourly Average Room Temperatures



(e) Year 2 Hourly Average Room-To-Thermostat Temperature Difference



(f) Year 2 ACCA Compliance Based on Room-To-Thermostat Temperature Difference

Figure 51: Time-of-Day Colored Map of KIT Temperature.

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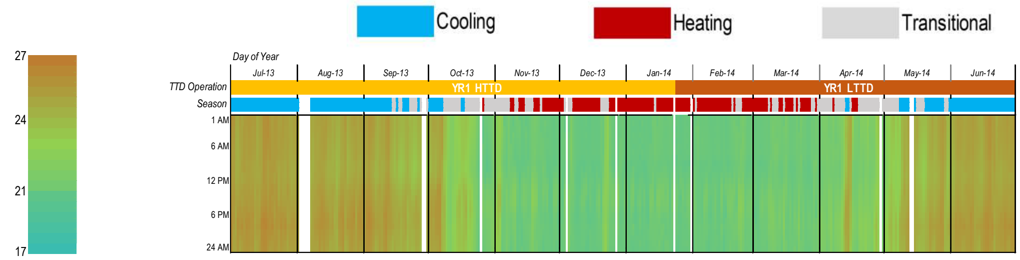
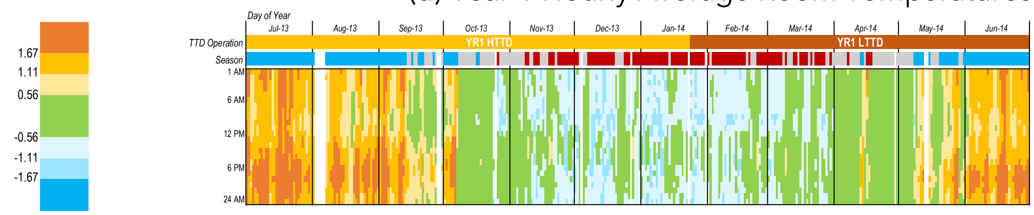
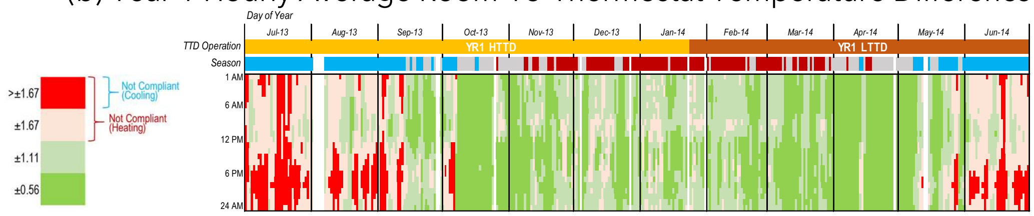


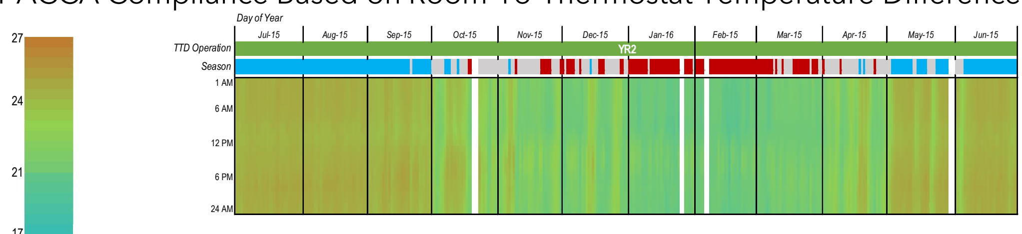
(a) Year 1 Hourly Average Room Temperatures



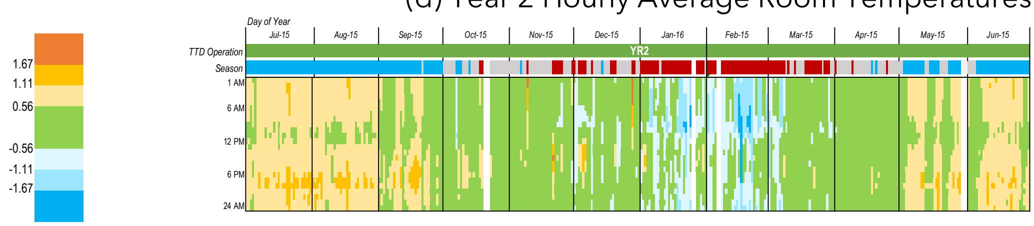
(b) Year 1 Hourly Average Room-To-Thermostat Temperature Difference



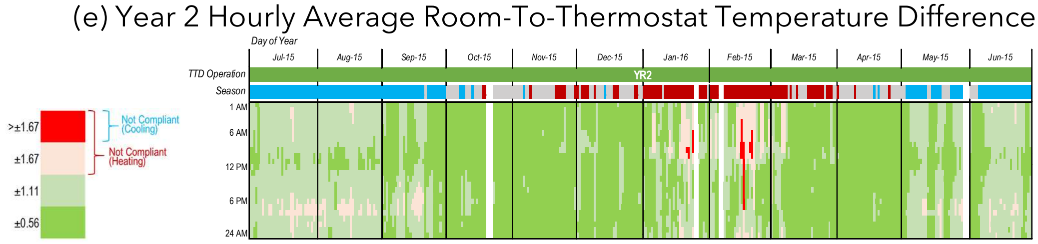
(c) Year 1 ACCA Compliance Based on Room-To-Thermostat Temperature Difference



(d) Year 2 Hourly Average Room Temperatures

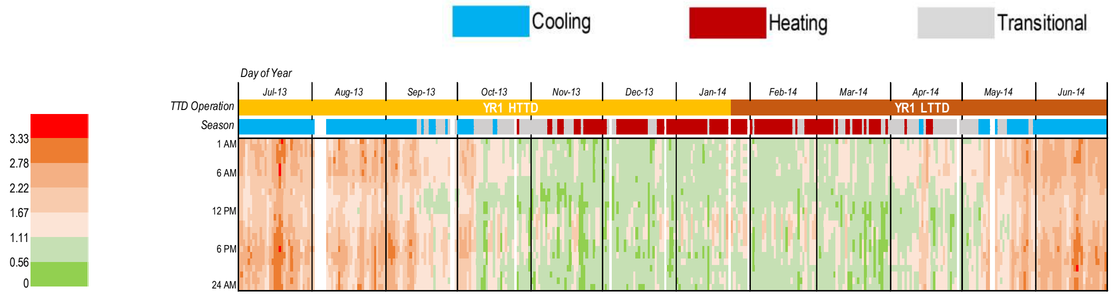


(e) Year 2 Hourly Average Room-To-Thermostat Temperature Difference

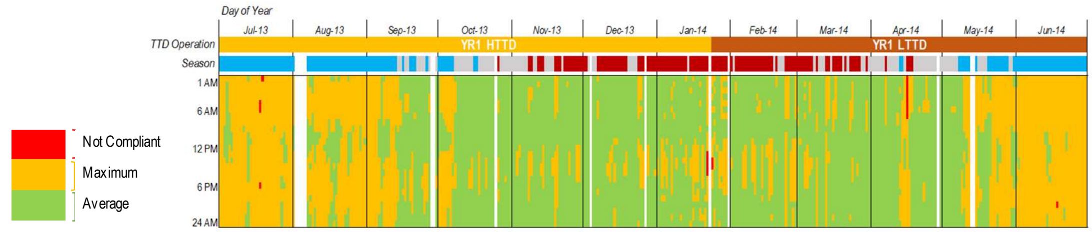


(f) Year 2 ACCA Compliance Based on Room-To-Thermostat Temperature Difference

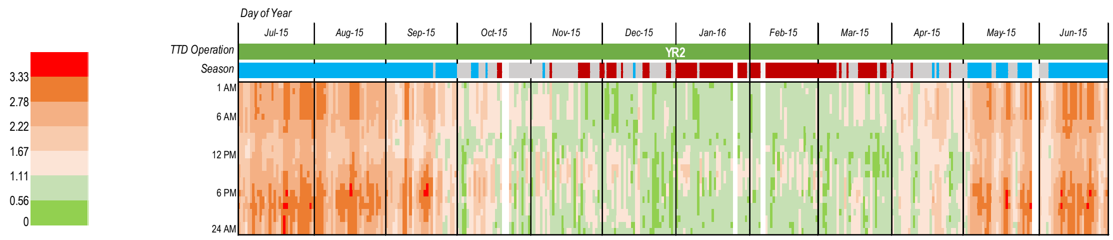
Figure 52: Time-of-Day Colored Map of BR2 Temperature.



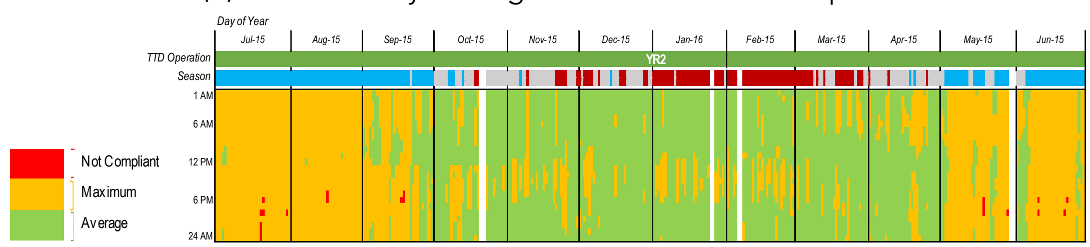
(a) Year 1 Hourly Average Room-To-Room Temperature Difference



(b) Year 1 ACCA Compliance Based on Room-To-Room Temperature Difference



(c) Year 2 Hourly Average Room-To-Room Temperature Difference



(d) Year 2 ACCA Compliance Based on Room-To-Room Temperature Difference

Figure 53: Time-of-Day Colored Map of Room-To-Room Temperature Difference.

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4. WHOLE-HOUSE THERMAL COMFORT METRICS

This section presents an analysis of whole-house thermal comfort performance using several whole-house thermal comfort metrics.

Section 4.1 presents the results of a room temperature deviation analysis from the setpoint temperature based on the room-to-thermostat temperature difference.

Section 4.2 presents the results of a room-to-room temperature difference analysis performed to evaluate the spatial thermal uniformity.

Section 4.3 presents the results of a cyclic discomfort analysis performed to evaluate the temporal thermal uniformity.

Section 4.4 presents the results of a room RH deviation analysis from the setpoint RH based on the room-to-humidistat RH difference.

4.1. TEMPERATURE DEVIATION FROM THE SETPOINT TEMPERATURE

Figures 54 to 56 present the percentage distributions of the 5-min average room-to-thermostat temperature difference for the cooling season (Figure 54), heating season (Figure 55), and transitional season (Figure 56), with the percentages[21] of the data points grouped based on a degree of temperature difference (ΔT) as follows:

- ΔT above 1.67°C (3°F);
- ΔT from 1.11°C to 1.67°C (2°F to 3°F);
- ΔT from 0.56°C to 1.11°C (1°F to 2°F);
- ΔT from 0°C to 0.56°C (0°F to 1°F);
- ΔT from -0.56°C to 0°C (-1°F to 0°F);
- ΔT from -1.11°C to -0.56°C (-2°F to -1°F);
- ΔT from -1.67°C to -1.11°C (-3°F to -2°F); and
- ΔT below -1.67°C (-3°F).

In these figures, the relevant ACCA Manual RS benchmarks (i.e., thermostat setpoint ±1.67°C (±3°F) for a cooling season; and thermostat setpoint ±1.11°C (±2°F) for a heating season) are also presented for comparison. The groups meeting the ACCA benchmarks were highlighted in green, while the groups unfavorably exceeding the ACCA benchmarks (i.e., ΔT above 1.67°C in the cooling season and ΔT below -1.11°C in the heating season) were highlighted in red. Data were color-coded by TTD operations: yellow for YR1 HTTD, dark orange for YR1 LTTD, and green for YR2.

Important observations on the room-to-thermostat temperature difference are:

- Cooling Season Results (Figure 54)
  - The first-floor room-to-thermostat temperature differences were mostly on the low side (i.e., ΔT below 0°C) for all three TTD operations. There were no occasions when the room-to-thermostat temperature difference unfavorably exceeded the ACCA cooling benchmark (i.e., ΔT above 1.67°C) in the first-floor rooms.

[21] 0.00% means there were still few data points in that corresponding group.

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  - Not surprisingly, the second-floor room-to-thermostat temperature differences were mostly on the high side (i.e., ΔT above 0°C) for all three TTD operations. There were occasions when the room-to-thermostat temperature difference unfavorably exceeded the ACCA cooling benchmark (i.e., ΔT above 1.67°C) in the second-floor rooms, which was the highest during the YR1 HTTD operation: 4.8% (MBR), 26.7% (BR2), and 3.0% (BR3).
  - The YR2 operation had the highest low-side ΔT deviation in the first floor rooms compared to the YR1 HTTD and YR1 LTTD operations with an average room-to-thermostat temperature differences of -1.3°C (LR), -1.6°C (KIT), -1.4°C (DR) and -1.3°C (BR4). In addition, the YR2 operation had the highest non-compliance percentages of the first-floor rooms on the low side: 5.6% (LR), 43.1% (KIT), 15.7% (DR), and 5.1% (BR4).
  - However, in the second-floor rooms, the YR2 operation had the lowest room-to-thermostat temperature differences of 0.4°C (MBR), 0.7°C (BR2), and 0.4°C (BR3), without any non-compliance percentages.
  - Between the two YR1 operations, the YR1 HTTD operation had slightly lower room-to-thermostat temperature differences in the first-floor rooms than the YR1 LTTD operation with comparable ACCA compliance percentages.
  - The whole-house room-to-thermostat temperature difference, which is a metric weighted by the floor areas of seven primary rooms (i.e., LR, KIT, DR, BR4, MBR, BR2, and BR3 representing 71% of the total floor area) had 100% ACCA compliance percentages for all three TTD operations although there were very few incidences of low-side non-compliance for the YR2 operation. However, this whole-house temperature did not well represent the actual temperature conditions of the house due to high temperature differences between the first-floor and second-floor rooms during the cooling season.

- Heating Season Results (Figure 55)
  - Compared to the cooling season, lower compliance percentages were reported during the heating season for all three TTD operations.
  - Like the cooling season, the first-floor room-to-thermostat temperature differences were mostly on the low side (i.e., ΔT below 0°C) for all three TTD operations. High non-compliance percentages were reported in the first-floor rooms where the room-to-thermostat temperature difference unfavorably exceeded the ACCA heating benchmark (i.e., ΔT below 1.1°C): from 7.7% (KIT) to 42.2% (DR) during the YR1 HTTD operation; from 2.7% (KIT) to 47.7% (DR) during the YR1 LTTD operation; and from 9.1% (KIT) to 22.2% (DR) during the YR2 operation.
  - On average, the second-floor room temperatures were closer to the setpoint temperature. However, the second-floor rooms also reported high ACCA non-compliance percentages except for BR3: 30.1% (MBR) and 17.2% (BR2) during the YR1 HTTD operation; 10.5% (MBR) and 6.2% (BR2) during the YR1 LTTD operation; and 12.7% (MBR) and 12.1% (BR2) during the YR2 operation.
  - Unlike the cooling season, the differences in the calculated room-to-thermostat temperature differences between the three TTD operations were less obvious, although the YR2 operation maintained the room temperatures nearest to the setpoint temperature on average.
  - The whole-house room-to-thermostat temperature difference better represented the actual temperature conditions of the house during the heating season when

there were lower temperature differences between the first-floor and second-floor rooms.

- Transitional Season Results (Figure 56)
  - The transitional season maintained its room temperature between the heating and cooling setpoint temperature, which resulted in room-to-thermoset temperature differences of 0°C. Otherwise, the first-floor room-to-thermostat temperature differences tended to be on the low side (i.e., ΔT below 0°C) like other seasons.
  - The reported non-compliance percentages were also on the low side (i.e., ΔT lower than - 1.11°C), which was the highest during the YR1 HTTD operation especially when the1st stage heating differential temperature was set higher before November 19, 2013.

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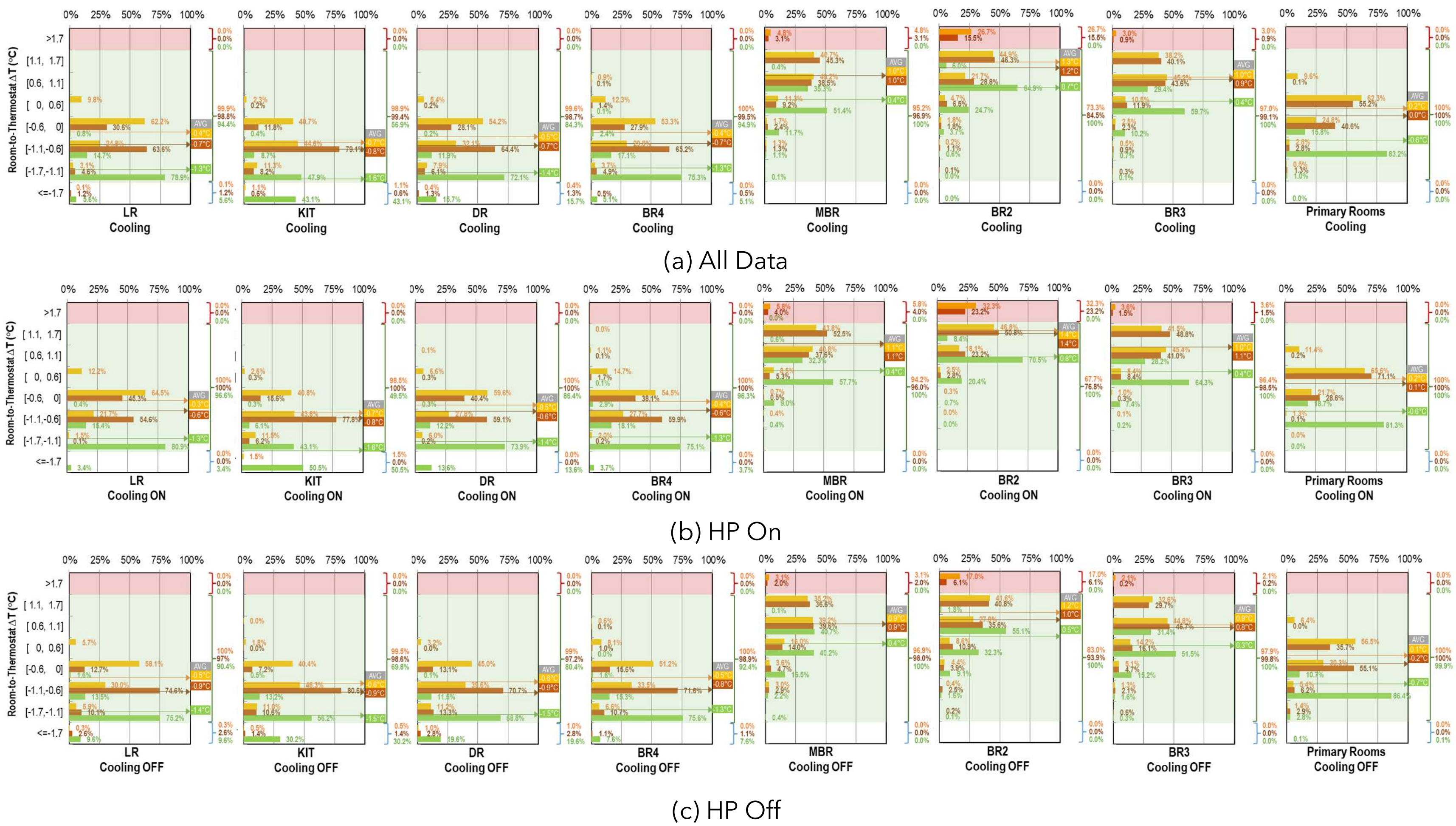

(a) All Data

(b) HP On

(c) HP Off

Figure 54: Graphical Summaries of the 5-Min Average Room-To-Thermostat Temperature Differences for the Cooling Season.

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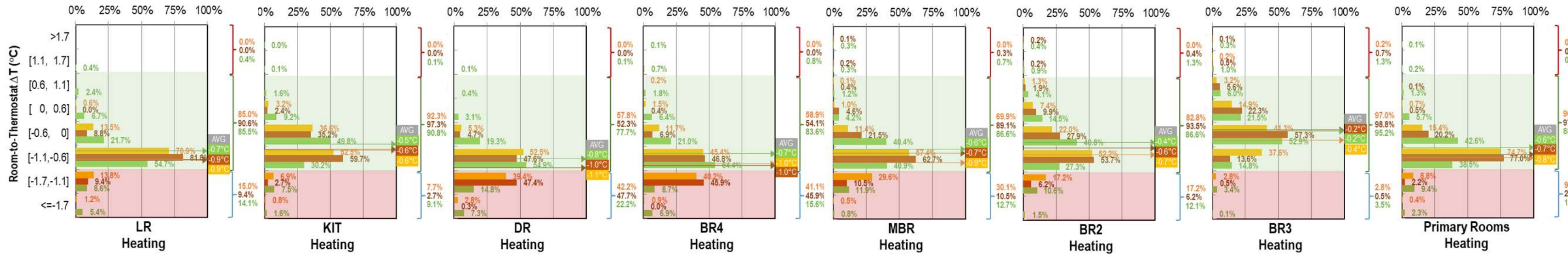
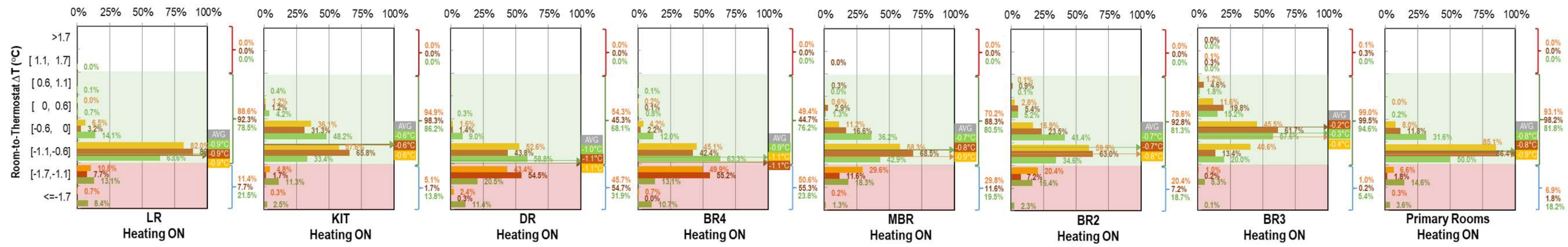
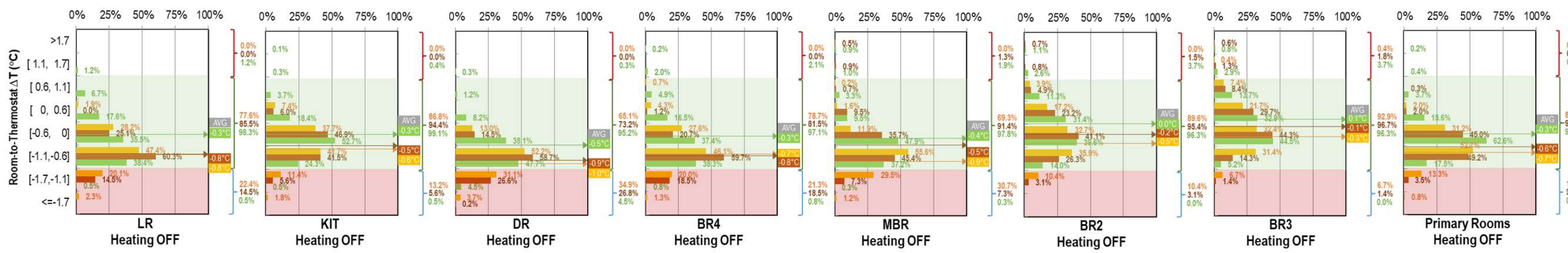


(a) All Data



(b) HP On



(c) HP Off

Figure 55: Graphical Summaries of the 5-Min Average Room-To-Thermostat Temperature Differences for the Heating Season.

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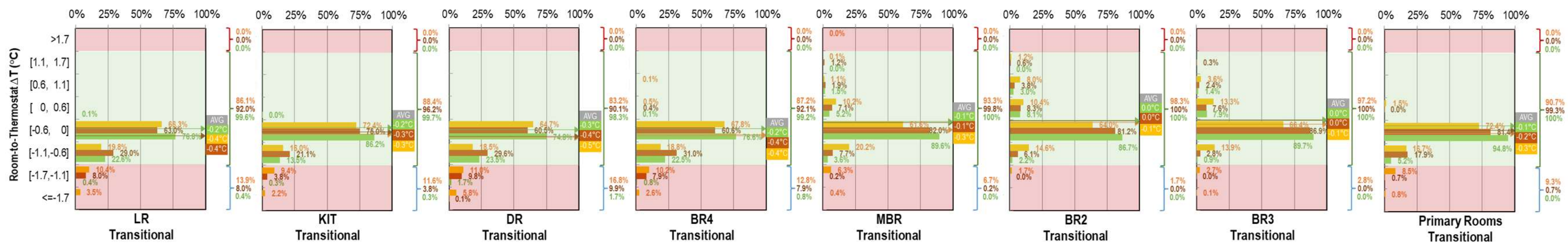
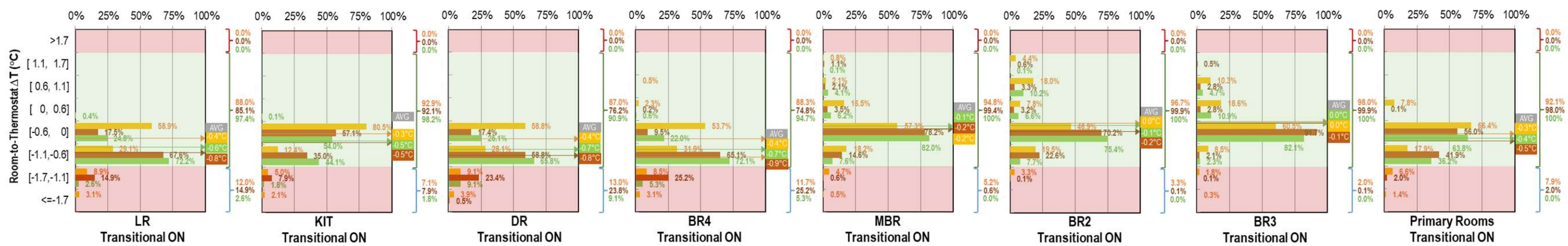
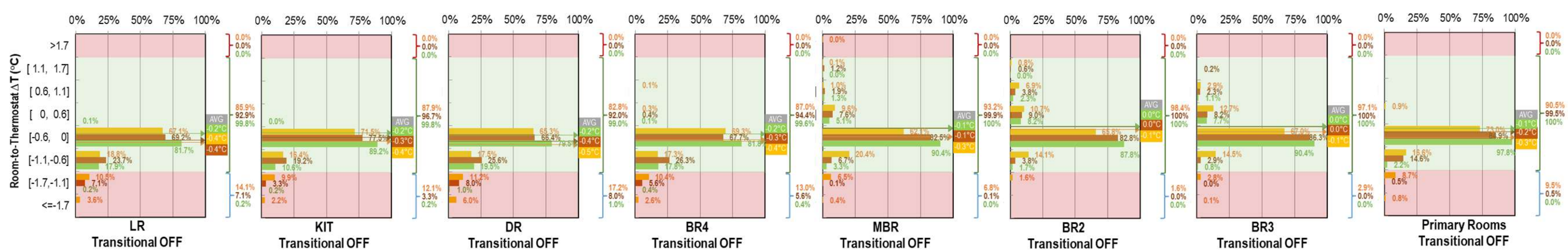


(a) All Data



(b) HP On



(c) HP Off

Figure 56: Graphical Summaries of the 5-Min Average Room-To-Thermostat Temperature Differences for the Transitional Season.

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4.2. ROOM-TO-ROOM TEMPERATURE DIFFERENCE

Figure 57 presents the percentage distributions of the 5-min average room-to-room temperature difference with the percentages of the data points grouped based on a degree of temperature difference (ΔT) as follows:

- ΔT above 3.33°C (6°F);
- ΔT from 2.78°C to 3.33°C (5°F to 6°F);
- ΔT from 2.22°C to 2.78°C (4°F to 5°F);
- ΔT from 1.67°C to 2.22°C (3°F to 4°F);
- ΔT from 1.11°C to 1.67°C (2°F to 3°F);
- ΔT from 0.56°C to 1.11°C (1°F to 2°F); and
- ΔT from 0°C to 0.56°C (0°F to 1°F).

In these figures, the relevant ACCA Manual RS benchmarks (i.e., 1.67°C (3°F) average and 3.33°C (6°F) maximum for cooling and transitional seasons; and 1.11°C (2°F) average and 2.22°C (4°F) maximum for a heating season) are also presented for a comparison. The groups meeting the ACCA average benchmarks (i.e., ΔT below 1.67°C for cooling and transitional seasons and ΔT above 1.11°C for a heating season) were highlighted in light green, while the groups exceeding the ACCA average benchmarks but still meeting its maximum benchmarks (i.e., ΔT above 3.33°C in cooling and transitional seasons and ΔT above 2.22°C in a heating season) were highlighted in light yellow. Lastly, the groups exceeding even the ACCA maximum benchmarks were highlighted in red. Data were also color-coded by TTD operations: yellow for YR1 HTTD, dark orange for YR1 LTTD, and green for YR2.

Important observations on the room-to-room temperature difference are:

- Cooling Season Results
  - All three TTD operations had an average room-to-room temperature difference exceeding the ACCA average cooling benchmark (i.e., 1.67°C). The compliance percentages with the ACCA average cooling benchmark were only 21.8% (YR1 HTTD), 14.4% (YR1 LTTD), and 13.1% (YR2).
  - Among the three TTD operations, the YR1 HTTD operation maintained smaller room-to-room temperature differences than the YR1 LTTD and YR2 operations with an average room-to-room temperature difference of 2.0°C.
  - There were occasions when the room-to-room temperature difference exceeded the ACCA maximum cooling benchmark (i.e., 3.33°C), which was about 0.4% (YR1 HTTD), 0.2% (YR1 LTTD), and 0.9% (YR2).
  - There was a difference in the compliance percentage with the ACCA average cooling benchmark when the heat pump cycled on versus off. Higher compliance percentages were reported when the heat pump cycled off for all three TTD operations.

- Heating Season Results
  - All three TTD operations had an average room-to-room temperature difference lower than the ACCA average heating benchmark (i.e., 1.11°C). The compliance percentages with the ACCA average heating benchmark were 80.3% (YR1 HTTD), 70.7% (YR1 LTTD), and 78.8% (YR2).
  - The maintained room-to-room temperature differences were comparable between the three TTD operations with an average room-to-room temperature differences of 0.9°C (YR1 HTTD), 1.0°C (YR1 LTTD), and 0.9°C (YR2).

- There were occasions when the room-to-room temperature difference exceeded the ACCA maximum heating benchmark (i.e., 2.22°C), which were about 0.3% (YR1 HTTD) and 0.7% (YR1 LTTD).
- There was a difference in the compliance percentage with the ACCA average heating benchmark when the heat pump cycled on versus off. Lower compliance percentages were reported when the heat pump cycled off for all three TTD operations.

- Transitional Season Results
  - The transitional season maintained the room-to-room temperature differences smaller than the cooling season but higher than the heating season. There were no occasions of exceeding the ACCA maximum cooling benchmark in all three TTD operations. This means the natural stratification of warm air in this two-story house during the transitional season when the heat pump system mostly cycled off still provided acceptable thermal uniformity across the house.
  - Among the three TTD operations, the YR1 HTTD operation maintained smaller room-to-room temperature differences than the YR1 LTTD and YR2 operations with an average room-to-room temperature difference of 1.0°C along with a higher compliance percentage with the ACCA average cooling benchmark of 93.1%.

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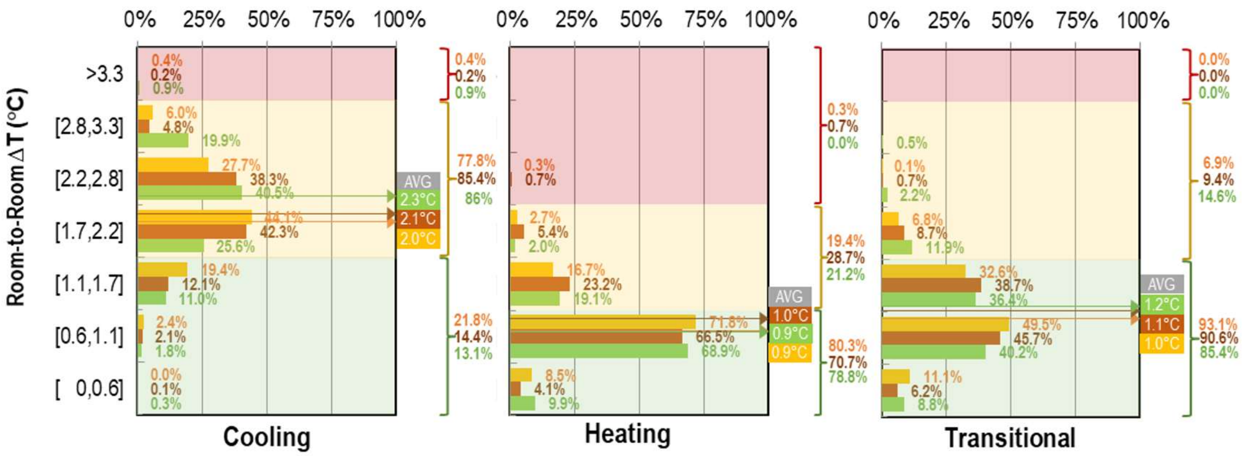
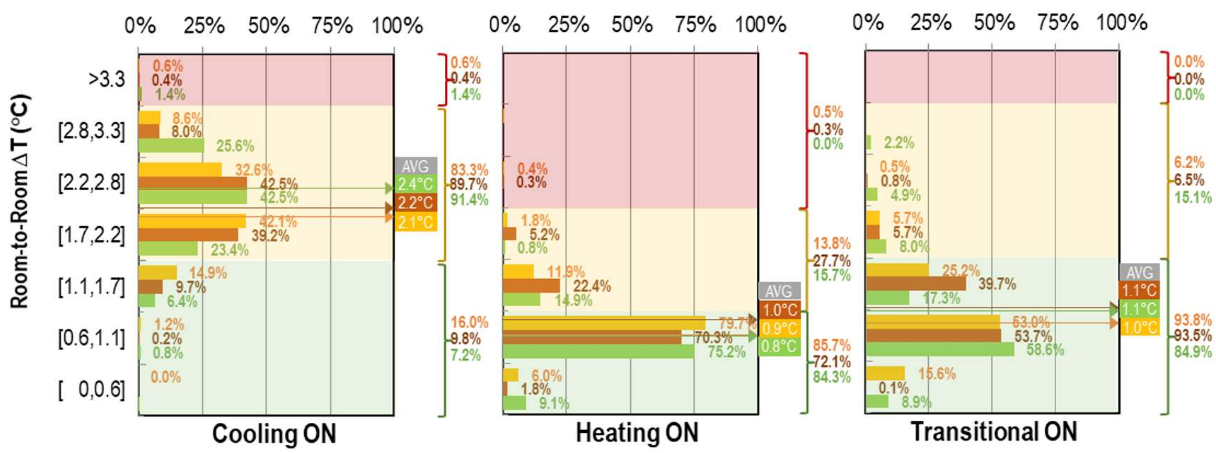
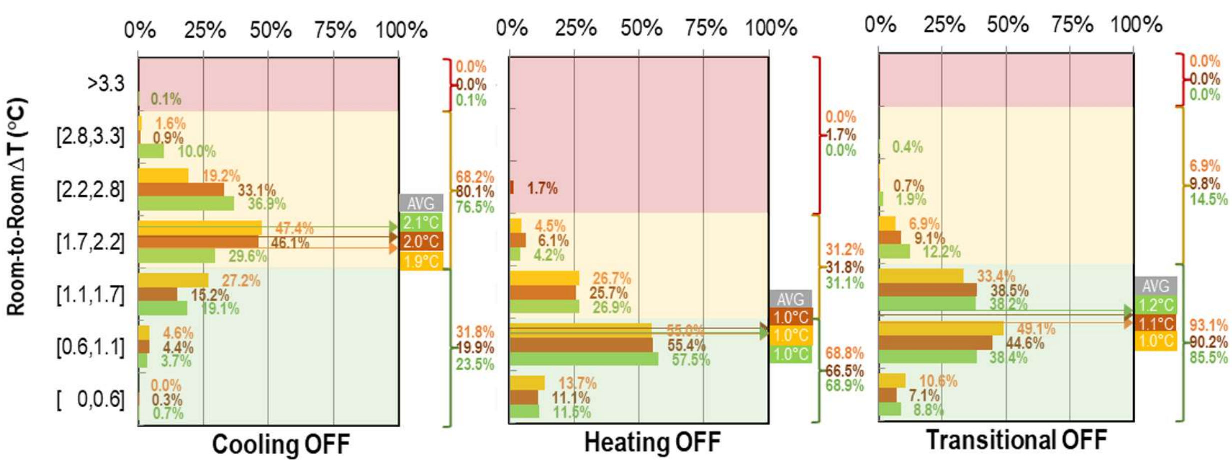


(a) All Data



(b) HP On



(c) HP Off

Figure 57: Graphical Summaries of the 5-Min Average Room-To-Room Temperature Differences by Season.

4.3. CYCLIC DISCOMFORT

Tables 4 (cooling season), 5 (heating season), and 6 (transitional season) report the percentage of failures in cyclic and drift temperature variations based on the ASHRAE Standard 55-2017 (ASHRAE 2017) with the number of data points (i.e., minutes) for the following time periods:

- 0.25h (15 minutes);
- 0.50h (30 minutes);
- 1h (60 minutes);
- 2h (120 minutes); and
- 4h (240 minutes).

The ASHRAE Standard 55-2017 specifies a peak-to-peak variation in operative temperature for any 15-minute period shall not exceed 1.1°C (2.0°F) to evaluate cyclic variations. The criteria for drift variations are based on maximum operative temperature change allowed: 1.1°C (2.0°F) for any 15-minute period; 1.7°C (3.0°F) for any 30-minute period; 2.2°C (4.0°F) for any 1-hour period; 2.8°C (5.0°F) for any 2-hour period; and 3.3°C (6.0°F) for any 4-hour period.

In general, the percentage of failures was negligible, which was less than 0.5% of the period except for the kitchen for the cooling season during the YR1 HTTD and YR2 operations and the MBR for the transitional season during the YR1 LTTD operation. No obvious difference was observed between the TTD operations and between seasons. Higher failure rates were observed for the shorter time periods. For example, no failures were reported for the longer time period such as 4h.

The kitchen and MBR still had quite low percentages of failures, which was below 1.25% of the period. The incidences were related to the schedule of internal loads in these rooms that were turned on to emulate electrical use of (i.e., appliances and lighting) of the activities of a family of four (i.e., two adults and two children) at NZERTF.

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Table 4: Percentage of Failures in Cyclic and Drift Temperature Variations Per ASHRAE Standard 55-2017 for the Cooling Season.

		YR1 HTTD					YR1 LTTD					YR2				
		0.25h	0.50h	1h	2h	4h	0.25h	0.50h	1h	2h	4h	0.25h	0.50h	1h	2h	4h
LR	minutes	9	0	0	0	0	30	0	0	0	0	162	70	0	0	0
	% of period	0.01%	0.00%	0.00%	0.00%	0.00%	0.04%	0.00%	0.00%	0.00%	0.00%	0.08%	0.03%	0.00%	0.00%	0.00%
KIT	minutes	1492	190	0	0	0	285	38	0	0	0	1633	719	200	87	0
	% of period	1.23%	0.16%	0.00%	0.00%	0.00%	0.41%	0.05%	0.00%	0.00%	0.00%	0.78%	0.34%	0.10%	0.04%	0.00%
MBR	minutes	143	162	215	0	0	202	248	165	0	0	427	360	278	0	0
	% of period	0.12%	0.13%	0.18%	0.00%	0.00%	0.29%	0.36%	0.24%	0.00%	0.00%	0.20%	0.17%	0.13%	0.00%	0.00%
BR2	minutes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	% of period	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
BR3	minutes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	% of period	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Primary Rooms	minutes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	% of period	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 5: Percentage of Failures in Cyclic and Drift Temperature Variations Per ASHRAE Standard 55-2017 for the Heating Season.

		YR1 HTTD					YR1 LTTD					YR2				
		0.25h	0.50h	1h	2h	4h	0.25h	0.50h	1h	2h	4h	0.25h	0.50h	1h	2h	4h
LR	minutes	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	% of period	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
KIT	minutes	14	0	0	0	0	0	0	0	0	0	214	5	0	0	0
	% of period	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.15%	0.00%	0.00%	0.00%	0.00%
MBR	minutes	239	295	63	0	0	156	192	72	70	0	285	351	10	0	0
	% of period	0.28%	0.34%	0.07%	0.00%	0.00%	0.20%	0.24%	0.09%	0.09%	0.00%	0.20%	0.25%	0.01%	0.00%	0.00%
BR2	minutes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	% of period	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
BR3	minutes	19	0	0	38	0	38	11	58	58	0	0	0	0	0	0
	% of period	0.02%	0.00%	0.00%	0.04%	0.00%	0.05%	0.01%	0.07%	0.07%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Primary Rooms	minutes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	% of period	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

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Table 6: Percentage of Failures in Cyclic and Drift Temperature Variations Per ASHRAE Standard 55-2017 for the Transitional Season.

		YR1 HTTD					YR1 LTTD					YR2				
		0.25h	**0.50h**	**1h**	**2h**	**4h**	**0.25h**	**0.50h**	**1h**	**2h**	**4h**	**0.25h**	**0.50h**	**1h**	**2h**	**4h**
LR	minutes	0	0	0	0	0	19	23	0	0	0	169	156	131	48	0
	% of period	0.00%	0.00%	0.00%	0.00%	0.00%	0.03%	0.03%	0.00%	0.00%	0.00%	0.10%	0.10%	0.08%	0.03%	0.00%
KIT	minutes	2	0	7	50	0	34	0	0	0	0	376	136	0	0	0
	% of period	0.00%	0.00%	0.01%	0.07%	0.00%	0.05%	0.00%	0.00%	0.00%	0.00%	0.23%	0.08%	0.00%	0.00%	0.00%
MBR	minutes	215	269	228	0	0	304	382	504	0	0	522	617	358	0	0
	% of period	0.29%	0.36%	0.30%	0.00%	0.00%	0.41%	0.52%	0.69%	0.00%	0.00%	0.32%	0.38%	0.22%	0.00%	0.00%
BR2	minutes	0	0	0	0	0	0	0	0	0	0	14	29	59	0	0
	% of period	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.02%	0.04%	0.00%	0.00%
BR3	minutes	0	0	0	0	0	52	35	83	154	0	0	0	0	0	0
	% of period	0.00%	0.00%	0.00%	0.00%	0.00%	0.07%	0.05%	0.11%	0.21%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Primary Rooms	minutes	0	0	0	0	0	0	0	0	0	0	14	29	59	0	0
	% of period	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.02%	0.04%	0.00%	0.00%

4.4. RH DEVIATION FROM THE SETPOINT RH

Figure 58 presents the percentage distributions of the 5-min average room-to-humidistat RH difference for the cooling season with the percentages[22] of the data points grouped based on a percentage of RH difference (ΔRH) as follows:

- ΔRH = 0% RH (i.e., room RH at or below 50% RH);
- ΔRH from 0 % RH to 2% RH;
- ΔRH from 2 % RH to 4% RH;
- ΔRH from 4 % RH to 6% RH;
- ΔRH from 6 % RH to 8% RH;
- ΔRH from 8 % RH to 10% RH;
- ΔRH from 10 % RH to 12% RH;
- ΔRH from 12 % RH to 14% RH; and
- ΔRH above 14 % RH.

Data were color-coded by TTD operations: yellow for YR1 HTTD, dark orange for YR1 LTTD, and green for YR2. In general, the room-to-humidistat RH differences were small except for the kitchen and the basement. In the kitchen the YR2 HTTD operation maintained the lowest average room-to-humidistat RH difference of 2.7% RH, which followed by YR1 LTTD (4.6% RH) and YR2 (5.2% RH). The LR where the humidistat was located had the average room-to humidistat RH differences of 0.3% RH (YR1 HTTD), 1.1% RH (YR1 LTTD), and 1.1% RH (YR2). In terms of the percentage distribution, the YR1 HTTD also had the highest percentage of 0% ΔRH (87.6%), which followed by YR1 LTTD (70.7%) and YR2 (56.3%).

In spite of the higher percentage of 0% ΔRH, YR1 LTTD and YR2 had about the same average room-to-humidistat RH difference (i.e., 1.1% RH) because the YR 1 LTTD operation had more occasions in the high ΔRH above 4% RH. This occurred because the YR1 LTTD includes only two cooling months such as May and June of which sensible cooling loads are relatively smaller compared to July and August. As a result, the YR1 HTTD operation showed better dehumidification performance with the lowest average room–to-humidistat RH difference and the highest percentage of 0% ΔRH.

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[22] 0.00% means there were still few data points in that corresponding group.

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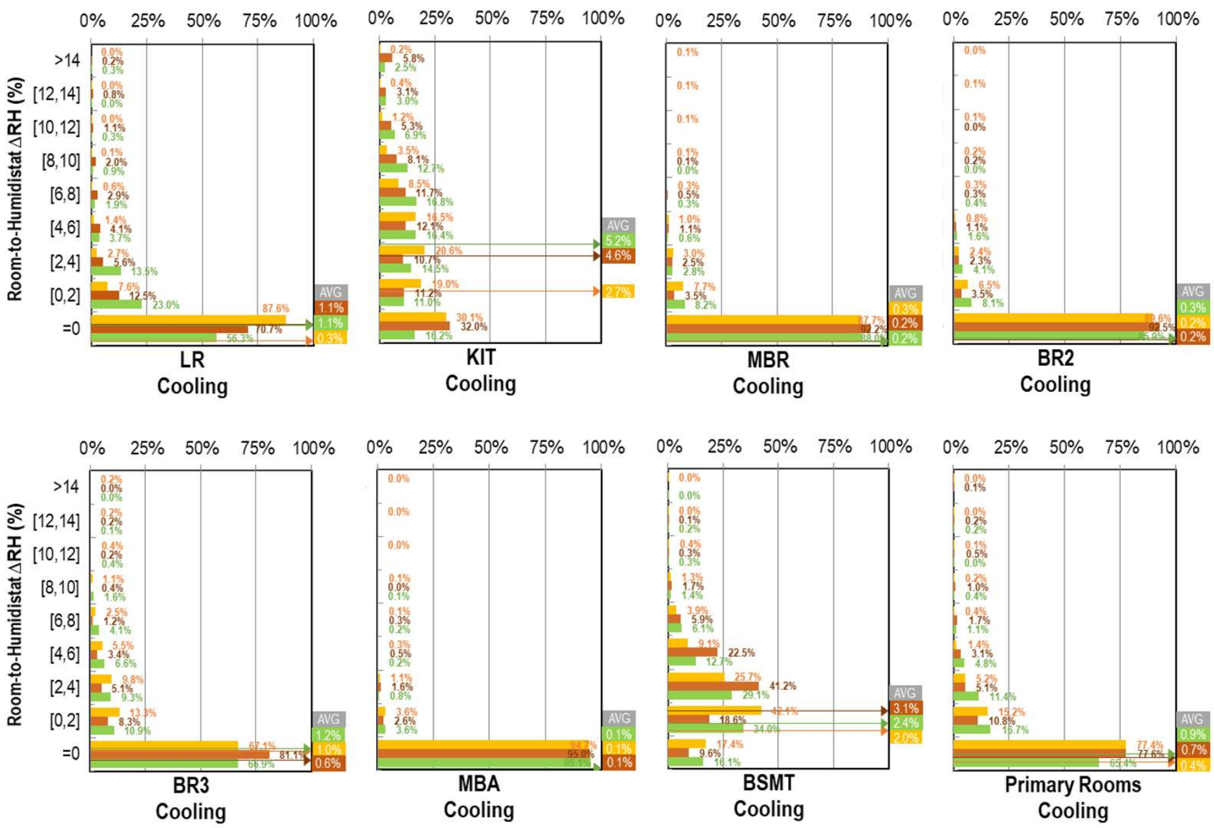

Figure 58: Graphical Summaries of the 5-Min Average Room-To-Humidistat RH Differences for the Cooling Season.

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5. INTEGRATIVE METHOD TO RATE WHOLE-HOUSE ENERGY AND COMFORT

This section demonstrates the use of the proposed rating method based on the weather dependent conditioning energy use (i.e., heating, cooling, and dehumidification) of the house and coincident whole-house thermal comfort metrics that were averaged over a particular range of weather condition using the Year 1 and Year 2 NZERTF performance data. This allowed a weather-normalized comparison of the three different TTD operations in terms of both energy and thermal comfort for a particular weather condition.

Section 5.1 presents the results using room-to-room temperature difference to compare the system's fundamental ability to produce and deliver the designed air temperature.

Section 5.2 presents the results using room-to-thermostat temperature difference to compare the efficiency of the respective TTD operation in terms of delivering the designed air temperature.

Section 5.3 presents the results using room-to-humidistat RH difference only for the cooling season to compare the dehumidification efficiency of the respective TTD operation in terms of maintaining the designed relative humidity.

5.1. ROOM-TO-ROOM TEMPERATURE DIFFERENCE

The daily OA dry-bulb temperature was sorted into 5°C (9°F) temperature bins while the mean coincident values of daily conditioning energy uses and daily room-to-room temperature differences (R-to-R TD) were determined for each bin, which were then paired and plotted using a scatter plot for three different TTD operations, as shown in Figure 59: (a) all TTD operations for a comparison and (b) each TTD operation separately along with corresponding daily data that were averaged over 5°C (9°F) OA temperature bins to form a line graph. Figure 60 presents the weather-dependent characteristics of the two metrics (i.e., daily average conditioning energy use and R-to-R TD) by plotting them against daily average OA temperature.

In addition to daily average R-to-R TD, the use of daily room-to-room discomfort hours (R-to-R DDH) was tested and presented in Figures 61 and 62. Not surprisingly the shapes of the plots were exactly same with larger values. Since the use of daily average R-to-R TD is a more intuitive metric which can be easily understandable by general public, this section discusses the results based on the R-to-R TD.

In all figures, the relevant ACCA Manual RS benchmarks are also presented for a comparison:

- Average Heating Benchmark (Avg. HBM) = 1.1°C (2°F)
- Average Cooling Benchmark (Avg. CBM) = 1.7°C (3°F)
- Maximum Heating Benchmark (Max. HBM) = 2.2°C (4°F)
- Maximum Cooling Benchmark (Max. CBM) = 3.3°C (6°F)

For both energy and comfort metrics, lower values mean good performance, while higher values mean poor performance. For example, the transitional season had metrics closer to the origin, which means better energy and comfort performance compared to the cooling and heating seasons. The line begins with a daily average outdoor air temperature of -10°C (no arrow) and ends with a daily average outdoor air temperature of 30°C (arrow). If the trend line forms a vertical line, it means the respective thermal comfort metric is less sensitive to OA temperature, while the conditioning energy use sharply increased with increased OA. On the other way, if the trend line forms a horizontal line, it means the respective thermal comfort metric is sensitive to OA temperature while the conditioning energy is not.

The YR1 HTTD operation had better thermal uniformity during the cooling season with lower daily average R-to-R TD at the same OA temperature bins, which followed by the YR1 LTTD and YR2 operations. The conditioning energy use of the YR1 HTTD operation was the highest among the three TTD operations. Both metrics (i.e., conditioning energy use and R-to-R TD) increased with increased OA temperature. The daily average R-to-R TD began to exceed the average CBM as the coincident daily average OA temperature exceeded 17.5°C (i.e., 20°C OA temperature bin). This indicates the importance of OA temperature condition when measuring and benchmarking energy and thermal comfort performance of a house during the cooling season.

During the heating season, the YR1 LTTD operation had the highest daily average R-to-R TD except for -10°C OA temperature bin, but the coincident conditioning energy use was also the highest among the three TTD operations. At -10°C OA temperature bin, the YR1 LTTD operation had lower R-to-R TD while using more conditioning energy, which was affected by lowered differential temperatures of the 2^{nd} and 3^{rd} stage compressor along with shortened delay time.

The YR1 HTTD and YR2 operations had comparable daily average R-to-R TD until the coincident daily average OA temperature reaches -2.5°C (i.e., 0°C OA temperature bin) during the heating season. On cold winter days of which daily average temperatures were below -2.5°C, the YR2 operation maintained better thermal uniformity with lower R-to-R TD along with lower daily average conditioning energy. This might be affected by the heat pump running constantly to meet the heating setpoint temperature at this low OA temperatures without activating the backup electric resistance heater during the YR2 operation.

Unlike the cooling season, the daily average R-to-R TD was less sensitive to OA temperature, while the conditioning energy use for heating sharply increased with increased OA temperature. The daily average R-to-R TD maintained below the average HBM except for -10°C OA temperature bin.

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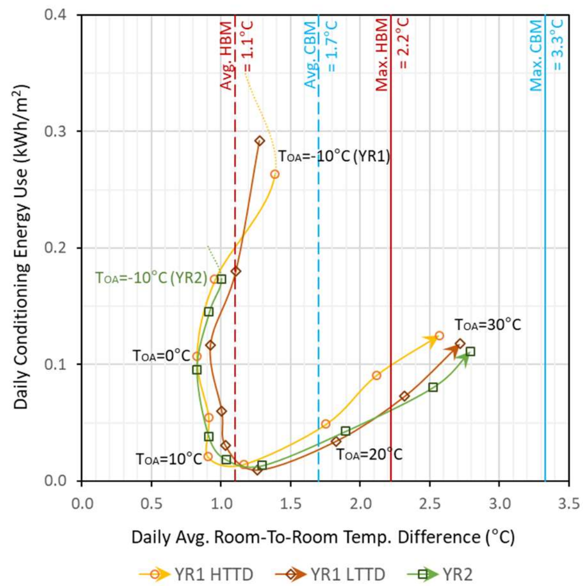
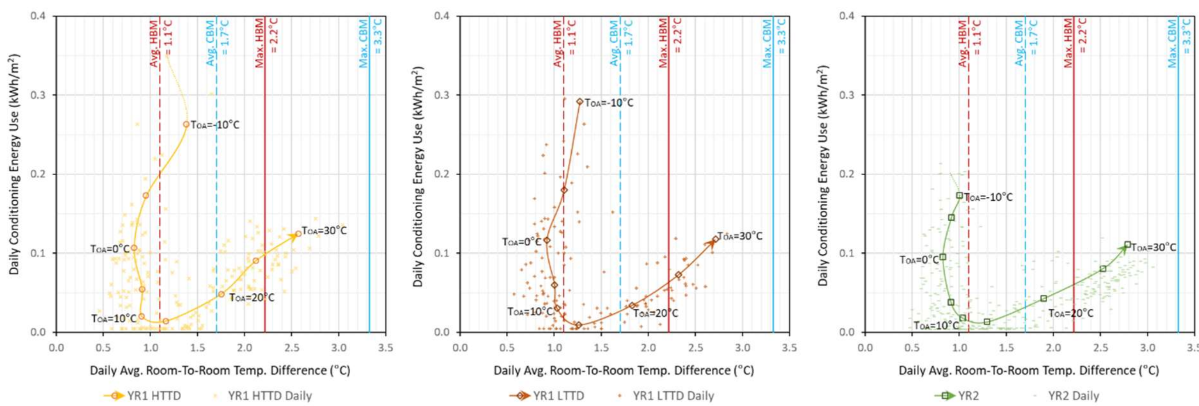


(a) All TTD Operations



(b) By TTD Operation

Figure 59: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average R-to-R TD.

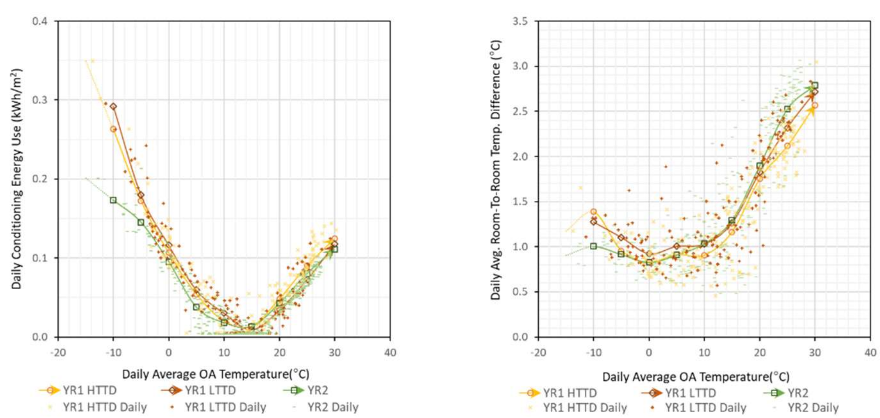


Figure 60: Weather-Dependent Characteristics of the Two Chosen Energy and Whole-House Thermal Comfort Metrics: Daily Average R-to-R TD.

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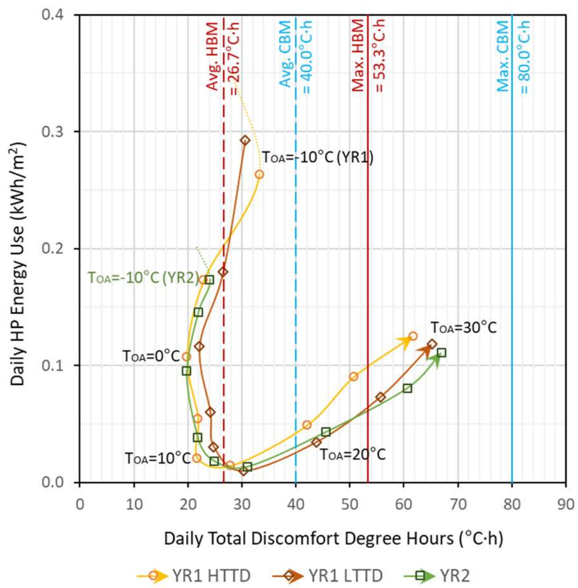
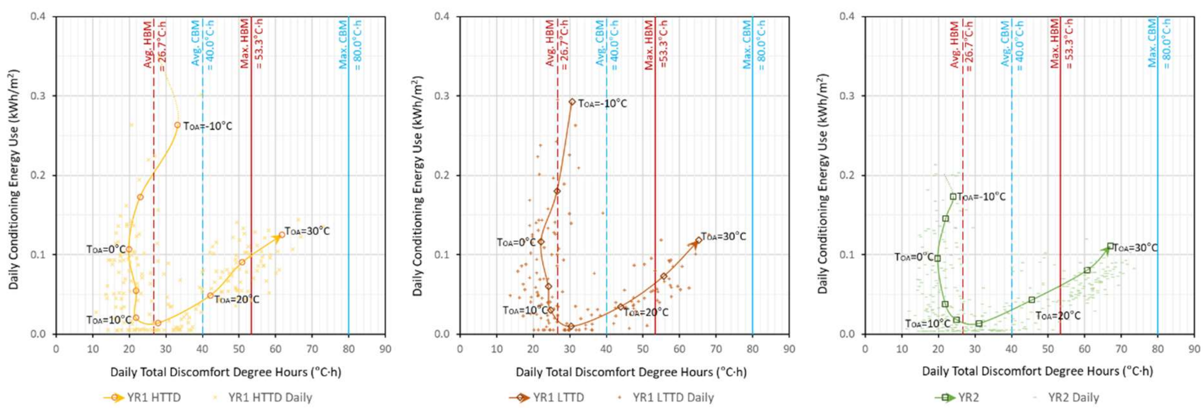


(a) All TTD Operations



(b) By TTD Operation

Figure 61: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Total R-to-R DDH.

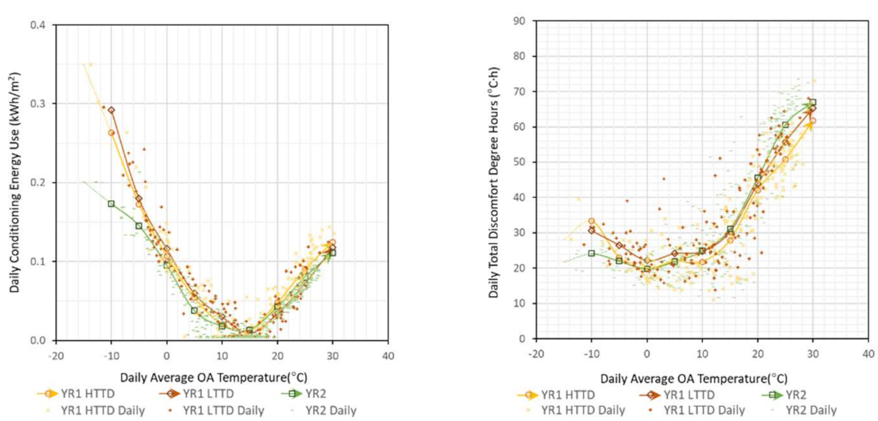


Figure 62: Weather-Dependent Characteristics of the Two Chosen Energy and Whole-House Thermal Comfort Metrics: Daily Total R-to-R DDH.

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5.2. ROOM-TO-THERMOSTAT TEMPERATURE DIFFERENCE

Similar to room-to-room temperature difference, the daily OA dry-bulb temperature was sorted into 5°C (9°F) temperature bins while the mean coincident values of daily conditioning energy uses and daily room-to-thermostat temperature differences (R-to-T TD) were determined for each bin, which were then paired and plotted using a scatter plot for three different TTD operations using the area-weighted whole-house temperature, which is the temperature weighted by the floor areas of seven primary rooms. For both energy and comfort metrics, lower values mean good performance, while higher values mean poor performance.

Three different daily average R-to-T TD metrics were calculated, including R-to-T total TD[23], R-to-T TD(-), and LR R-to-T TD(+). Figures 63 to 68 present the results using the area-weighted whole-house temperature:

- Whole-house R-to-T total TD (Figures 63 and 64)
- Whole-house R-to-T TD(-) (Figures 65 and 66)
- Whole-house R-to-T TD(+) (Figures 67 and 68)

In addition to the whole-house R-to-T TD metrics, the use of 1F and 2F R-to-T TD using the area-weighted 1F temperature and 2F temperature, respectively, was tested and presented in Figures 69 and 74 (1F R-to-T TD) and Figures 75 and 80 (2F R-to-T TD):

- 1F R-to-T total TD (Figures 69 and 70)
- 1F R-to-T TD(-) (Figures 71 and 72)
- 1F R-to-T TD(+) (Figures 73 and 74)
- 2F R-to-T total TD (Figures 75 and 76)
- 2F R-to-T TD(-) (Figures 77 and 78)
- 2F R-to-T TD(+) (Figures 79 and 80)

In all figures, the relevant ACCA Manual RS benchmarks are also presented for a comparison:

- Heating Benchmark (HBM) = 1.1°C (2°F)
- Cooling Benchmark (CBM) = 1.7°C (3°F)

Important observations on the whole-house R-to-T total TD are:

- During the cooling season, the YR2 operation had noticeably larger daily average R-to-T TD at the whole-house level under the same OA temperature conditions, which was caused by overcooled first-floor bedrooms during the YR2 operation when the average of two temperature sensors (i.e., thermostat sensor in the living room and the remote sensor in the second-floor hallway) was used to control the heat pump system.
- The whole-house temperatures used in these plots were weighted by the floor areas of the seven primary rooms consisting of 1F rooms (59%) and 2F rooms (41%). The observed difference between the three TTD operations reduced when this study tested a different whole-house temperature, which was weighted by the floor areas of all rooms including bathrooms and hallways as well as the seven primary rooms, consisting of 1F (53%) and 2F (47%).
- The YR 1 LTTD operation maintained the smallest daily average R-to-T TD at the whole-house level under the same OA temperature conditions during the cooling

[23] Daily R-to-T TD is the sum of absolute differences between the room temperature and the setpoint temperature.

season. The conditioning energy use of the YR1 LTTD operation was also slightly lower than other operations in general.

- Unlike the R-to-R TD, the daily average R-to-T TD was less sensitive to OA temperature, while the conditioning energy use for cooling sharply increased with increased OA temperature. The daily average R-to-T TD were much lower than the CBM.
- During the heating season, the YR2 operation also showed larger daily average R-to-T TD at the whole-house level on cold winter days of which daily average temperatures were below -2.5°C (i.e., -5°C and -10°C OA temperature bins). This was affected by an improved control strategy of the backup electric resistance heater to minimize its use, which was a penalty in terms of thermal comfort but an advantage for energy savings.
- Between the two Year 1 operations, YR1 LTTD maintained slightly lower daily average R-to-T TD at the whole-house level than YR1 HTTD while the associated conditioning energy for heating was also higher. This was affected by lowered differential temperatures of the 2nd and 3rd stage compressor along with shortened delay time.
- Like the cooling season, the daily average R-to-T TD was also less sensitive to OA temperature, while the conditioning energy use sharply increased with increased OA temperature. The daily average R-to-T TD maintained below the average HBM except for the YR2 operation at -10°C OA temperature bin.

Important observations on the whole-house R-to-T TD(-) and R-to-T TD(+) are:

- It was found that separating negative and positive room-to-thermostat temperature differences was helpful in the interpretation process. For example, the heating season daily average R-to-T TD(+) was 0, which means the area-weighted whole-house temperature was always lower than the setpoint temperature during the heating season. However, during the cooling season, the YR1 HTTD and YR1 LTTD operations had both negative and positive room-to-thermostat temperature differences. At the very high OA temperatures, the area-weighted whole-house temperature was higher than the setpoint temperature, while it was lower than the set point temperature on mild summer days.

Important observations on the 1F and 2F R-to-T metrics are:

- The shapes of the 1F and 2F plots were similar during the heating season when there were lower temperature differences between the first-floor and second-floor rooms and their deviations were in the same direction (i.e., both had R-to-T TD(-) only). However, during the cooling season when the first-floor and second-floor temperature deviation were in the opposite direction (i.e., R-to-T TD(-) for 1F; and R-to-T TD(+) for 2F), the cooling shapes of the whole-house plots did not well represent the actual temperature conditions of the house because the area-weighted whole-house temperature[24] took the average of the high-side deviation of the second-floor rooms and the low-side deviation of the first-floor rooms.
- As a result, to accurately characterize the whole-house thermal comfort performance, it would be important not to combine the rooms that have different thermal conditions for the temperature deviation calculations from the setpoint. For example, the use of whole-house R-to-T TD resulted in the daily average R-to-T TD much lower

[24] The whole-house temperatures used in this section were weighted by the floor areas of the seven primary rooms (i.e., LR, KIT, DR, BR4, MBR, BR2, and BR3 representing 71% of the total floor area) consisting of 1F rooms (59%) and 2F rooms (41%) as shown in Figure 7.

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than the CBM. However, the daily average 1F R-to-T TD for the YR2 operation and 2F R-to-T TD for the YR1 HTTD and YR1 LTTD operations approached the CBM with increased outdoor temperature. In addition, the daily average 2F R-to-T TD was no longer less sensitive to OA temperature.

- In addition, the impact of the applied TTD on thermal comfort was different by floor. The Year 2 operation had the largest temperature deviation from the setpoint in the first-floor rooms but maintained the second-floor temperature closer to the setpoint than other TTD operations.

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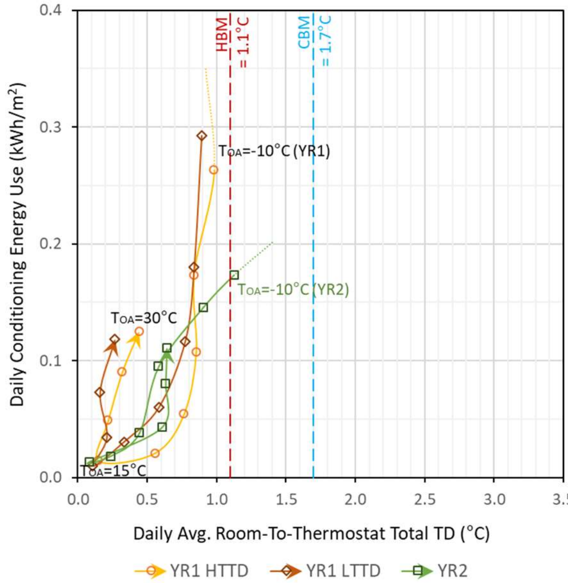
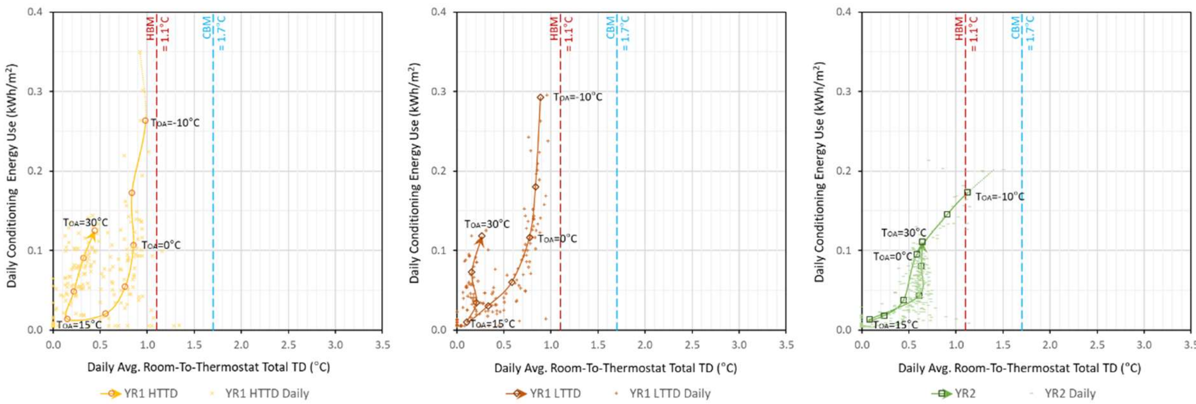


(a) All TTD Operations



(b) By TTD Operation

Figure 63: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average Whole-House R-to-T Total TD.

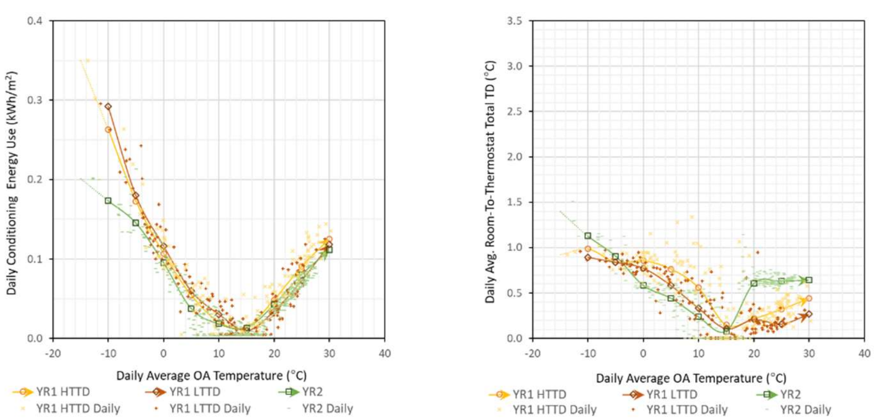


Figure 64: Weather-Dependent Characteristics of the Two Chosen Energy and Thermal Comfort Metrics: Daily Average Whole-House R-to-T Total TD.

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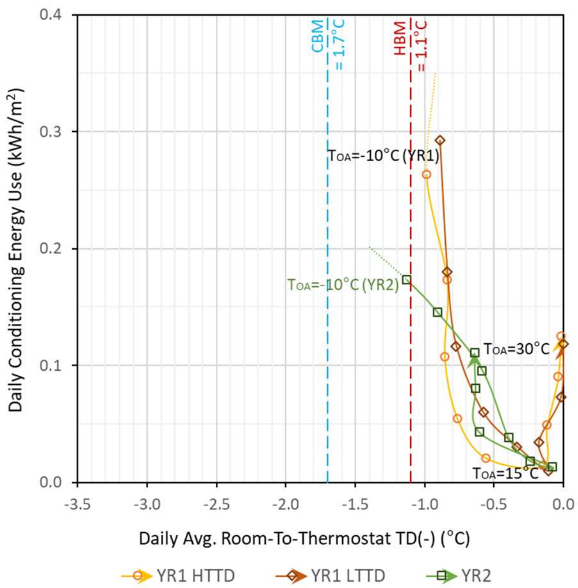
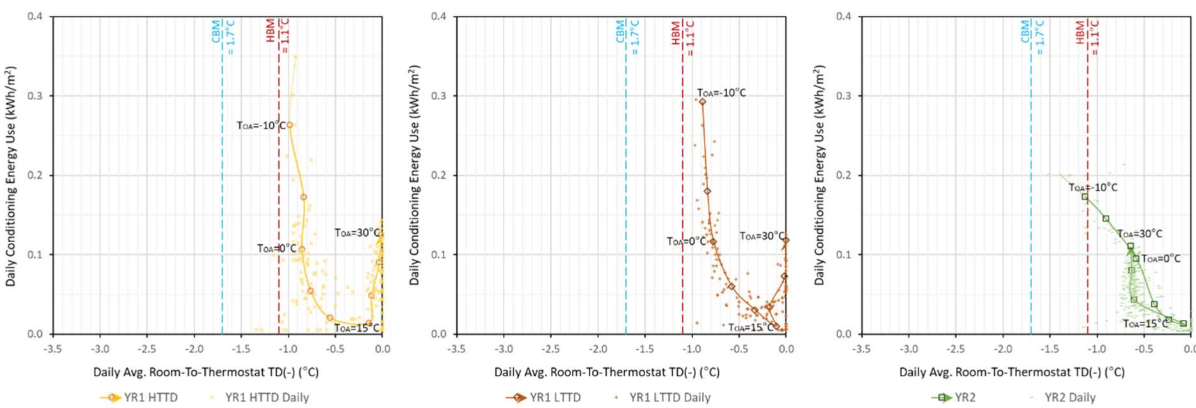


(a) All TTD Operations



(b) By TTD Operation

Figure 65: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average Whole-House R-to-T TD(-).

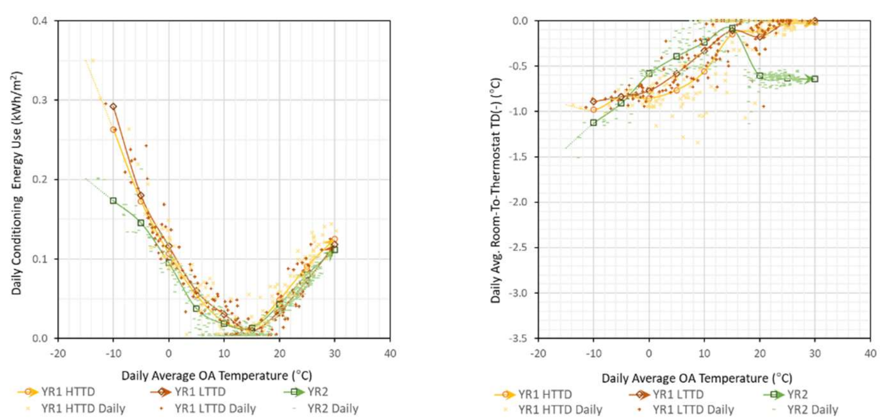


Figure 66: Weather-Dependent Characteristics of the Two Chosen Energy and Thermal Comfort Metrics: Daily Average Whole-House R-to-T TD(-).

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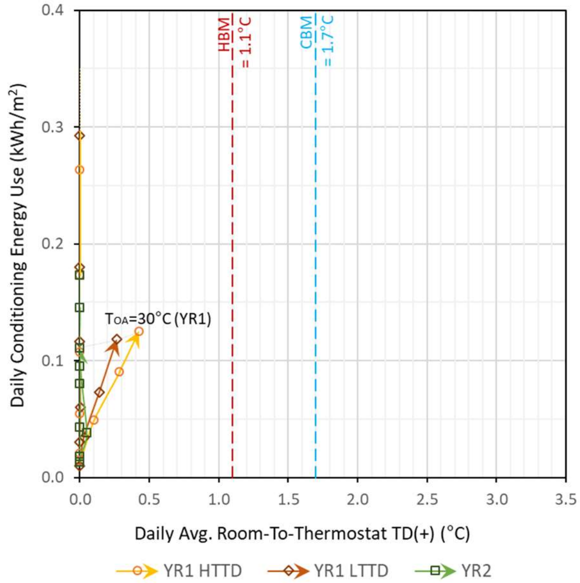
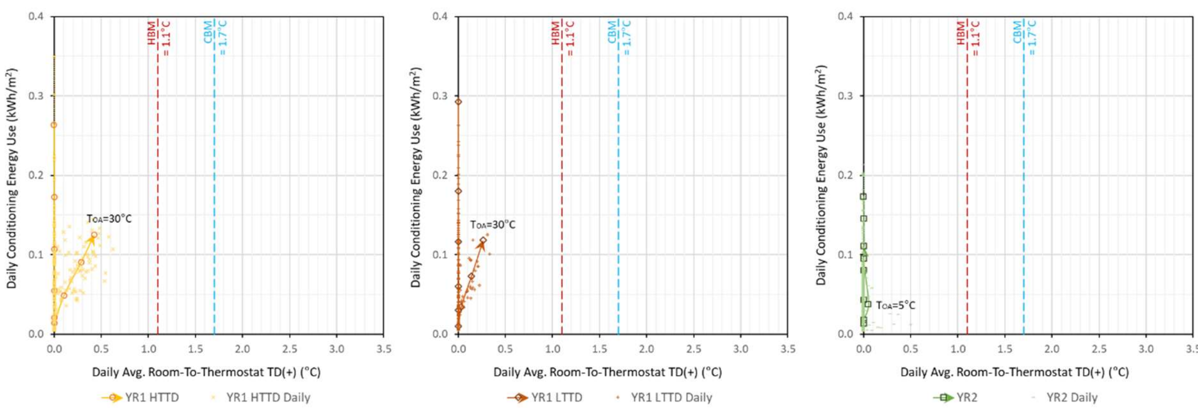


(a) All TTD Operations



(b) By TTD Operation

Figure 67: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average Whole-House R-to-T TD(+).

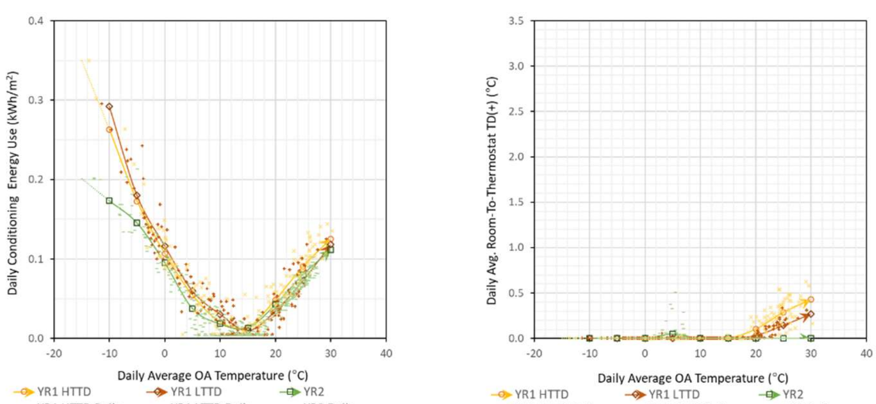


Figure 68: Weather-Dependent Characteristics of the Two Chosen Energy and Thermal Comfort Metrics: Daily Average Whole-House R-to-T TD(+).

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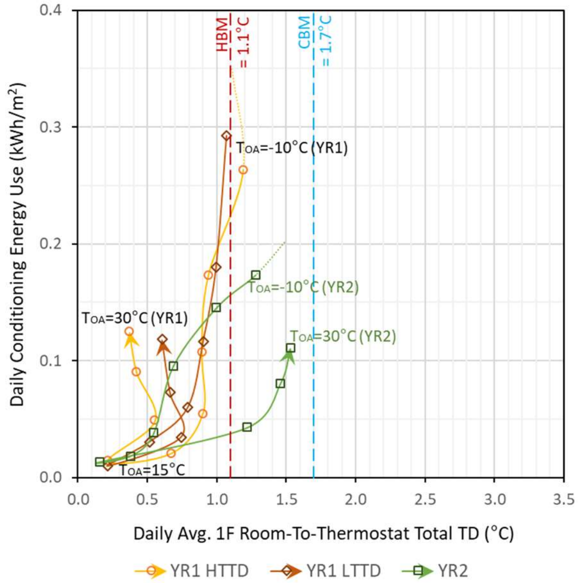
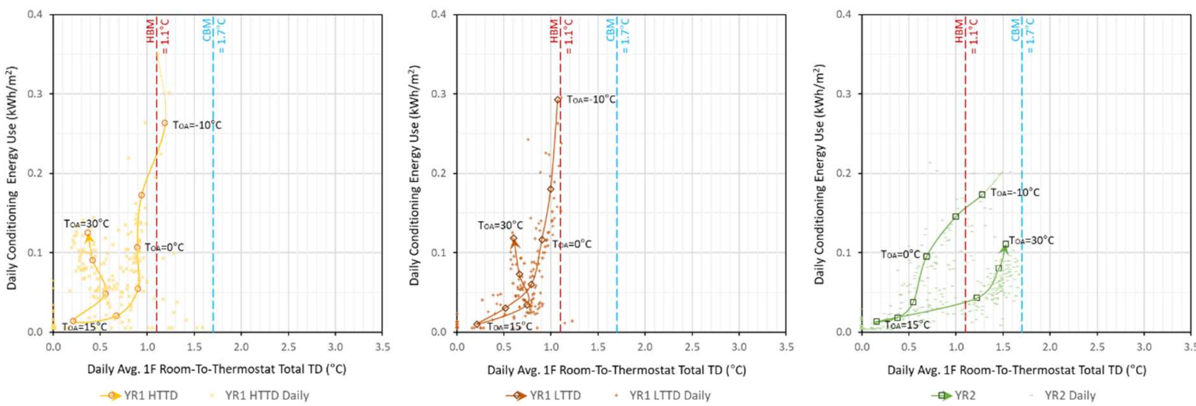


(a) All TTD Operations



(b) By TTD Operation

Figure 69: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average 1F R-to-T Total TD.

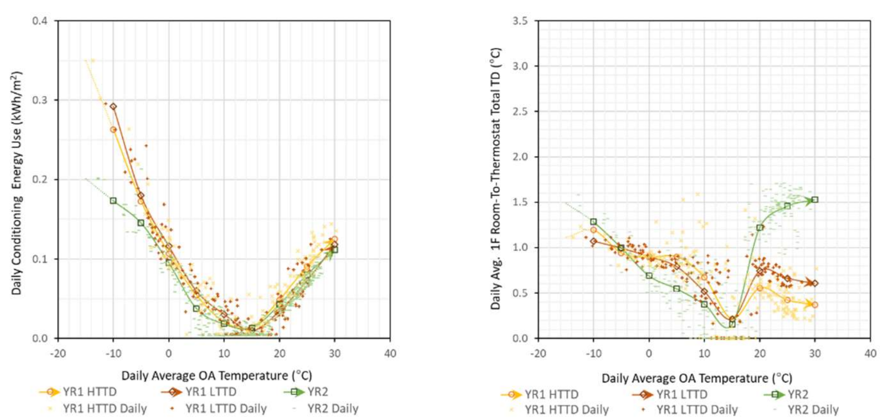


Figure 70: Weather-Dependent Characteristics of the Two Chosen Energy and Thermal Comfort Metrics: Daily Average 1F R-to-T Total TD.

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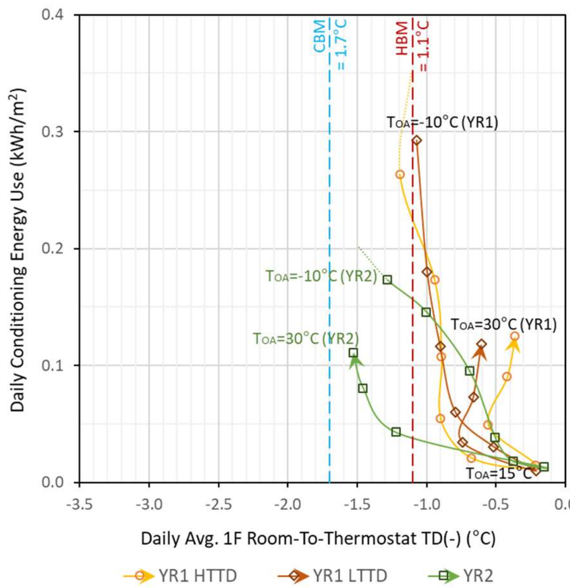
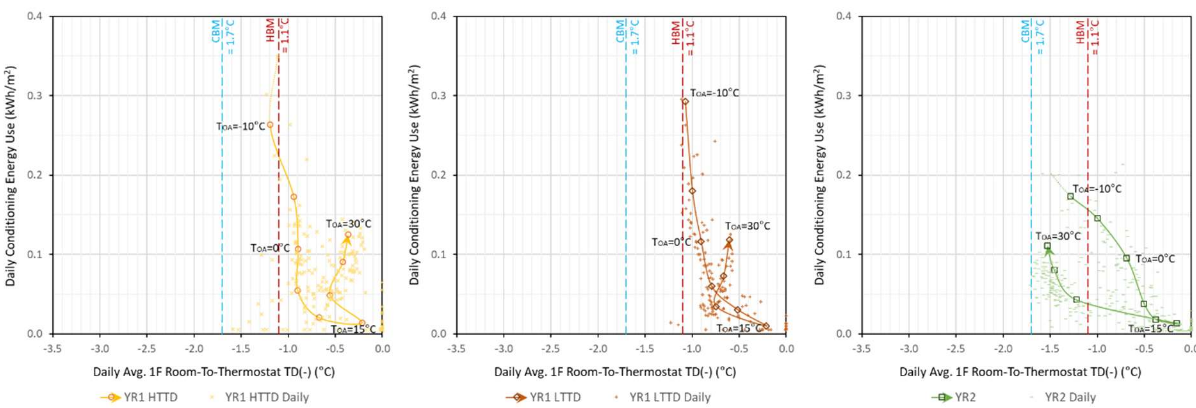


(a) All TTD Operations



(b) By TTD Operation

Figure 71: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average 1F R-to-T TD(-).

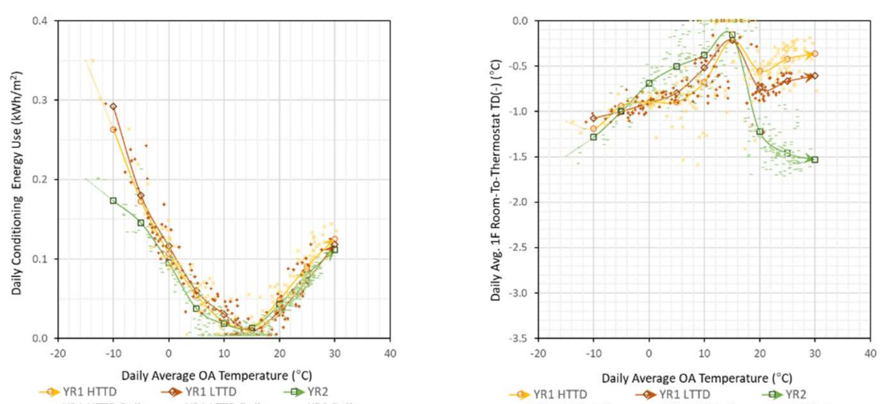


Figure 72: Weather-Dependent Characteristics of the Two Chosen Energy and Thermal Comfort Metrics: Daily Average 1F R-to-T TD(-).

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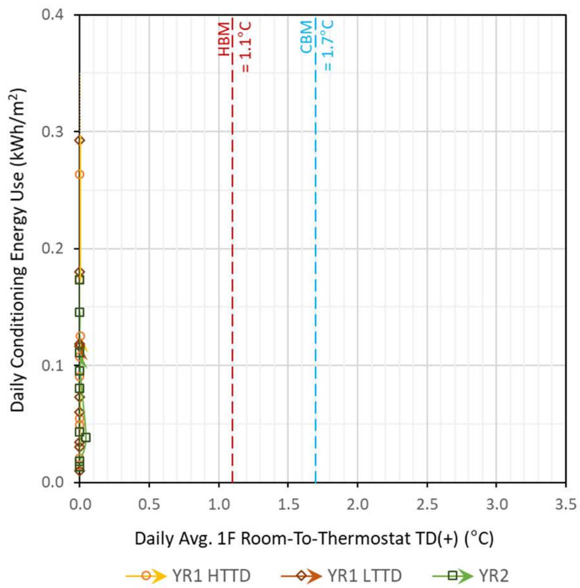
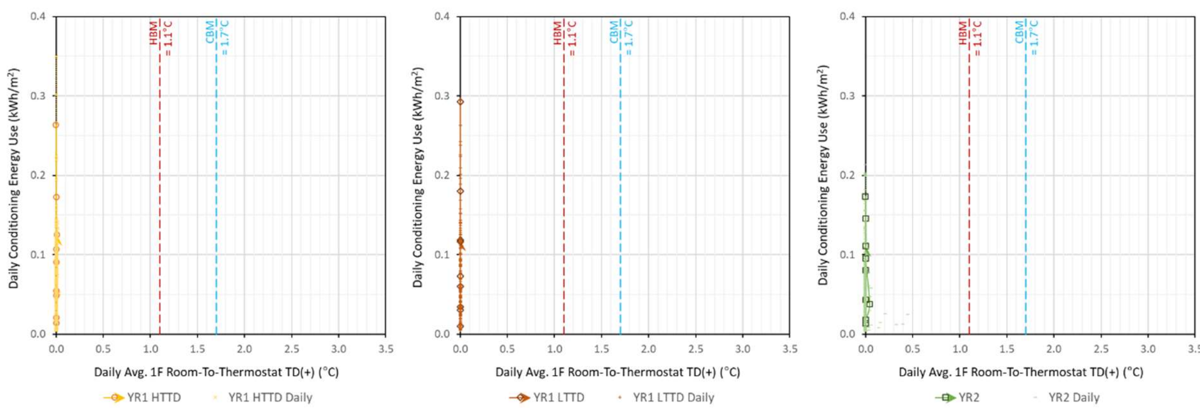


(a) All TTD Operations



(b) By TTD Operation

Figure 73: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average 1F R-to-T TD(+).

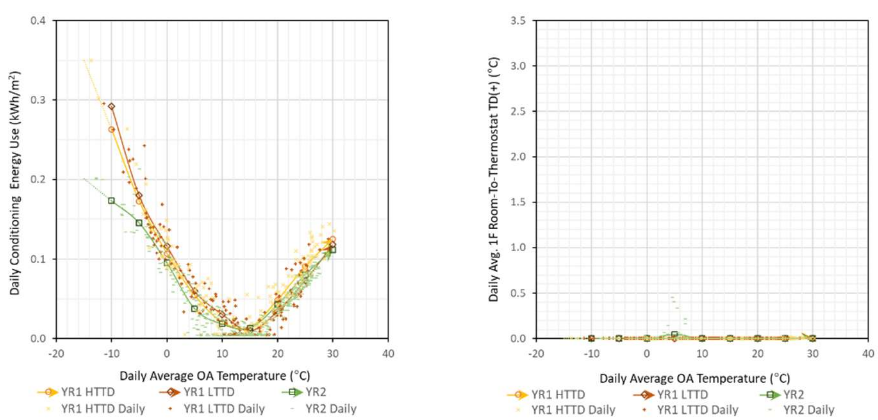


Figure 74: Weather-Dependent Characteristics of the Two Chosen Energy and Thermal Comfort Metrics: Daily Average 1F R-to-T TD(+).

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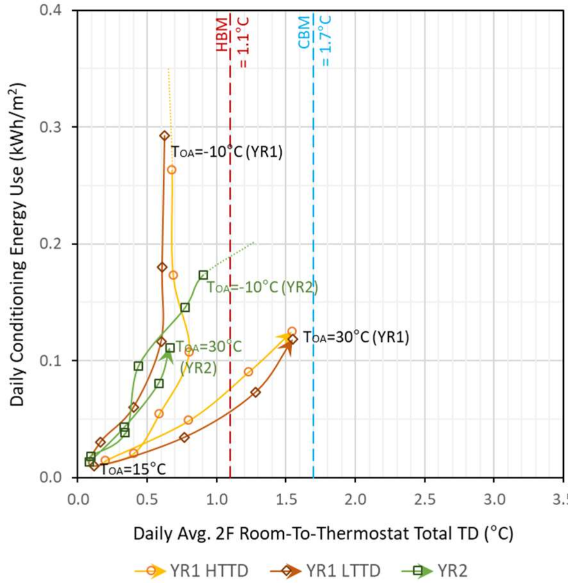
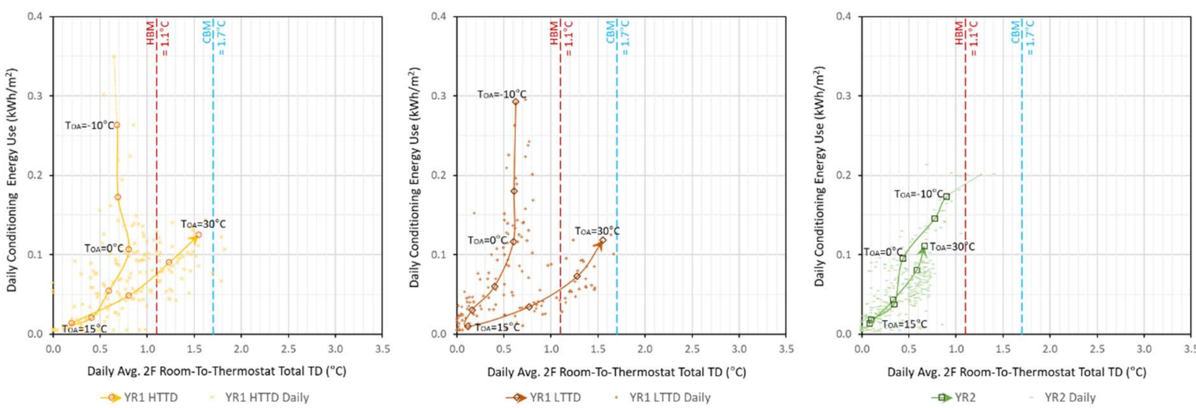


(a) All TTD Operations



(b) By TTD Operation

Figure 75: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average 2F R-to-T Total TD.

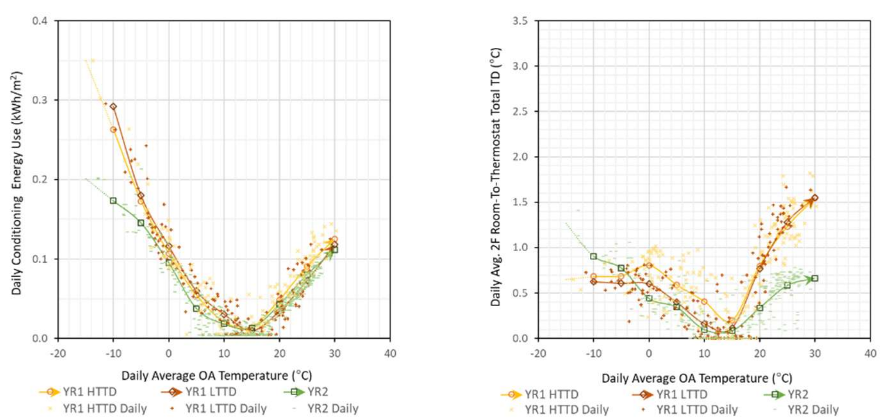


Figure 76: Weather-Dependent Characteristics of the Two Chosen Energy and Thermal Comfort Metrics: Daily Average 2F R-to-T Total TD.

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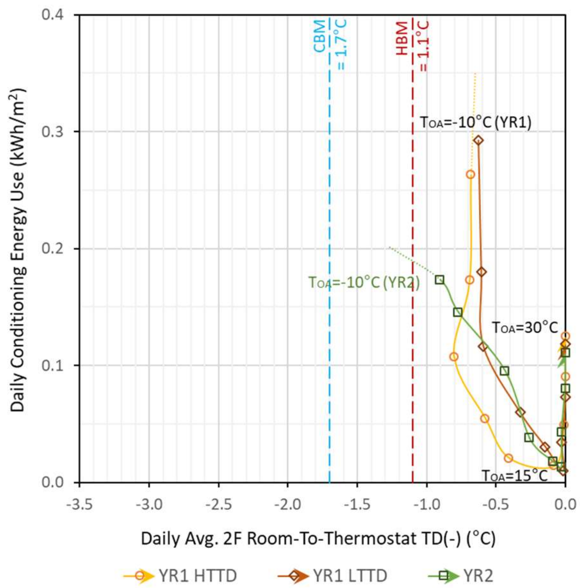
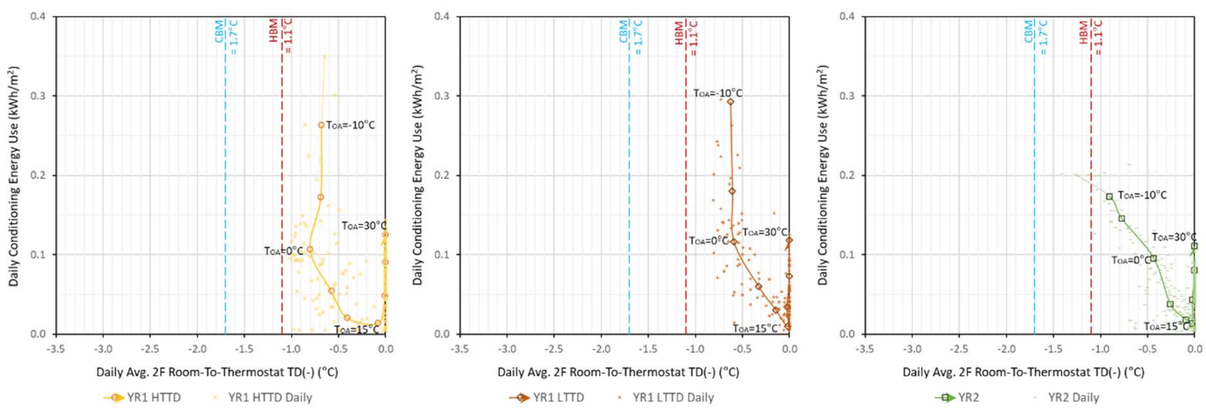


(a) All TTD Operations



(b) By TTD Operation

Figure 77: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average 2F R-to-T TD(-).

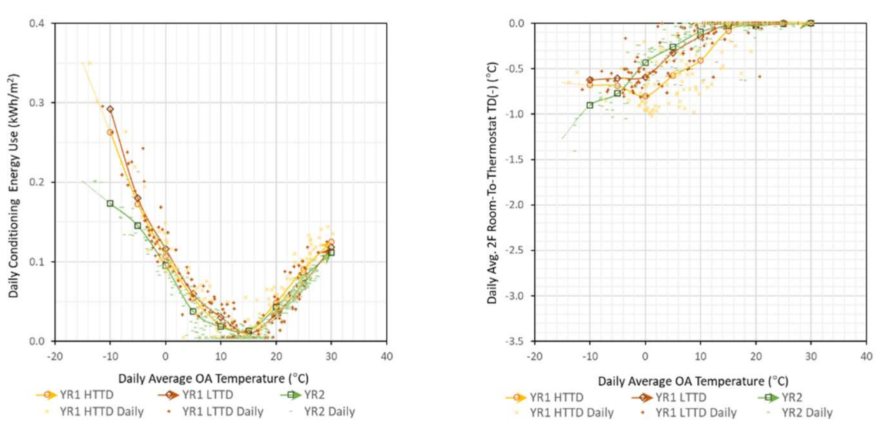


Figure 78: Weather-Dependent Characteristics of the Two Chosen Energy and Thermal Comfort Metrics: Daily Average 2F R-to-T TD(-).

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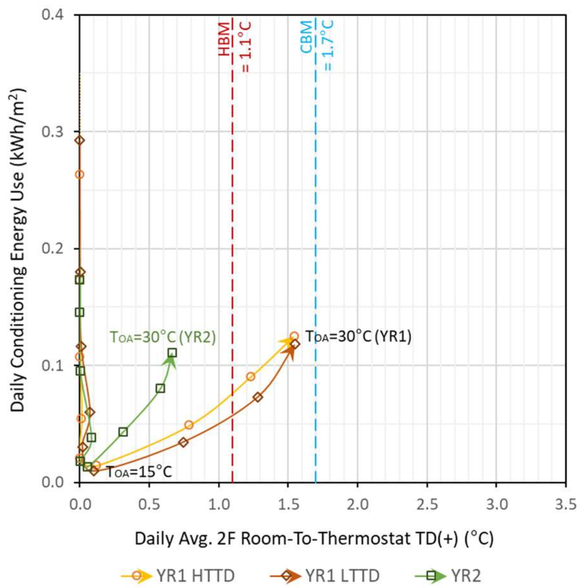
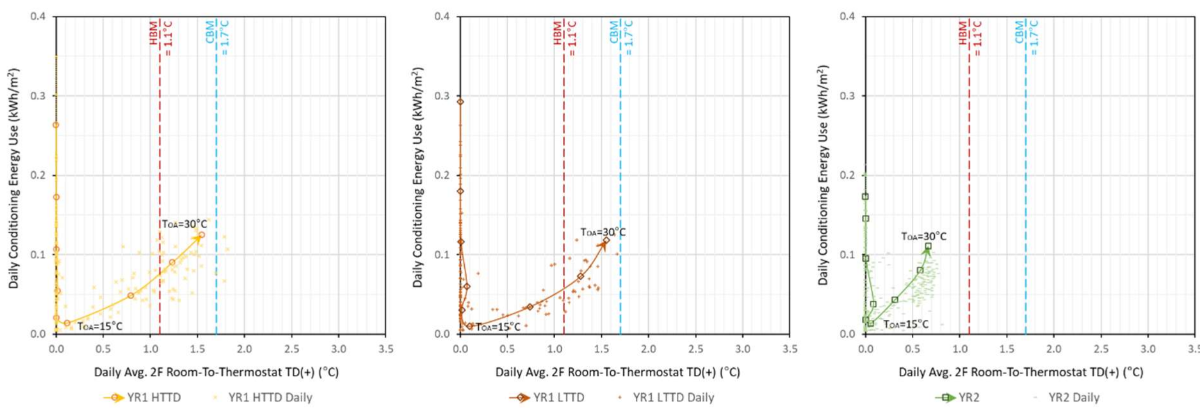


(a) All TTD Operations



(b) By TTD Operation

Figure 79: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average 2F R-to-T TD(+).

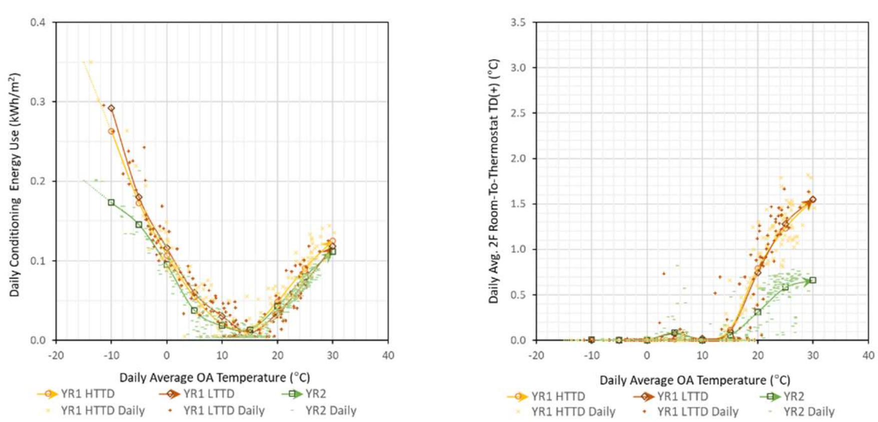


Figure 80: Weather-Dependent Characteristics of the Two Chosen Energy and Thermal Comfort Metrics: Daily Average 2F R-to-T TD(+).

5.3. ROOM-TO-HUMIDISTAT RH DIFFERENCE

Daily OA dew point temperature was sorted into 5°C (9°F) temperature bins while the mean coincident values of daily conditioning energy uses and daily room-to-humidistat RH differences (R-to-H RHD) were determined for each bin, which were then paired and plotted using a scatter plot for three different TTD operations using the area-weighted whole-house RH only for the cooling season. The area-weighted whole-house RH is the RH weighted by the floor areas of five primary rooms (i.e., LR, KIT, MBR, BR2, and BR3 representing 50% of the total floor area). Figure 81 presents (a) all TTD operations for a comparison and (b) each TTD operation separately along with corresponding daily data that were averaged over 5°C (9°F) OA dew point temperature bins to form a line graph. Figure 82 presents the weather-dependent characteristics of the two metrics (i.e., daily average conditioning energy use and R-to-H RHD) by plotting them against daily average OA dew point temperature.

In addition to daily average whole-house R-to-H RHD, the use of LR R-to-H RHD using the living room RH was tested and presented in Figures 83 and 84. Although the shapes of the LR plots were different from those of the whole-house R-to-H RHD, the same conclusion could be obtained in terms of the dehumidification efficiency of the respective TTD operation. Since the proposed method aims to evaluate energy and comfort performance at the whole-house level, this section discusses the results based on the whole-house R-to-H RHD.

For both energy and comfort metrics, lower values mean good performance, while higher values mean poor performance. The YR1 HTTD operation had the lowest daily average R-to-H RHD at the same OA dew point temperature bins. The YR1 LTTD and YR2 operations had comparable R-to-H RHD, but the YR2 operation reported higher conditioning energy use compared to the YR1 LTTD operation.

The dehumidification performance difference observed between the YR1 HTTD and YR1 LTTD operations that had the same dehumidification control strategy (i.e., dedicated dehumidification cycle of the heat pump system) was caused because the YR1 LTTD includes only two cooling months such as May and June of which sensible cooling loads are relatively smaller compared to July and August. As a result, the YR1 HTTD operation showed better dehumidification performance with lowered R-to-H RHD at the very high OA dew point temperature bin (i.e., 20°C OA dew point temperature bin), which is clearer in the living room where the humidistat was located as shown in Figure 83(a).

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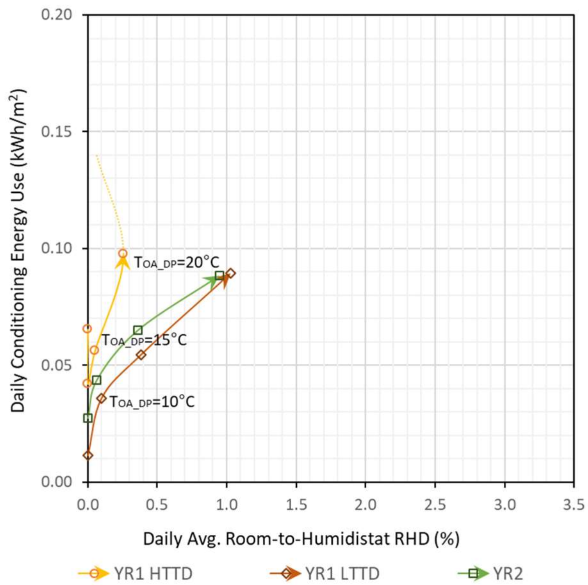
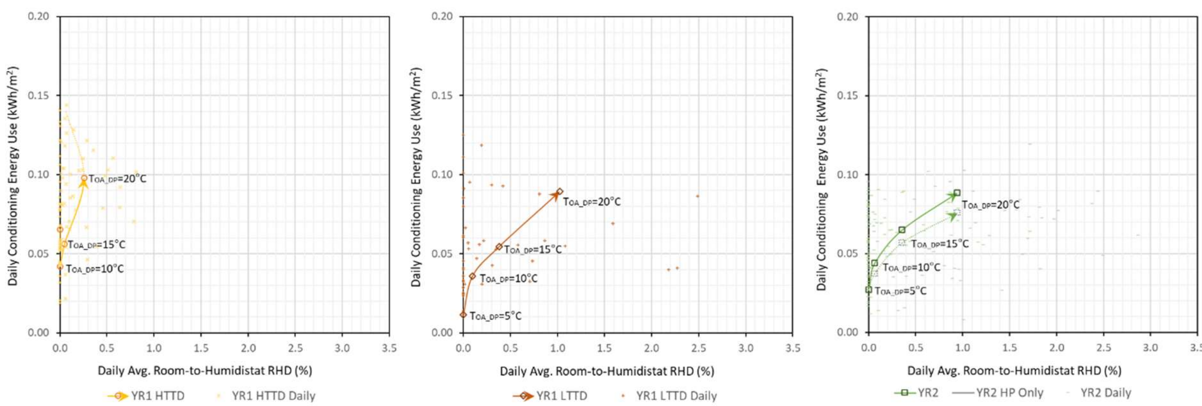


(a) All TTD Operations



(b) By TTD Operation

Figure 81: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average Whole-House R-to-H Total RHD.

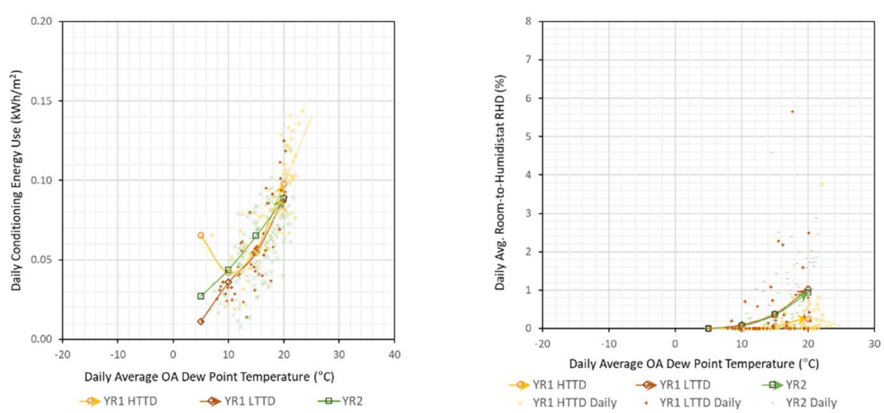


Figure 82: Weather-Dependent Characteristics of the Two Chosen Energy and Thermal Comfort Metrics: Daily Average Whole-House R-to-H Total RHD.

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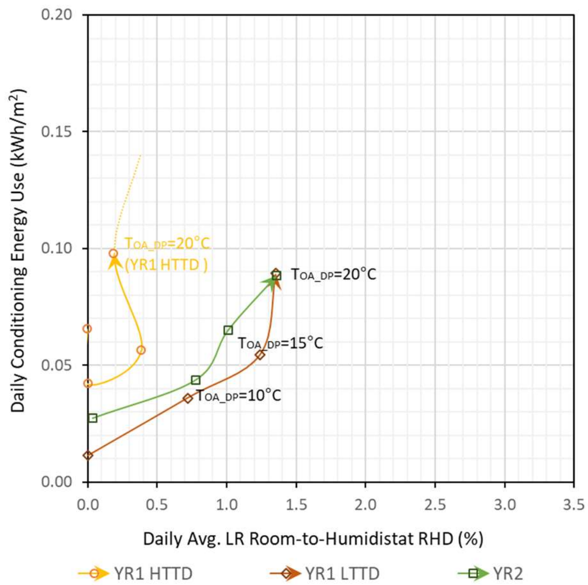
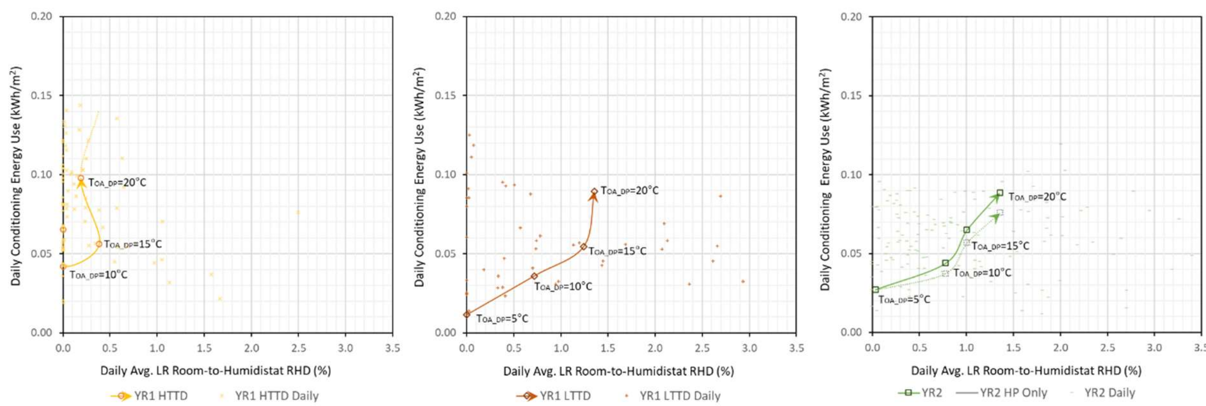


(a) All TTD Operations



(b) By TTD Operation

Figure 83: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Daily Average LR R-to-H Total RHD.

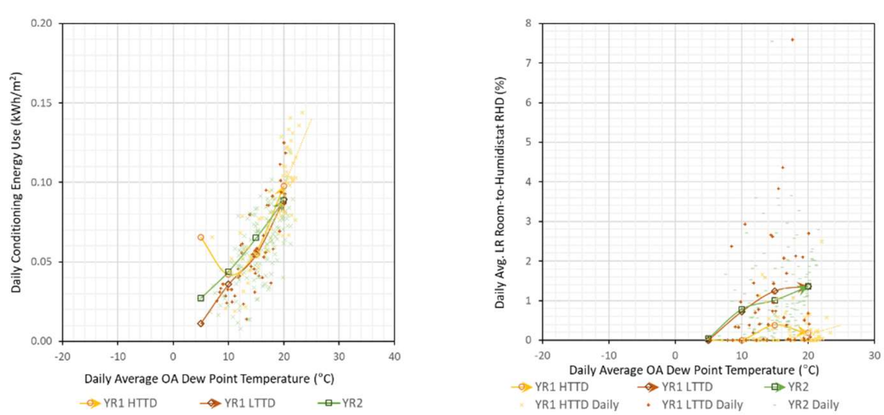


Figure 84: Weather-Dependent Characteristics of the Two Chosen Energy and Thermal Comfort Metrics: Daily Average LR R-to-H Total RHD.

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6. CONCLUSIONS

This section summarizes the key findings from this research and discusses the recommendations for future research, which will contribute to improved design, operation, and measurements of whole-house performance for energy efficiency and thermal comfort.

This research investigated how thermal comfort dynamics were impacted by energy-efficient or thermal comfort improvements applied to NZERTF and proposed and demonstrated a method to rate a whole-house performance in an integrative way based on measured energy and comfort performance of the house. During the analysis period, the major energy-efficient or thermal comfort improvements applied to the NZERTF throughout is Year 1 and Year 2 operations include:

- Lowered 2nd stage and 3rd stage differential temperature settings along with shortened delay time to control the same heat pump system;
- Improved control strategy of the backup electric resistance heater of the same heat pump system (i.e., 3rd stage heating) by removing associated delay time to minimize its use;
- Use of a thermostat with an additional remote sensor located in the second-floor hallway in lieu of the combined thermostat/humidistat by the heat pump manufacturer located in the living room of the house;
- Use of a whole-house dehumidifier in lieu of the heat pump's dedicated dehumidification cycle; and
- Lowered outdoor ventilation rate per ASHRAE Standard 62.2-2010 (ASHRAE 2010b), which resulted in a 20% reduced outdoor ventilation compared to Year 1 operation.

To accomplish this, the quality-controlled 1-min data were divided into several subgroups to accurately characterize and report the whole-house energy and thermal comfort performance of NZERTF. This includes partitioning long-term energy and thermal comfort data by season based on the heat pump system's actual operation mode under given weather conditions and by three Thermostat's Temperature Differential (TTD) settings that were used to control the heat pump system (i.e., Year 1 High TTD (YR1 HTTD); Year 1 Low TTD (YR1 Low TTD); and Year 2 (YR2)).

The sub-grouped data were then used to calculate weather-dependent energy models for the whole house and five major end uses (e.g., conditioning, ventilation, lighting, plug loads+ appliances, and domestic hot water). The weather-dependent changing-point regression models for conditioning energy use were then used to estimate the energy performance changes between the different subgroups. It was found that the conditioning electricity use would increase with tighter TTD control during the heating season, while the improved control strategy of the backup electric resistance heater during the Year 2 operation would result in high energy savings during the heating season.

In addition, this study calculated several whole-house thermal comfort metrics for each subgroup to reveal the impact of major energy-efficient or thermal comfort improvements applied to NZERTF on its thermal comfort performance. The calculated metrics include:

- Temperature deviation from the setpoint temperature (i.e., room-to-thermostat temperature difference) to evaluate the system's fundamental ability to produce and deliver the designed air temperature;
- Room-to-room temperature difference to evaluate spatial thermal uniformity;

- Cyclic discomfort to evaluate temporal thermal uniformity; and
- Relative humidity (RH) deviation from the setpoint RH (i.e., room-to-humidistat RH difference) to evaluate dehumidification efficiency in terms of maintaining a setpoint humidity.

The calculated metrics for each subgroup were then compared against relevant benchmarks such as the ACCA Manual RS and the ASHRAE Standard 55-2017.

Besides, to fully understand the long-term thermal comfort data, this study performed statistical and advanced characterization of the granular thermal comfort data relative to the outdoor weather and the time of the day not only for the primary rooms but also for the attic and the basement that are thermally important due to possible heat transfer from/to the primary rooms. These analyses revealed weather-dependent characteristics of the thermal comfort metrics, which led to the development of the proposed rating method, and their dynamic interactions with uneven internal heat gains from occupants, lighting, appliances, and miscellaneous electronic devices.

Finally, this study proposed an integrative rating method based on the weather-dependent conditioning energy use of the house and coincident whole-house thermal comfort metrics that were averaged over a particular range of weather conditions. The proposed method was demonstrated using the Year 1 and Year 2 NZERTF performance data, which allowed a weather-normalized comparison of the three different TTD operations in terms of both energy and thermal comfort for a particular weather condition.

As shown in Figures 85, lower values mean good performance, while higher values mean poor performance for both energy and comfort metrics. For example, the transitional season had metrics closer to the origin, which means better energy and comfort performance compared to the cooling and heating seasons. The line begins with a daily average outdoor air temperature of -10°C (no arrow) and ends with a daily average outdoor air temperature of 30°C (arrow). If the trend line forms a vertical line, it means the respective thermal comfort metric is less sensitive to OA temperature, while the conditioning energy use sharply increased with increased OA. On the other way, if the trend line forms a horizontal line, it means the respective thermal comfort metric is sensitive to OA temperature while the conditioning energy is not.

For example, during the cooling season, the Year 2 operation had the largest temperature deviation from the setpoint in the first-floor rooms but maintained the second-floor temperature closer to the setpoint. The first-floor overcooling during the Year 2 operation was caused by using the average of two temperature sensors (i.e., thermostat sensor in the living room and the remote sensor in the second-floor hallway) to control the heat pump system. It was also found that the use of a thermostat with remote sensing capability during the Year 2 operation did not improve thermal uniformity between the rooms/floors with the largest room-to-room temperature differences at the same outdoor air temperature conditions.

During the heating season, different results were obtained by the outdoor air temperature. On mild winter days, the Year 2 operation maintained a smaller temperature deviation from the setpoint with comparable room-to-room temperature differences. On colder winter days, the Year 2 operation had the largest room-to-thermostat temperature deviation, which was a

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comfort penalty due to an improved control strategy to minimize the use of the backup electric resistance heater. As a result, the heat pump system ran constantly to meet the heating setpoint temperature, which was actually helpful to maintain better thermal uniformity with smaller room-to-room temperature differences during the Year 2 operation.

The impact of lowered differential temperatures was also revealed by comparing different TTD settings that had been changed over the Year 1 operation. For example, a larger low-side temperature deviation from the setpoint was observed along with unfavorable non-compliant periods based on the ACCA Manual RS benchmarks when the 1st stage heating differential temperature was set higher before November 19, 2013. In addition, delayed or no responses of the heat pump's 2nd and 3rd stage heating were occasionally observed during the Year 1 high TTD operation. The observed thermal discomfort improved with the lowered TTD setting. However, there was an energy penalty (i.e., increased heating energy use).

In conclusion, the proposed rating method allowed an integrative and rigorous assessment of a whole-house performance in terms of both energy efficiency and comfort of which assessments were often made separately in the history of the disciplines. In the absence of high-quality residential datasets, the results of this study can serve as rigorous benchmarks to which other houses and conditioning systems can be compared for respective outdoor weather conditions. For example, based on the NZERTF data, the energy and comfort conditions in a house can be classified into three categories that are highlighted in different colors as shown in Figure 85.

To improve the proposed rating system, it is highly recommended that research to be performed to develop more reliable residential benchmarks based on multiple datasets representing different types of systems, control strategies, or envelope characteristics. In addition, to improve the validity of the proposed rating method, more metrics should be tested and included in this rating system. For example, the energy performance of a house can include electricity demand in addition to daily energy use.

From practicality perspective, it is recommended that research be performed to demonstrate the proposed rating method based on short-term measurements or measurements with a lower spatial/temporal resolution. For example, the proposed rating method is expected to be applicable for both short-term and long-term measurements using the data sorted by respective outdoor temperature, although long-term measurements would provide a more accurate characterization. In addition, if thermal comfort measurements in multiple rooms across the house is not readily available, this rating system can be used even with a single temperature measurement at the most problematic location. (i.e., the room with the largest temperature deviation from the setpoint) or in a room where the thermostat is located

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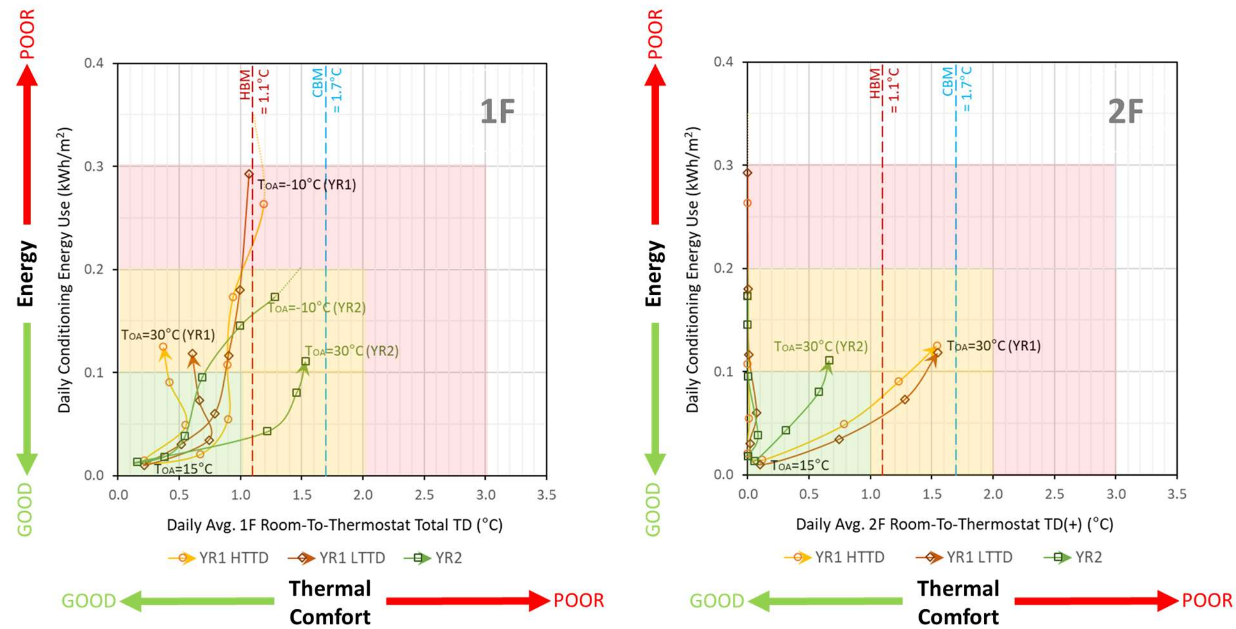
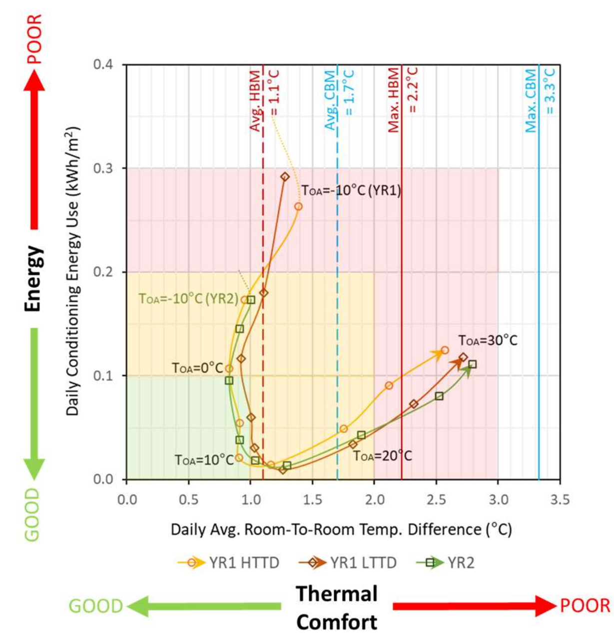


(a) Room-to-Thermostat Total Temperature Difference to Evaluate Temperature Controls



(b) Room-to-Room Temperature Difference to Evaluate Spatial Uniformity

Figure 85: Integrative Rating Method based on Weather-Dependent Daily Conditioning Energy Use and Coincident Whole-House Thermal Comfort Metrics

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APPENDIX A: Data Gaps

Appendix A describes the rule that was applied to fill the data gaps identified in the raw data. Data gaps include missing timestamps (e.g., midnight missing data for two to three minutes) and bad data. Most long-term data gaps (> 2 hours) occurred in the days to exclude. The following rule was applied to fill the data gaps identified:

- If gaps ≤ 1 hour, the gaps were filled with previous values.
- If gaps > 1 hour and ≤ 2 hours, the gaps were filled with interpolation.
- If gaps > 2 hours, the gaps were filled with -99.

The data gaps identified in the Year 1 raw data from July 2013 to June 2014 include:

- Midnight missing data for two to three minutes;
- 123 non-midnight data gaps ≤ 1 hour; and
- 11 long-term data gaps > 1 hour.

123 non-midnight data gaps randomly occurred throughout the Year 1, but they tend to repeatedly occur at around 11 PM in the first few months of Year 1 dataset. Out of the 11 long-term data gaps, 8 data gaps occurred in the days to exclude (i.e., no need for filling gaps). 1 data gap occurred to forward one hour due to DST on March 9, 2014. 2 data gaps include 100 1-min data points (i.e., equivalent to 1 hour 40 minutes) from December 5, 2013 6:03 AM to 7:42AM; and 103 1-min data points (i.e., equivalent to 1 hour 43 minutes) from May 15, 2014 0:01 AM to 1:43 AM.

The data gaps identified in the Year 2 raw data from February 2015 to January 2016 include:

- Midnight missing data for two to three minutes;
- 10 non-midnight data gaps ≤ 1 hour; and
- 3 long-term data gaps > 1 hour.

Out of the three long-term data gaps, 2 data gaps occurred in the days to exclude (i.e., no need for filling gaps), and 1 data gap occurred to forward one hour due to DST on March 8, 2015.

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APPENDIX B: DAYS TO EXCLUDE

Appendix B provides a list of the 25 days that were excluded from the analysis (i.e., 15 days in Year 1 and 10 days in Year 2) along with additional 24 days (i.e., 15 days in Year 1 and 9 days in Year 2) that were partially excluded from the analysis due to long-term bad data in OA dew point temperature data.

The days to exclude for Year 1 from July 2013 to June 2014 include:

- The following 10 days were excluded due to the exclusion from the PV data reported in Fanney et al. (2015).
  - August 2, 2013 through August 6, 2013
  - December 4, 2013
  - December 27, 2013
  - January 31, 2014
  - May 13, 2014
  - May 14, 2014

- The following 2 days were excluded due to bad/missing data in the heat pump performance data.
  - September 28, 2013
  - September 29, 2013

- The following 1 day was excluded due to the event log recorded errors and no heating response from HP at low temperature.
  - October 25, 2013

- The following 1 day was excluded due to the change of the thermostat's differential temperature setting in the middle of the day.
  - January 23, 2014

- The following 1 day was excluded due to long-term bad data in NIST OA temperature data.
  - April 29, 2014

- The following 15 days were partially excluded due to bad/missing data in NIST OA dew point temperature data.
  - September 12, 2013
  - October 11, 2013 through October 13, 2013
  - October 16, 2013
  - October 17, 2013
  - November 24, 2013 through November 27, 2013
  - January 6, 2014 through January 8, 2014
  - February 13, 2014
  - February 14, 2014

The days to exclude for Year 2 from February 2015 to January 2016 include:

- The following 2 days were excluded due to the time response test at NZERTF.
  - February 5, 2015
  - February 6, 2015

- The following 3 days were excluded due to the failure of a relay in the heat pump outdoor unit.
  - May 30, 2015 through June 1, 2015

- The following 3 days were excluded due to system shutdown.
  - October 20, 2013 through October 22, 2013

- The following 2 days were excluded due to NIST close down.
  - January 25, 2016
  - January 26, 2016

- The following 9 days were partially excluded due to bad/missing data in NIST OA dew point temperature data.
  - February 15, 2015
  - February 16, 2015
  - February 19, 2015 through February 21, 2015
  - February 23, 2015
  - February 24, 2015
  - January 23, 2016
  - January 24, 2016

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APPENDIX C: GRAPHICAL SUMMARIES OF 1-MIN THERMAL COMFORT AND ENERGY DATA

Appendix C presents graphical summaries of the 1-min temperature, humidity, and electricity data from July 2013 to June 2014 (i.e., Year 1) and from February 2015 to January 2016 (i.e., Year 2) for the following data channels:

- 24 room air temperature channels (Appendix C-1);
- 5 room globe temperature channels (Appendix C-2);
- 2 outdoor air temperature channels (Appendix C-3);
- 7 room relative humidity channels (Appendix C-4);
- 1 outdoor humidity channel (Appendix C-5); and
- 3 heat pump electricity channels (Appendix C-6).

Standard time-series plots present the 1-min temperatures in degrees Celsius using the primary Y-axis on the left and the same temperatures in Fahrenheit on the secondary Y-axis on the right. In addition, the heating and cooling setpoint temperatures are presented as a reference for all rooms.

APPENDIX C-1: 1-MIN AIR TEMPERATURES BY ROOM
ROOMS ON THE FIRST FLOOR

- LR: Living Room

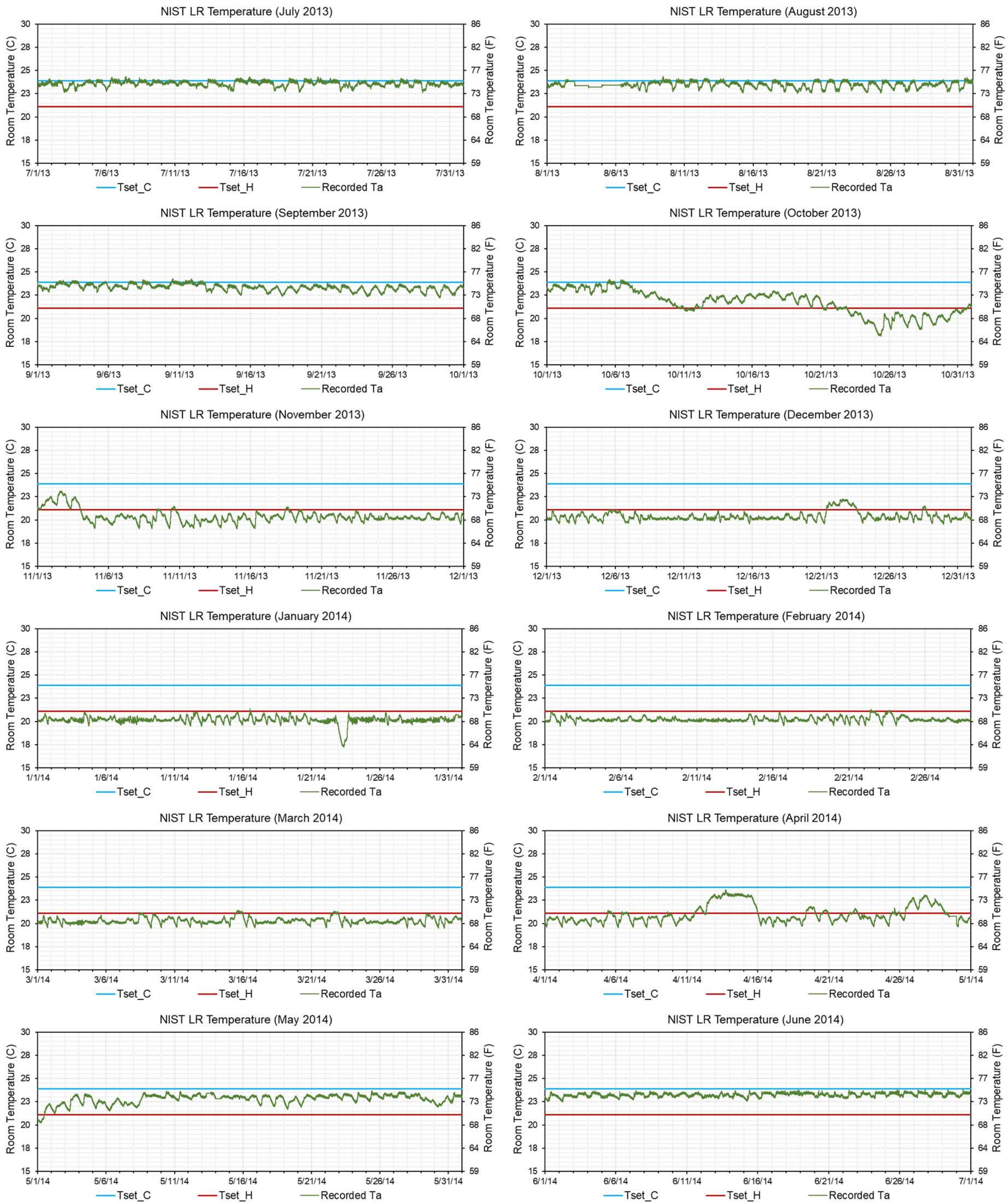

Figure C-1: Year 1 1-Min LR Temperature.

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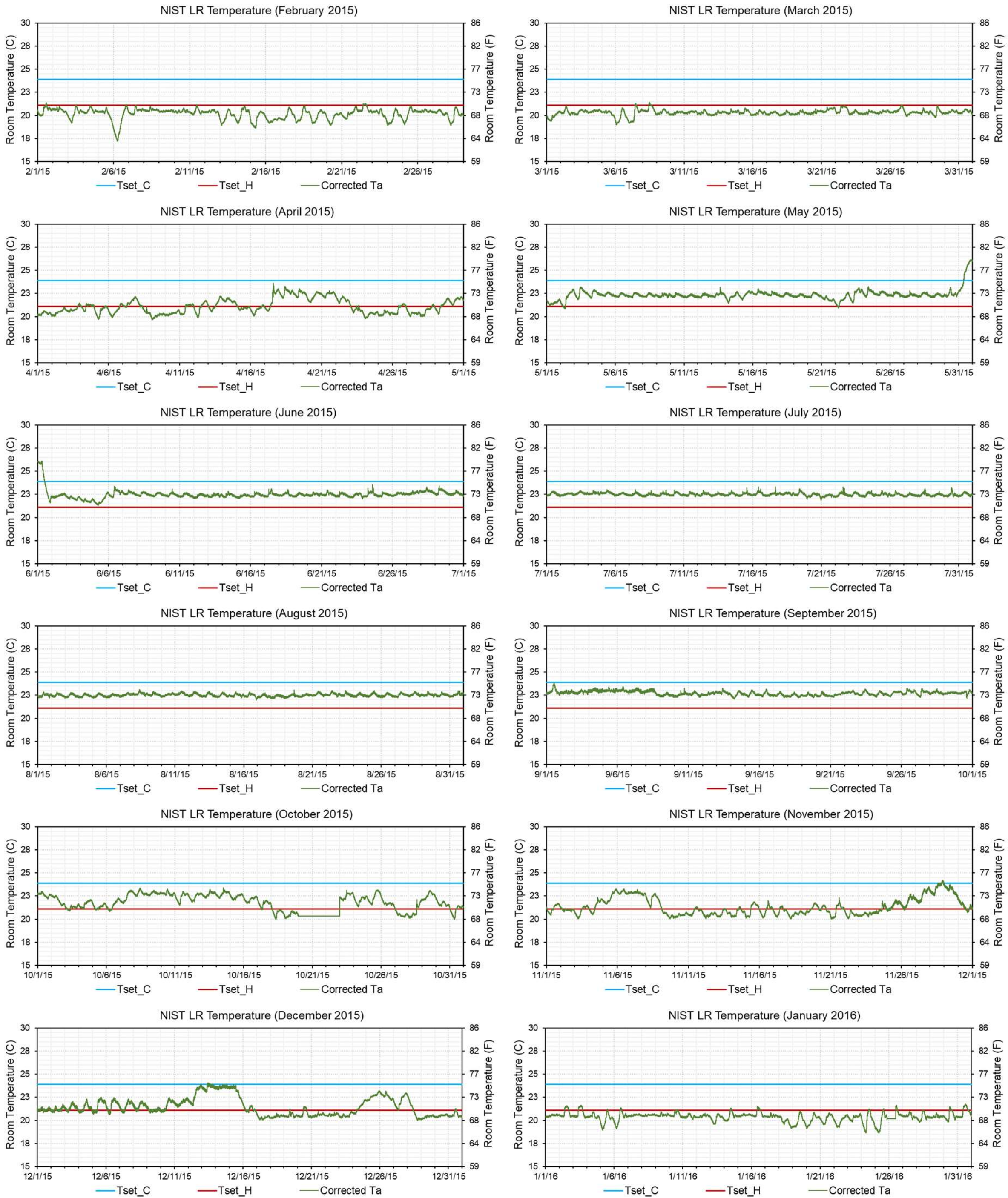

Figure C-2: Year 2 1-Min LR Temperature.

- KIT: Kitchen

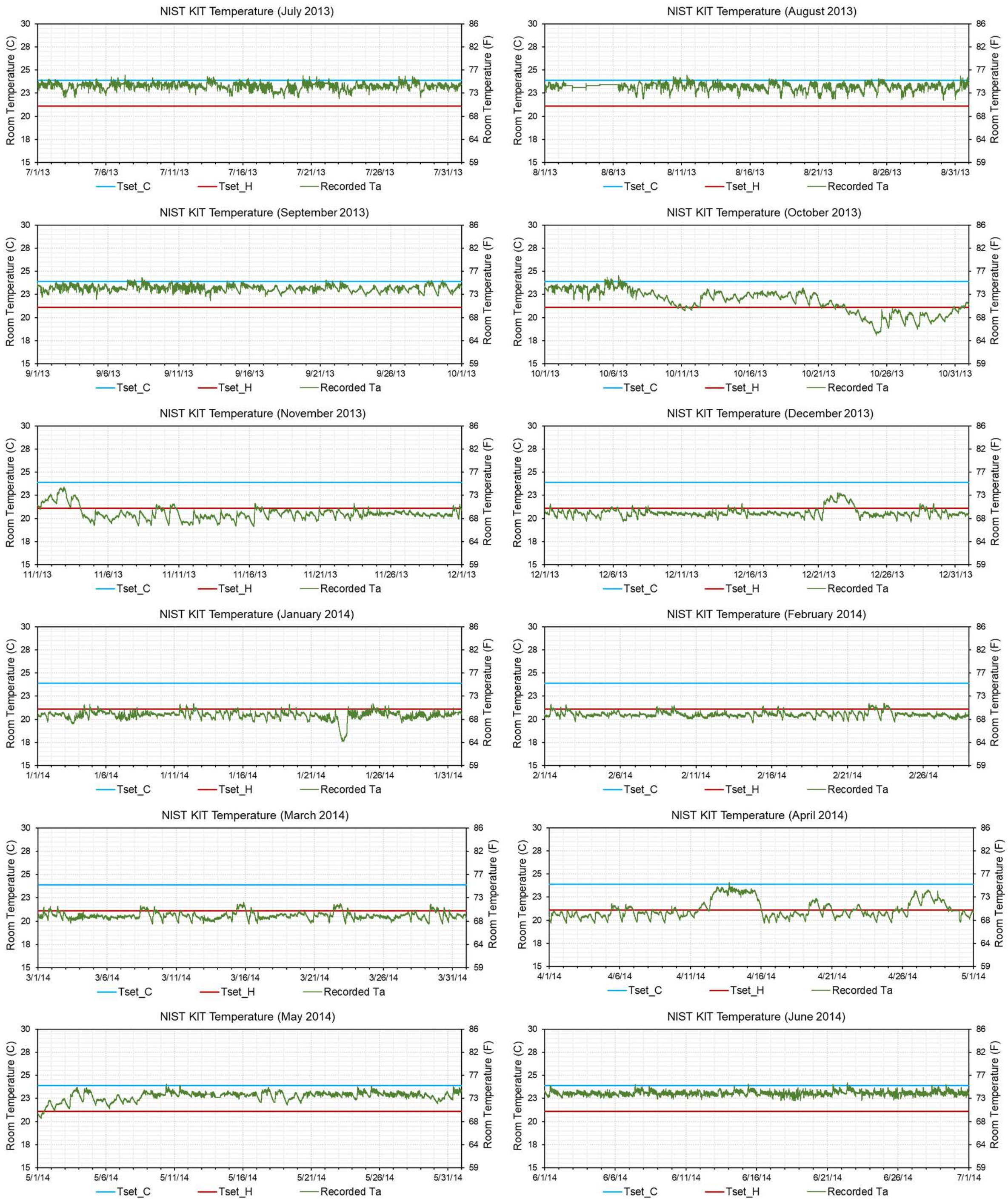

Figure C-3: Year 1 1-Min KIT Temperature.

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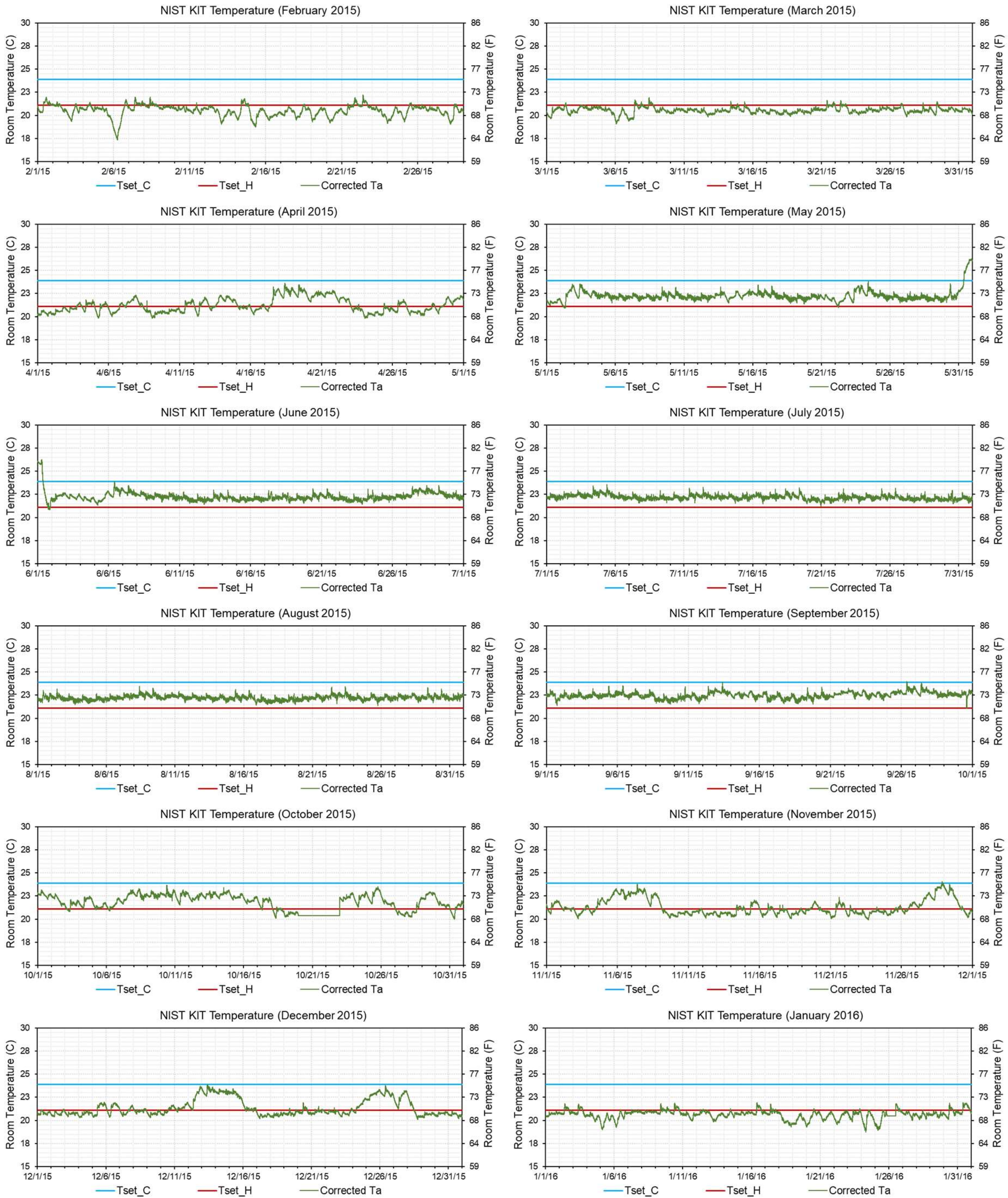

Figure C-4: Year 2 1-Min KIT Temperature.

- DR: Dining Room

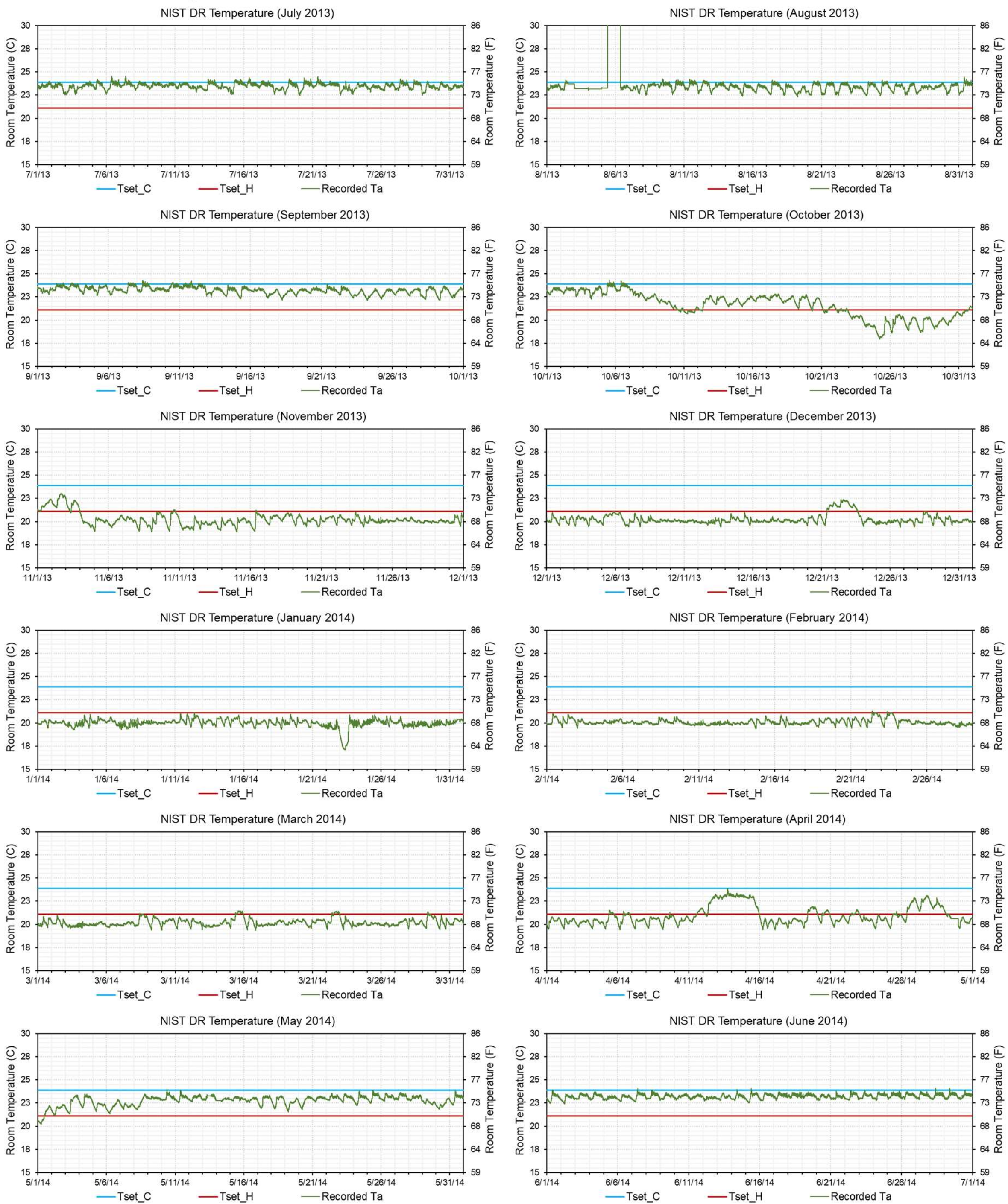

Figure C-5: Year 1 1-Min DR Temperature.

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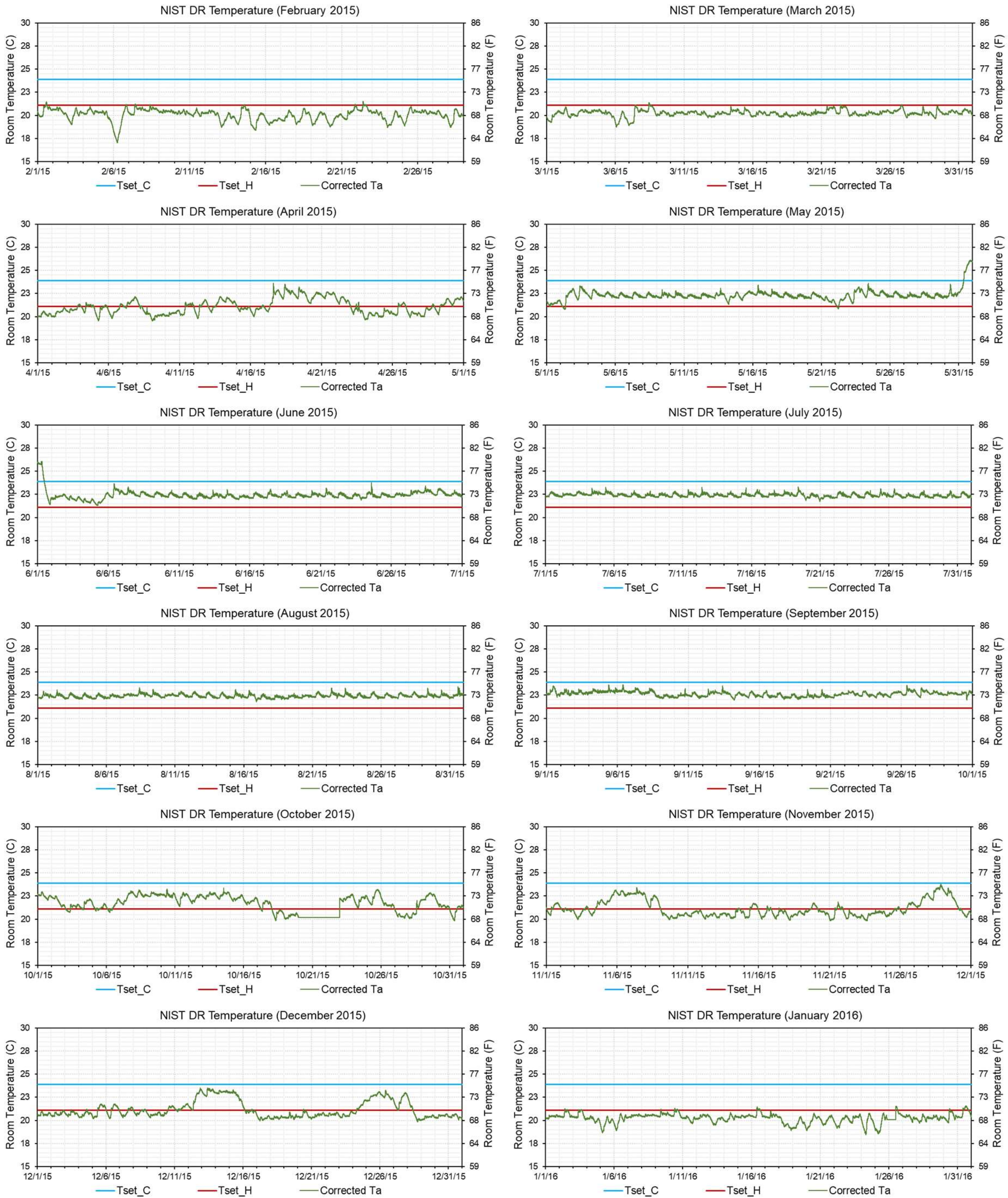

Figure C-6: Year 2 1-Min DR Temperature.

- BR4: Bedroom 4

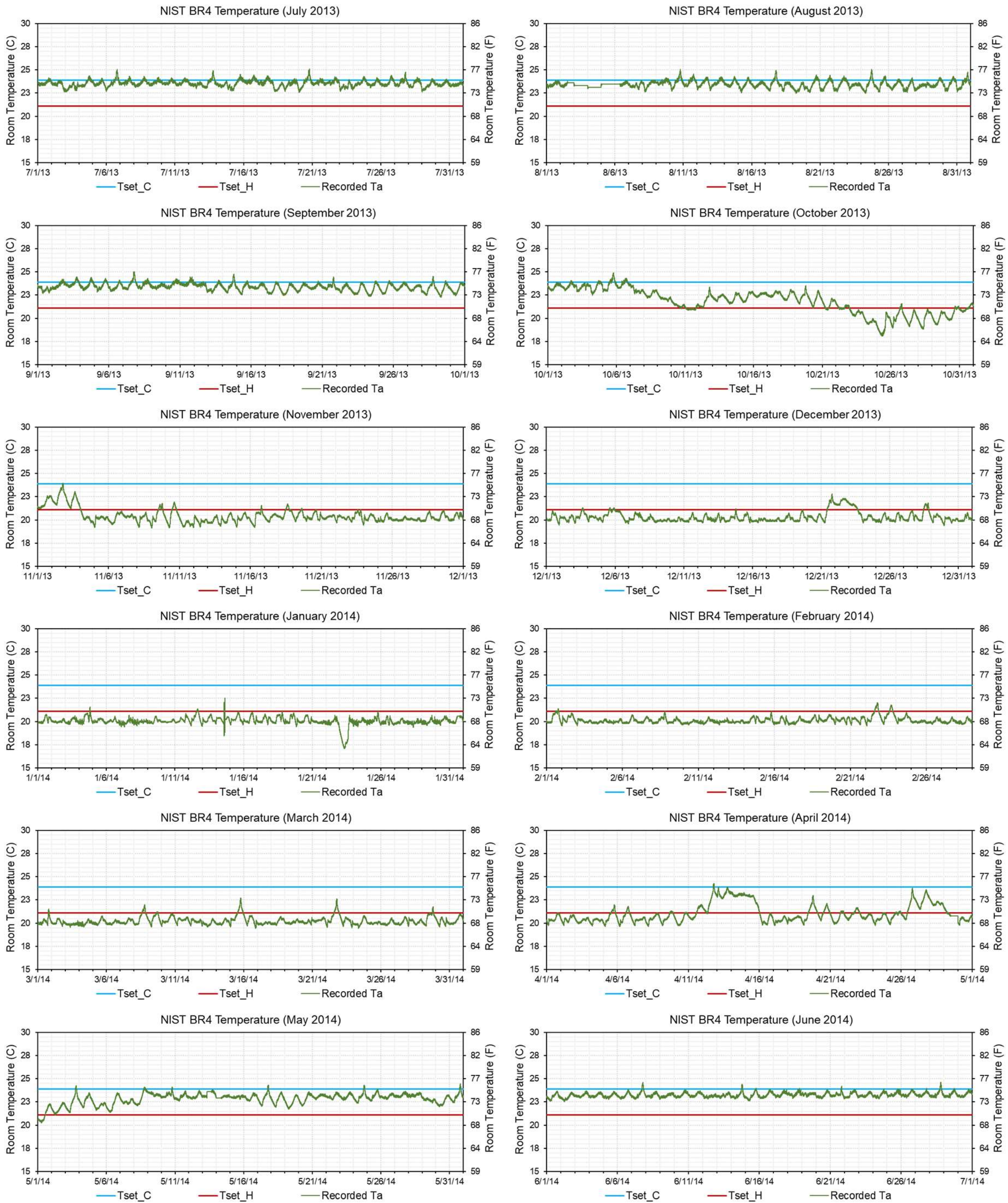

Figure C-7: Year 1 1-Min BR4 Temperature.

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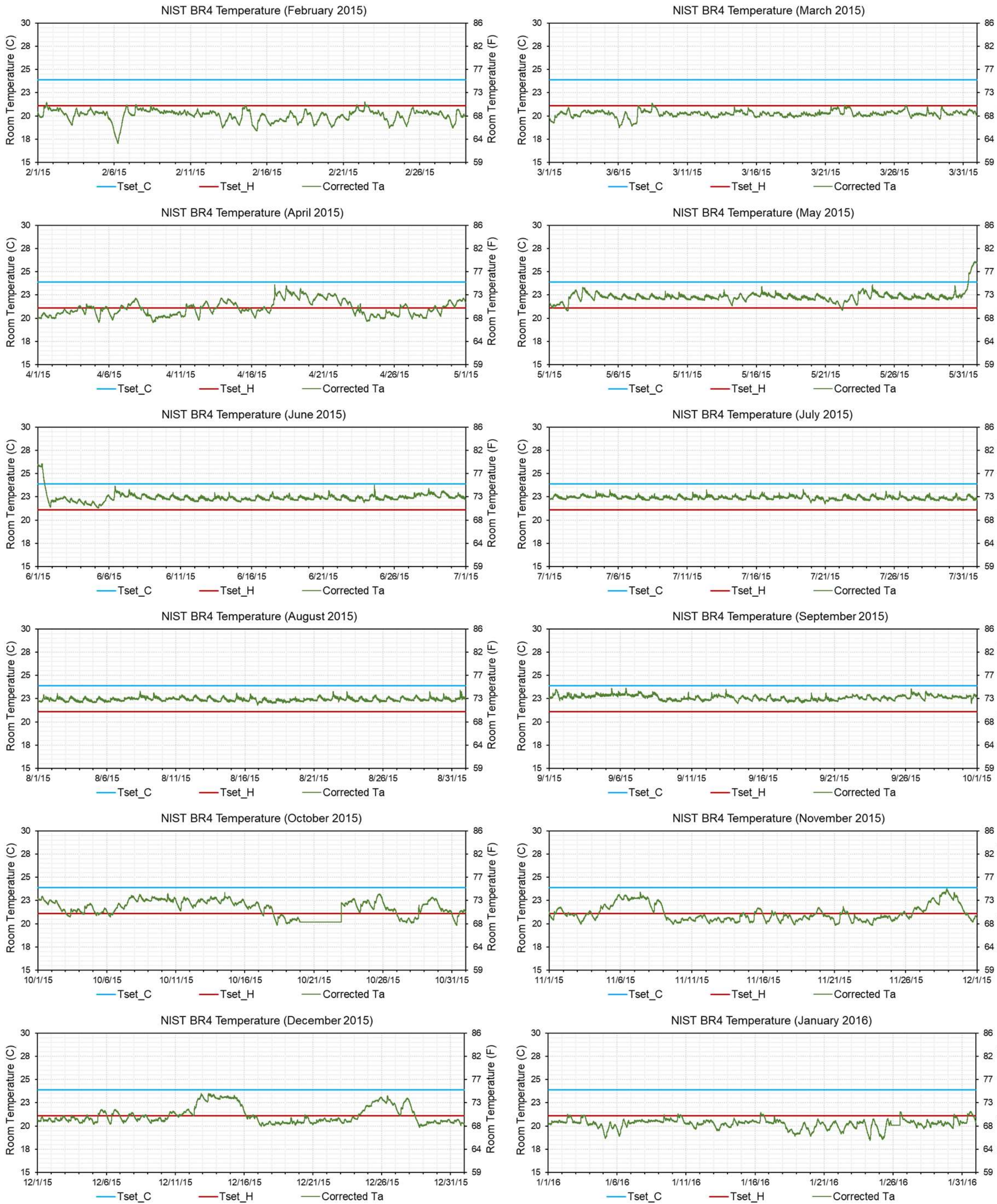

Figure C-8: Year 2 1-Min BR4 Temperature.

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- BA1: Bathroom 1

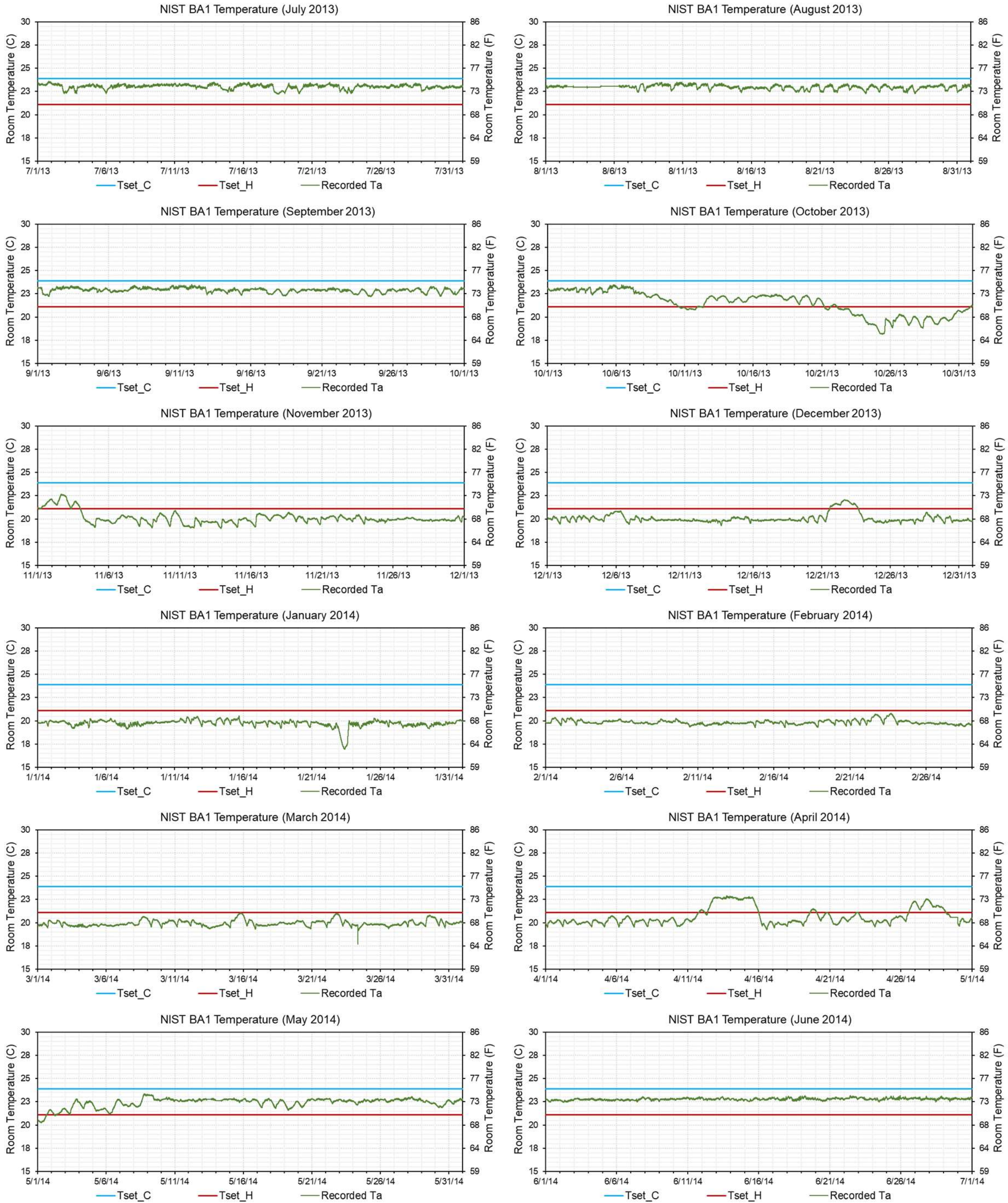

Figure C-9: Year 1 1-Min BA1 Temperature.

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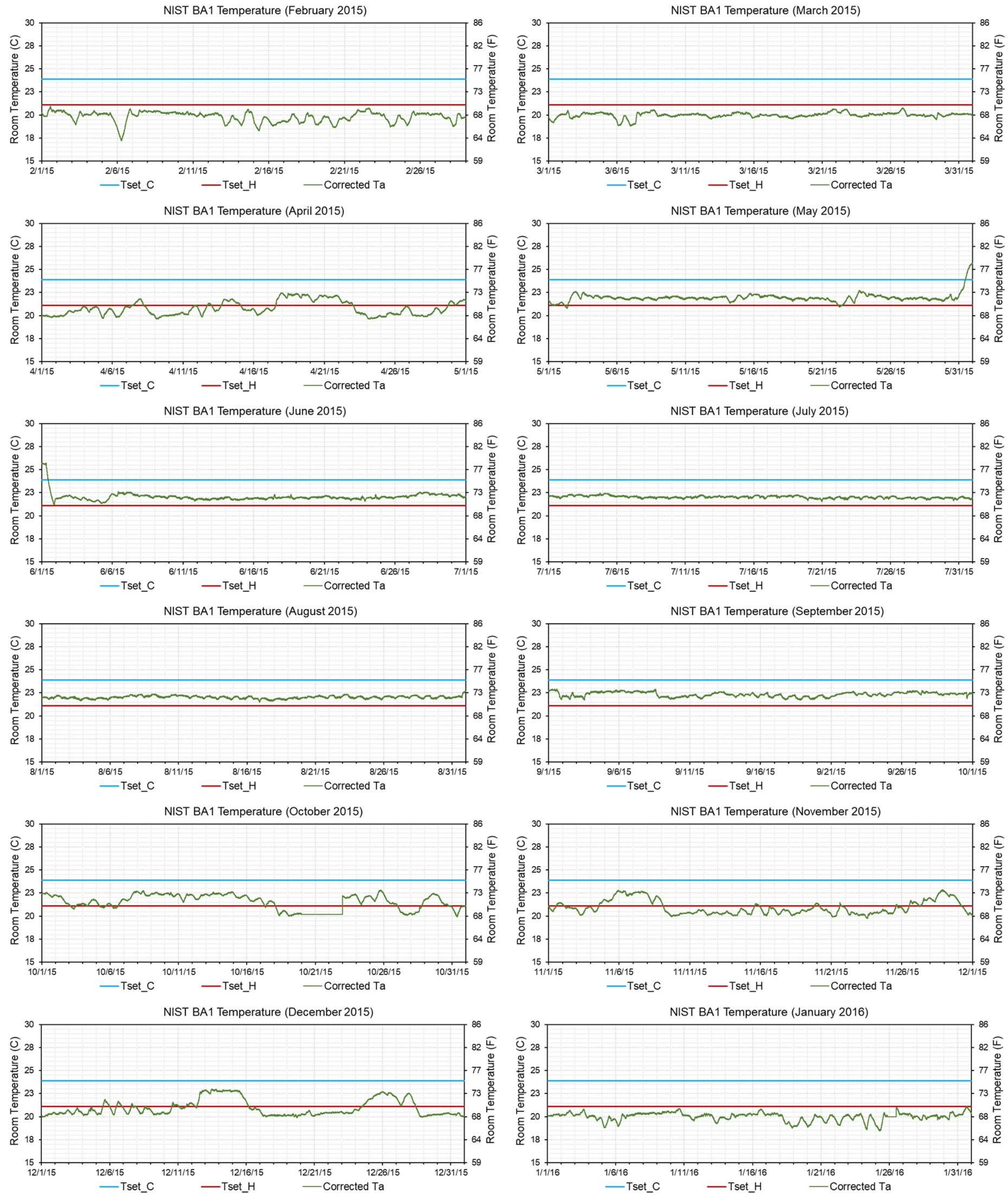

Figure C-10: Year 2 1-Min BA1 Temperature.

- WD: Washer and Dryer

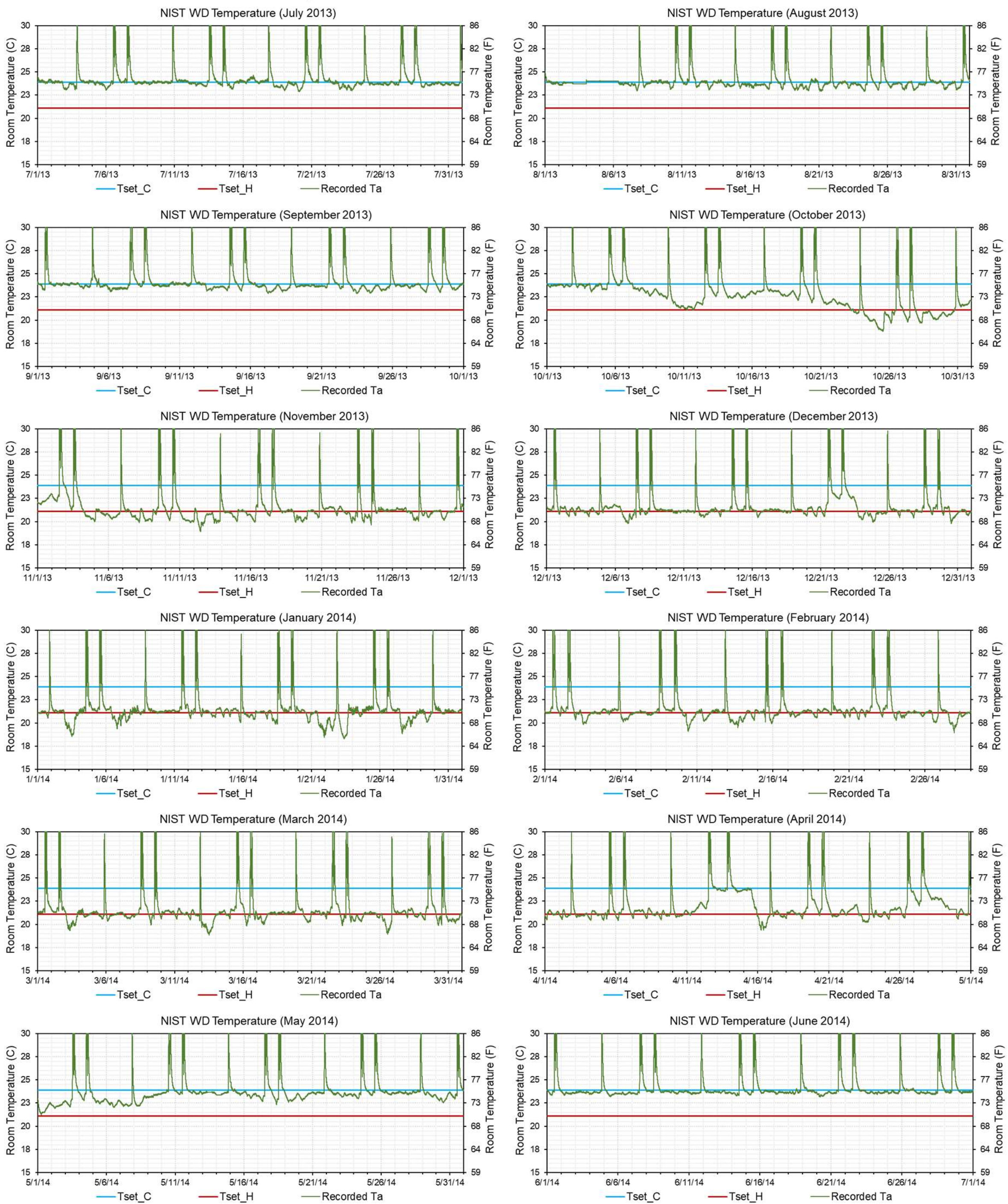

Figure C-11: Year 1 1-Min WD Temperature.

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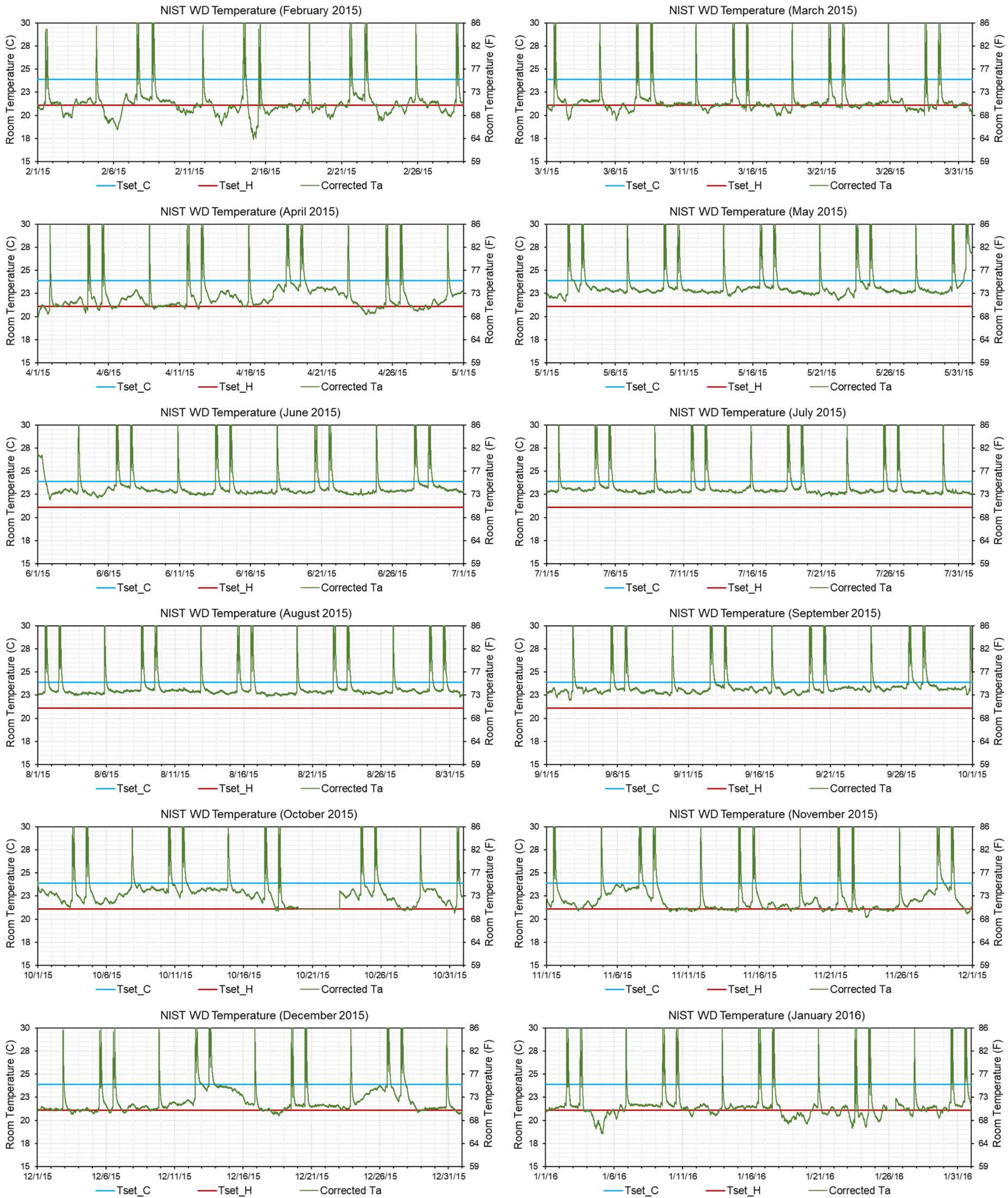

Figure C-12: Year 2 1-Min WD Temperature.

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ROOMS ON THE SECOND FLOOR

- MBR: Master Bedroom

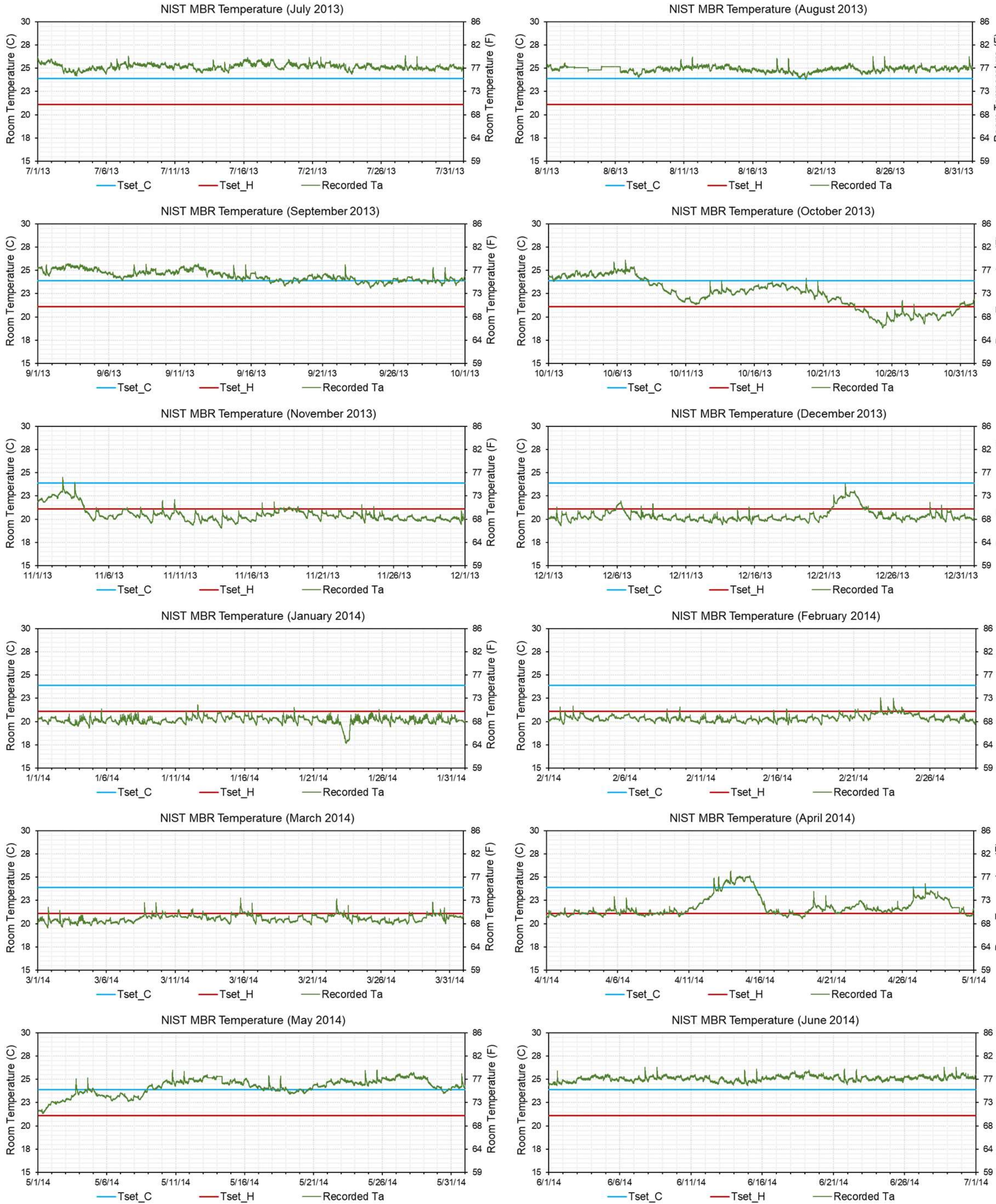

Figure C-13: Year 1 1-Min MBR Temperature.

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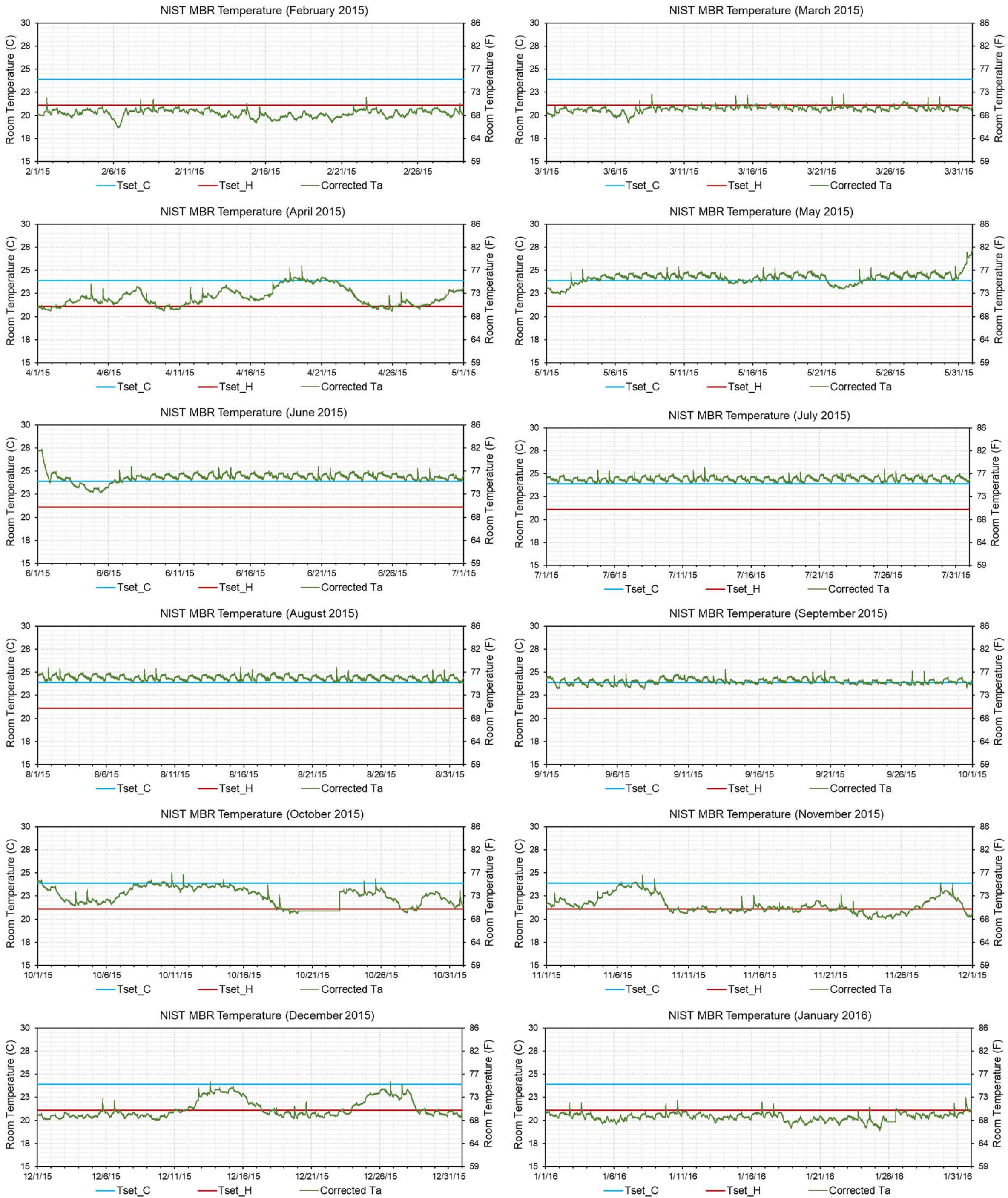

Figure C-14: Year 2 1-Min MBR Temperature.

- BR2: Bedroom 2

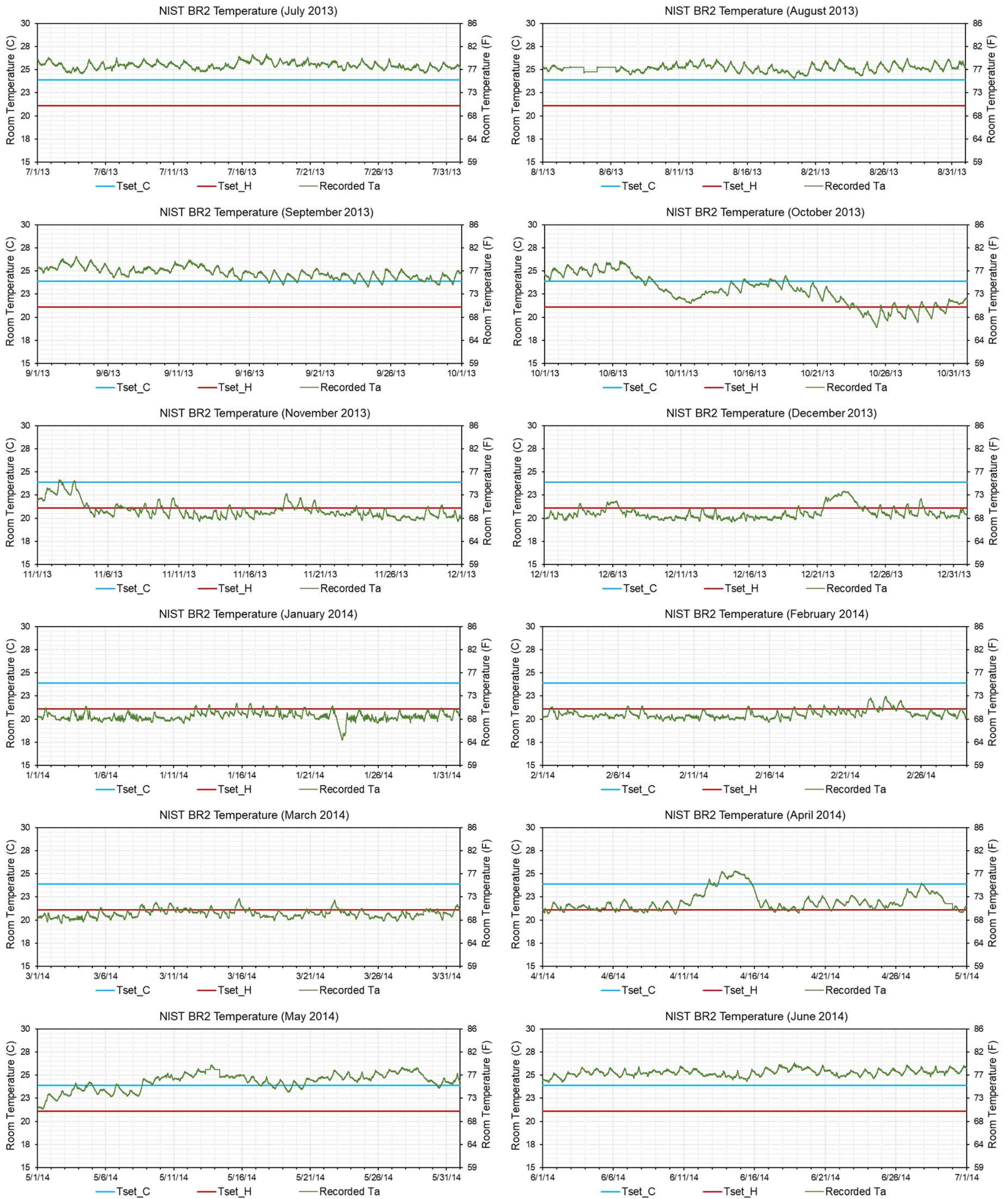

Figure C-15: Year 1 1-Min BR2 Temperature.

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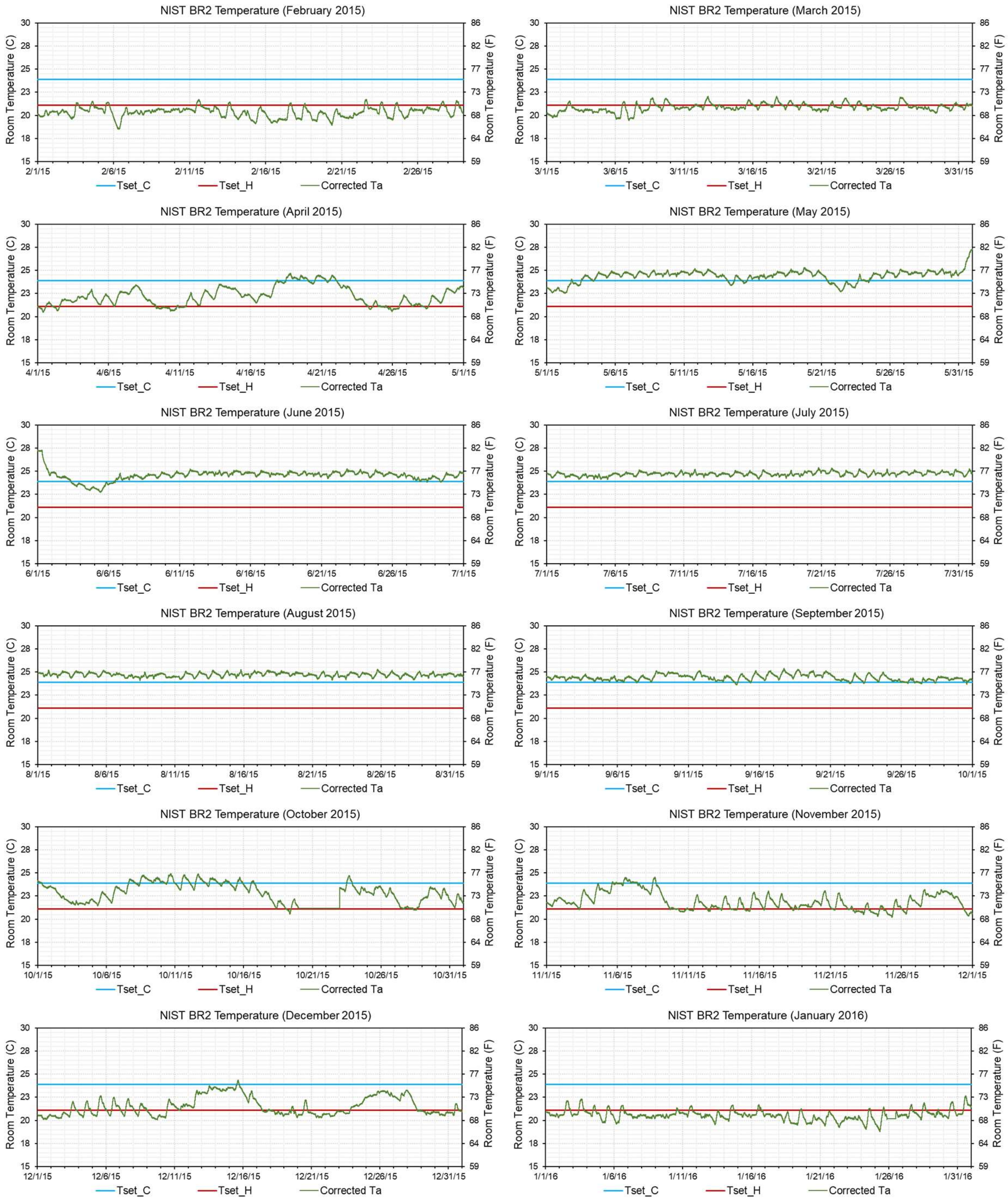

Figure C-16: Year 2 1-Min BR2 Temperature.

- BR3: Bedroom 3

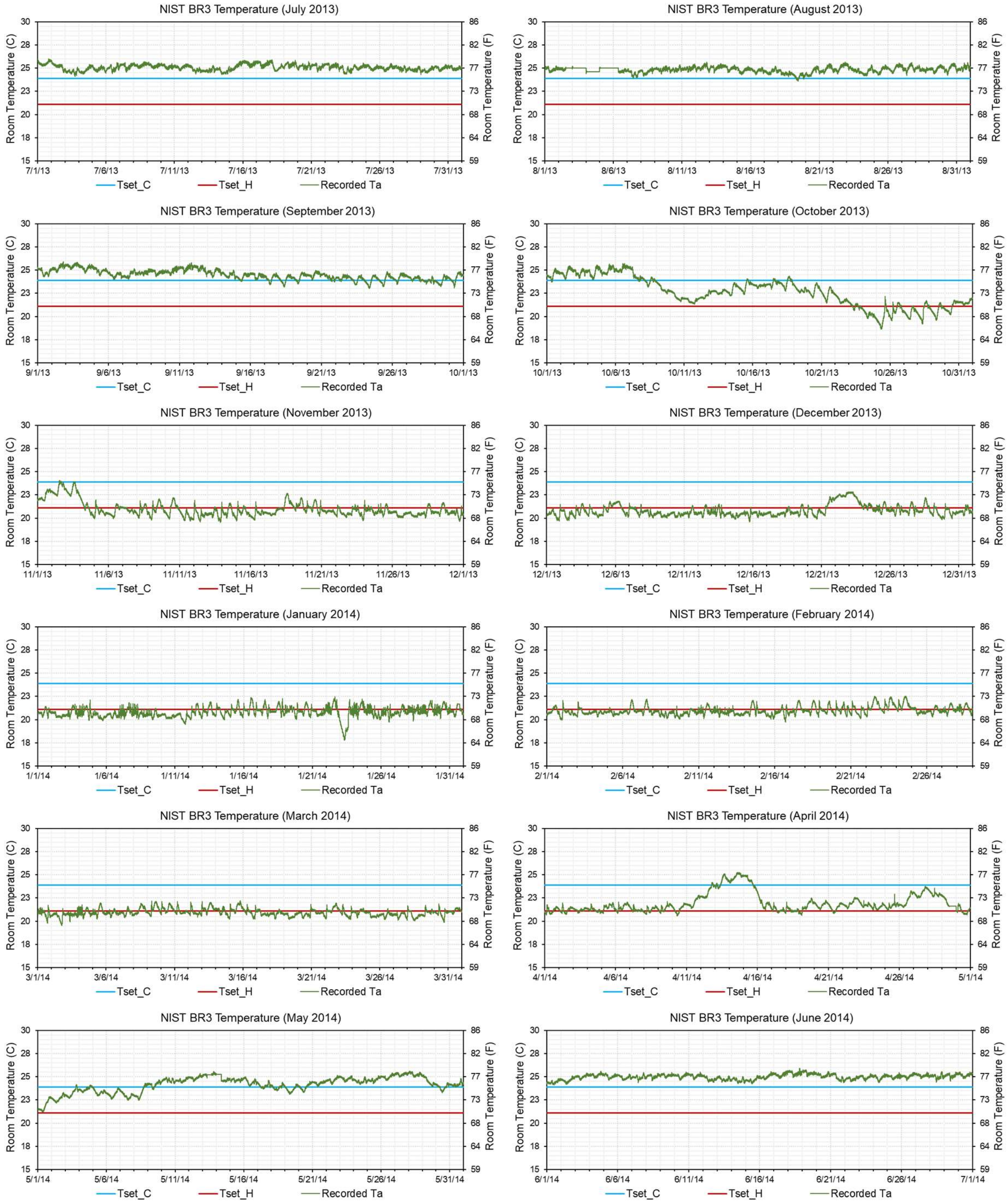

Figure C-17: Year 1 1-Min BR3 Temperature.

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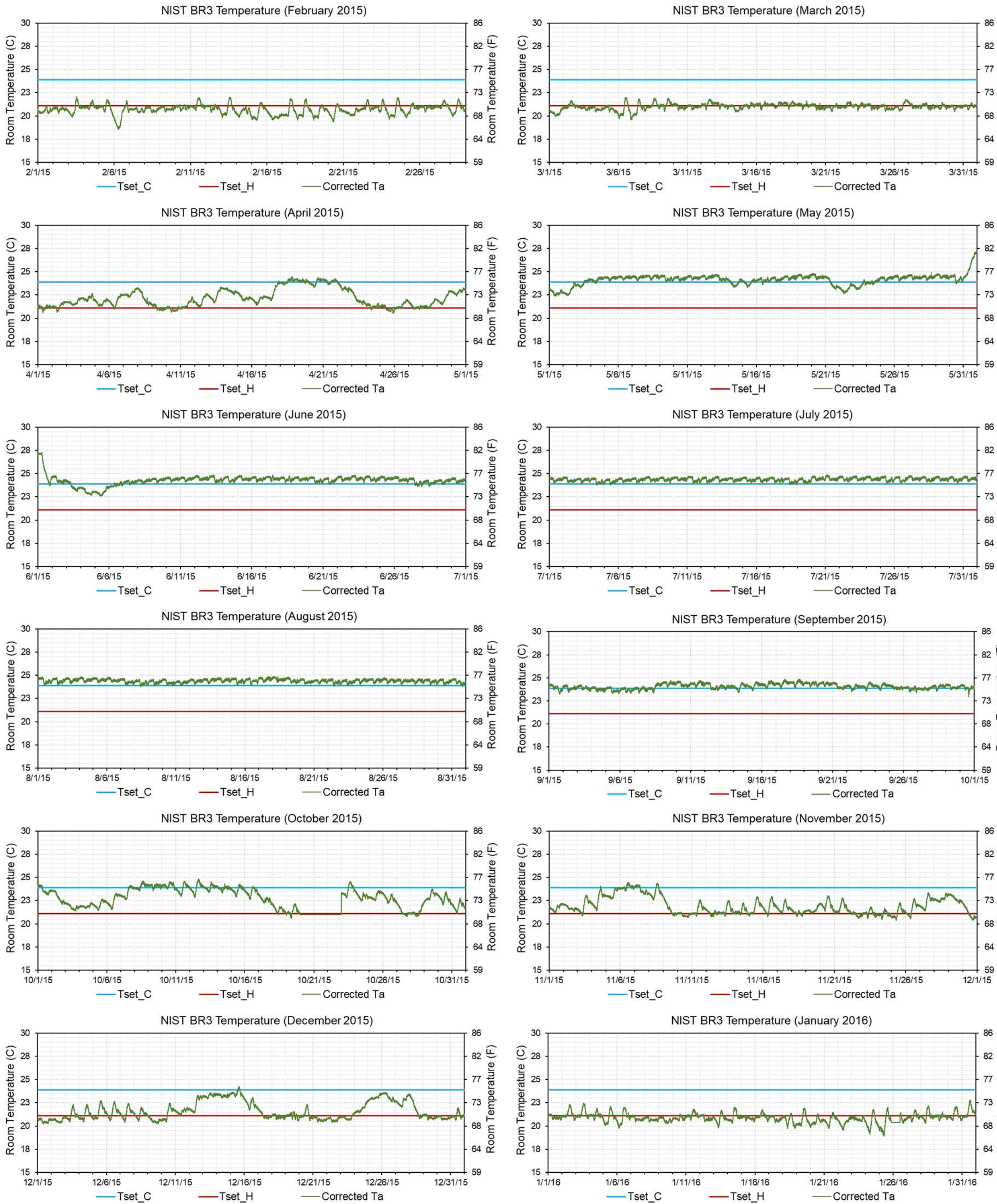

Figure C-18: Year 2 1-Min BR3 Temperature.

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- MBA: Master Bathroom

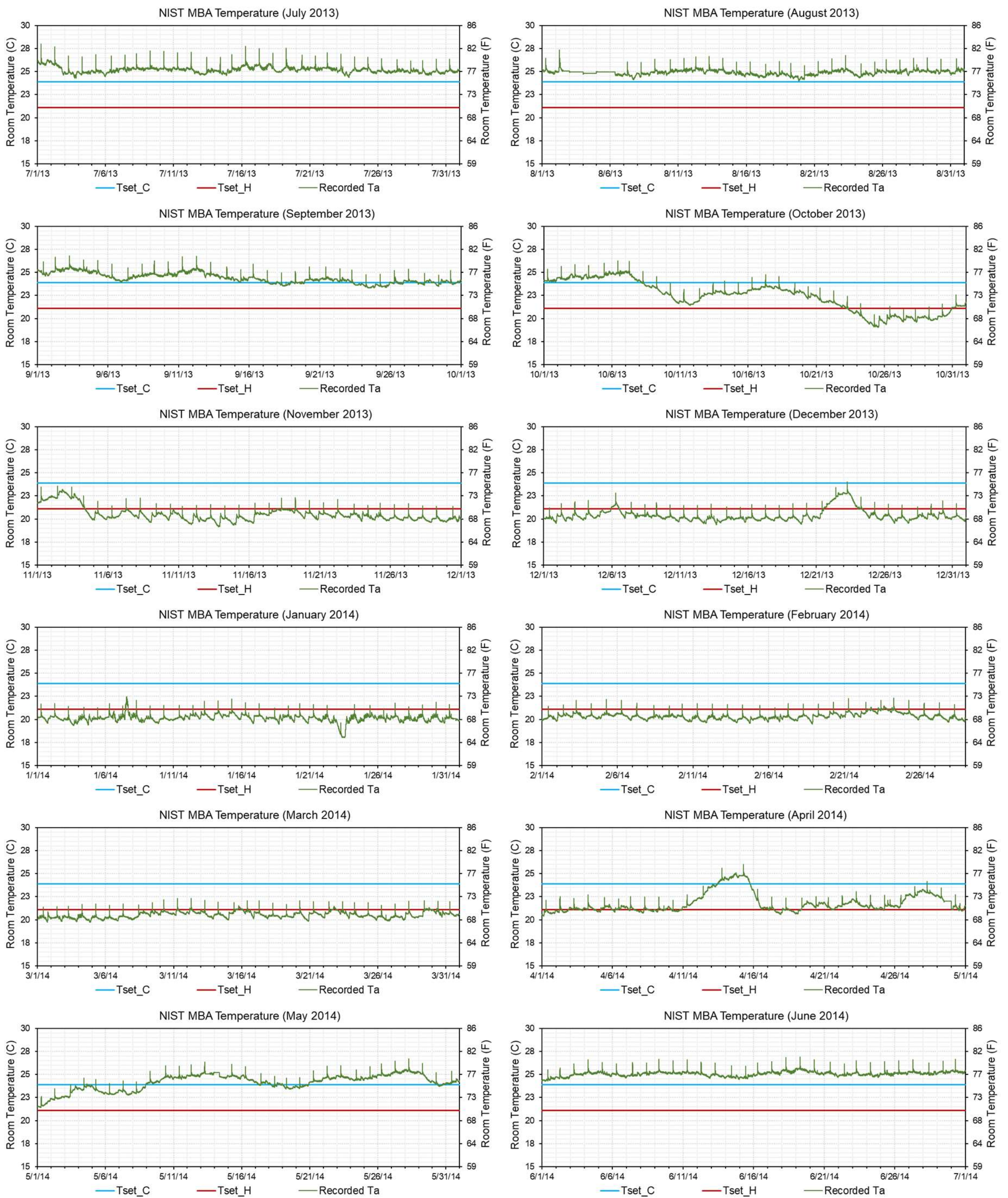

Figure C-19: Year 1 1-Min MBA Temperature.

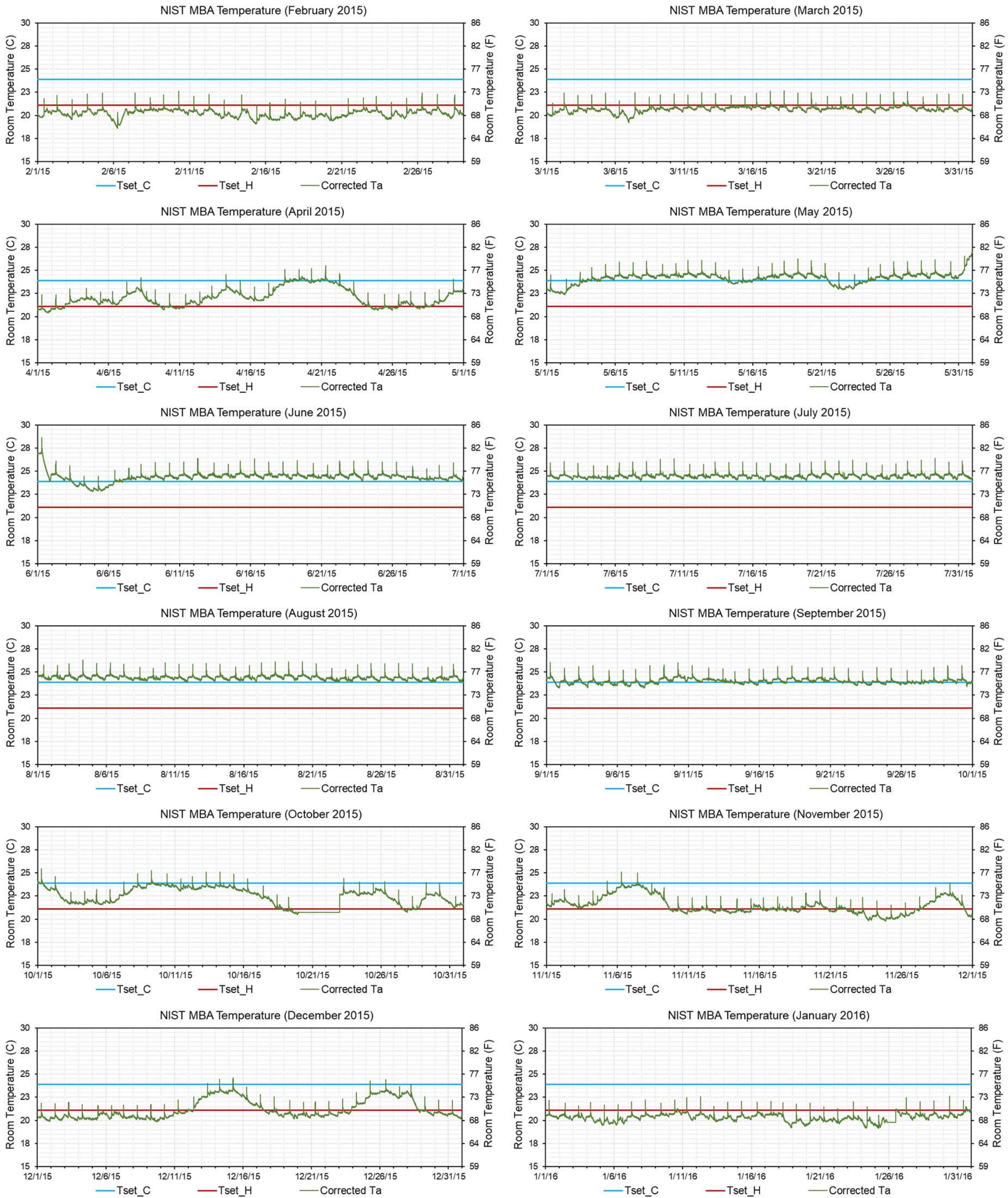

Figure C-20: Year 2 1-Min MBA Temperature.

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- BA2: Bathroom 2

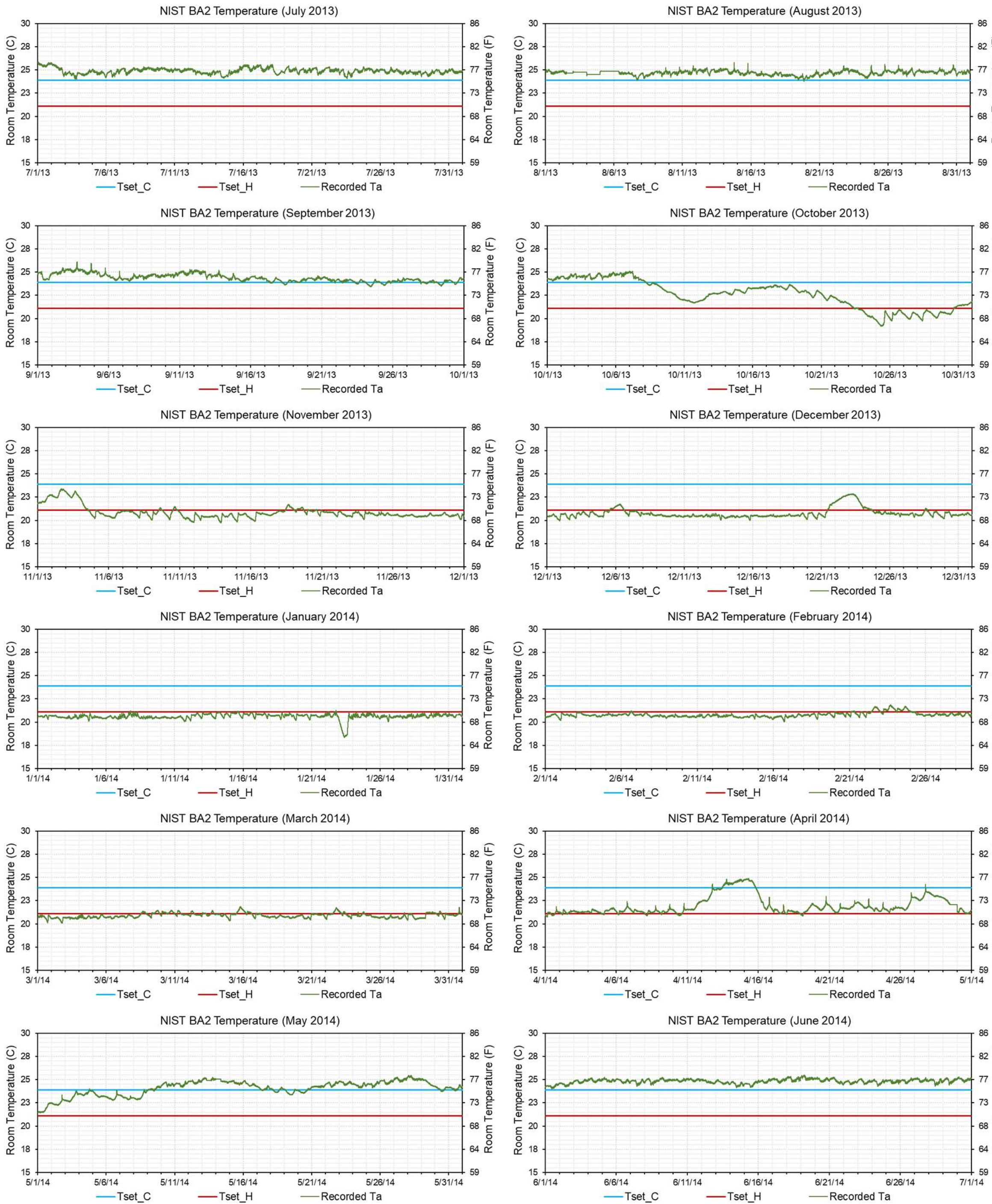

Figure C-21: Year 1 1-Min BA2 Temperature.

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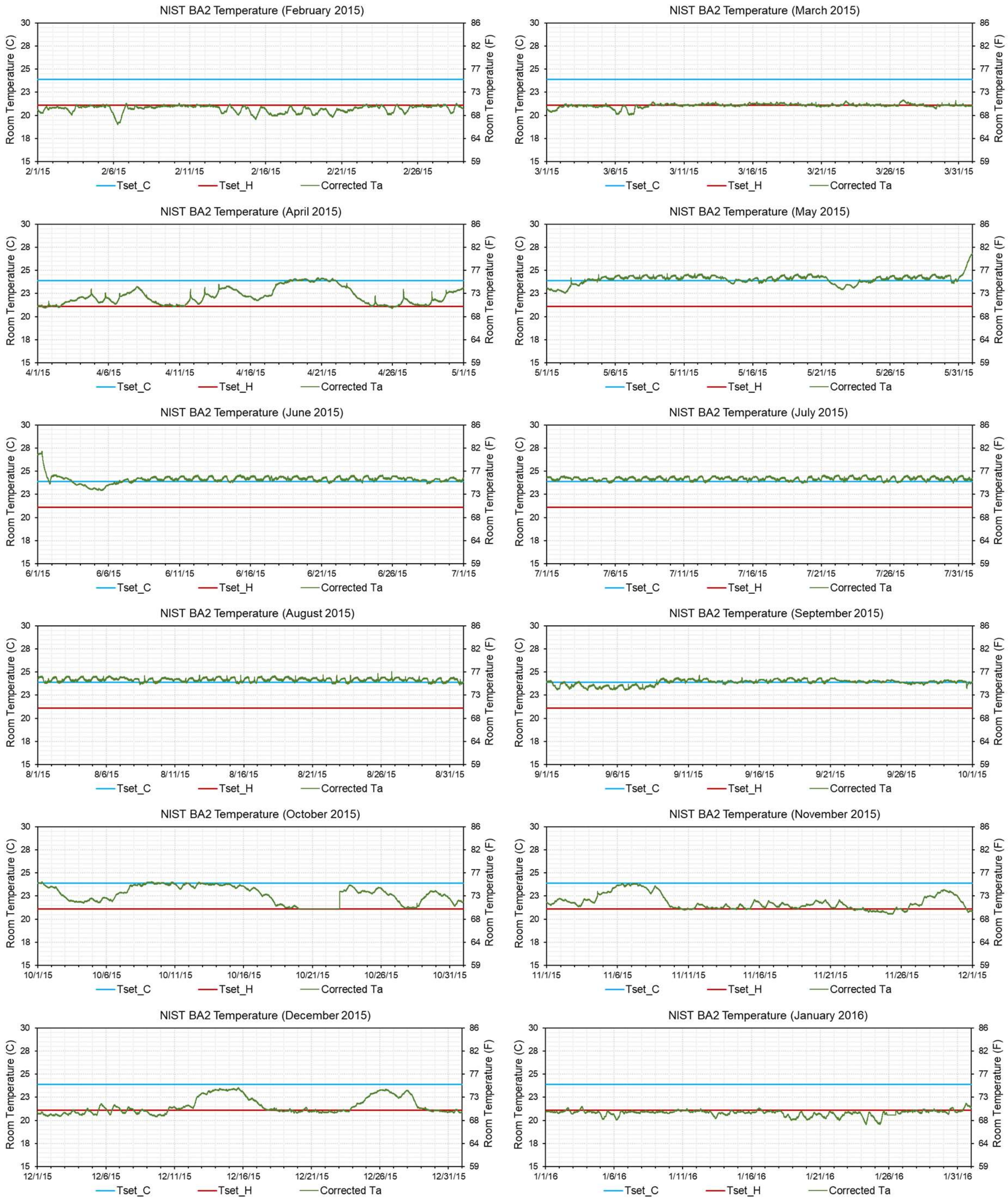

Figure C-22: Year 2 1-Min BA2 Temperature

ATTIC

- A_NW: Attic – Northwest

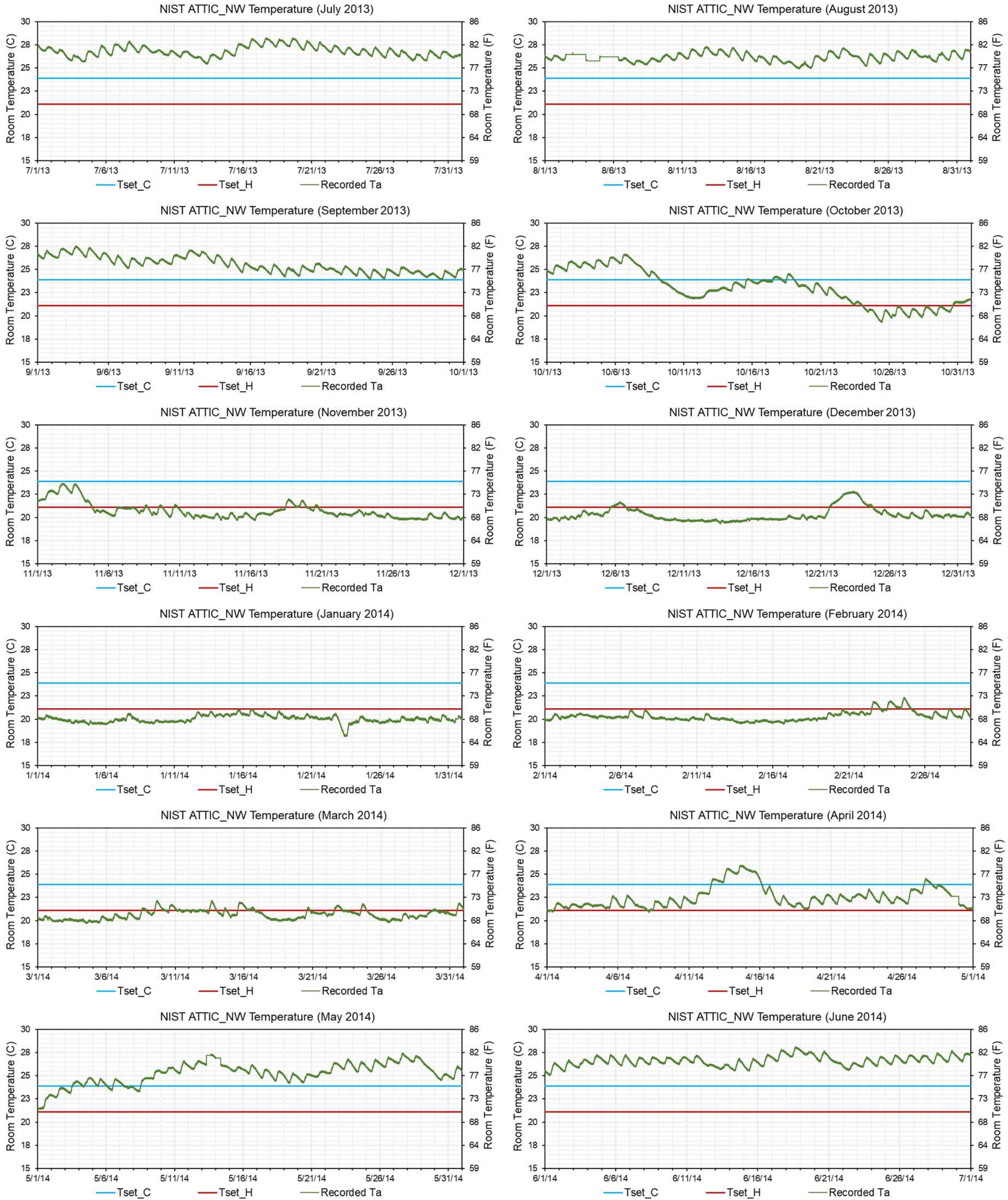

Figure C-23: Year 1 1-Min Attic Northwest Temperature.

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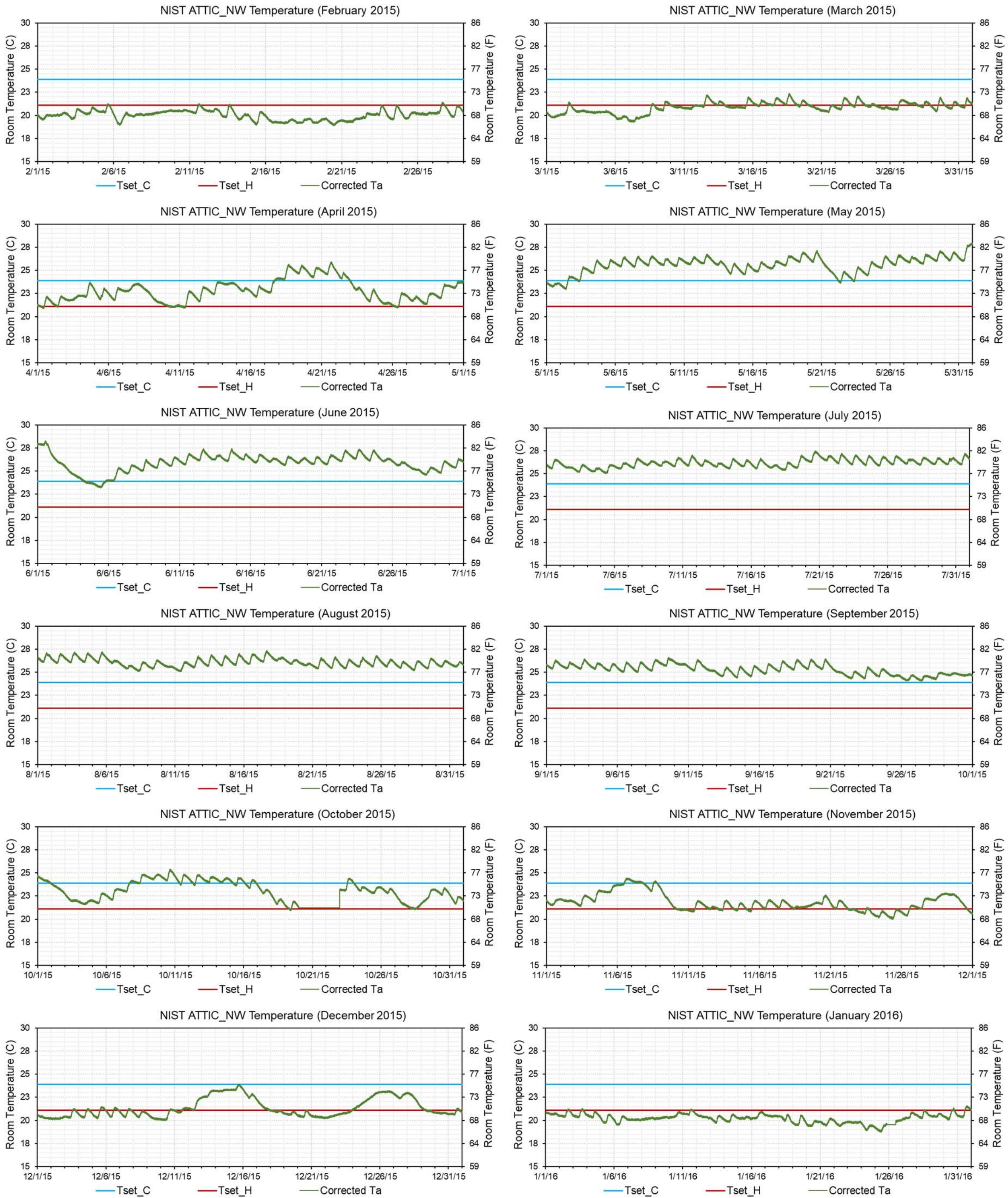

Figure C-24: Year 2 1-Min Attic Northwest Temperature.

- A_NE: Attic – Northeast

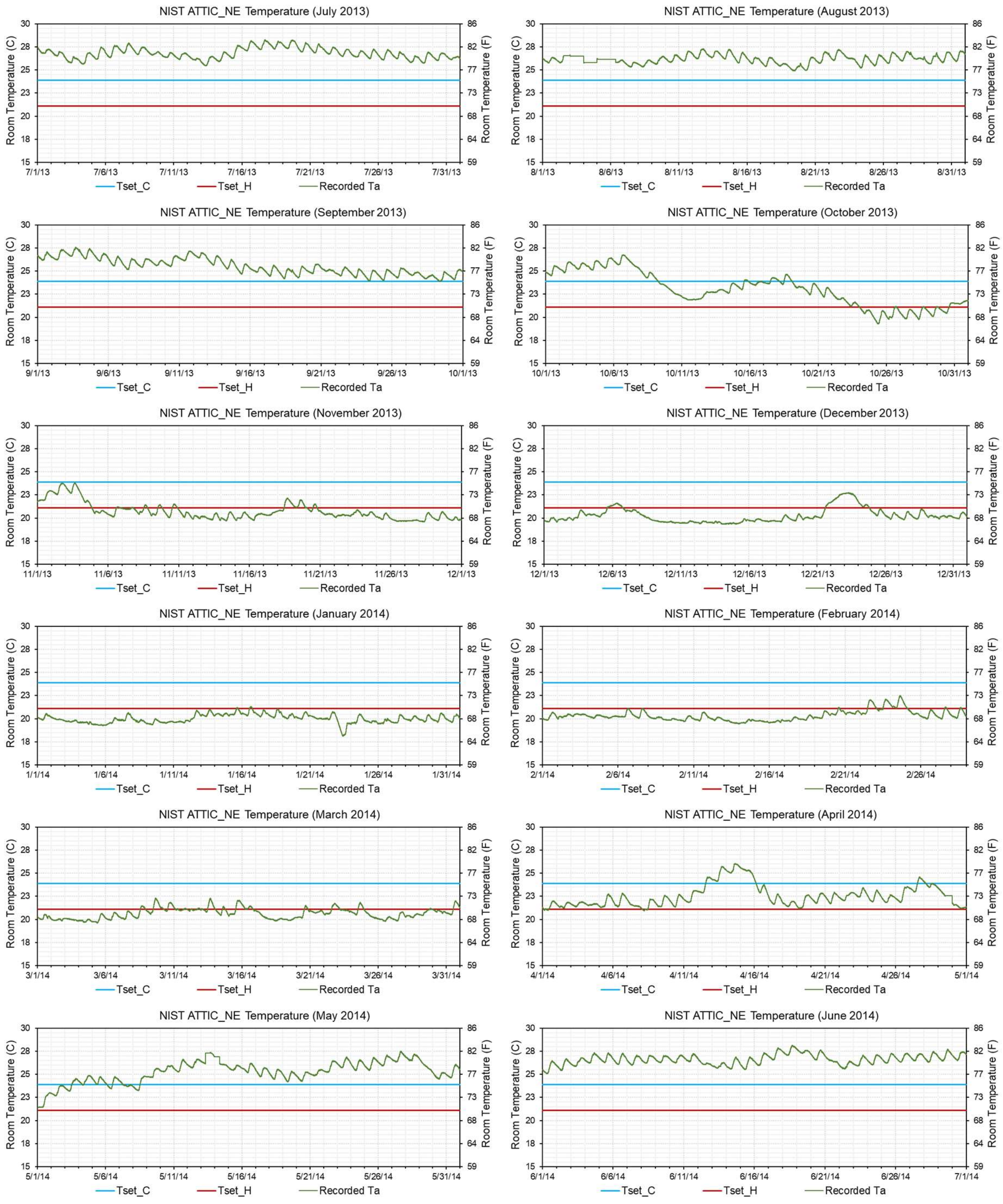

Figure C-25: Year 1 1-Min Attic Northeast Temperature.

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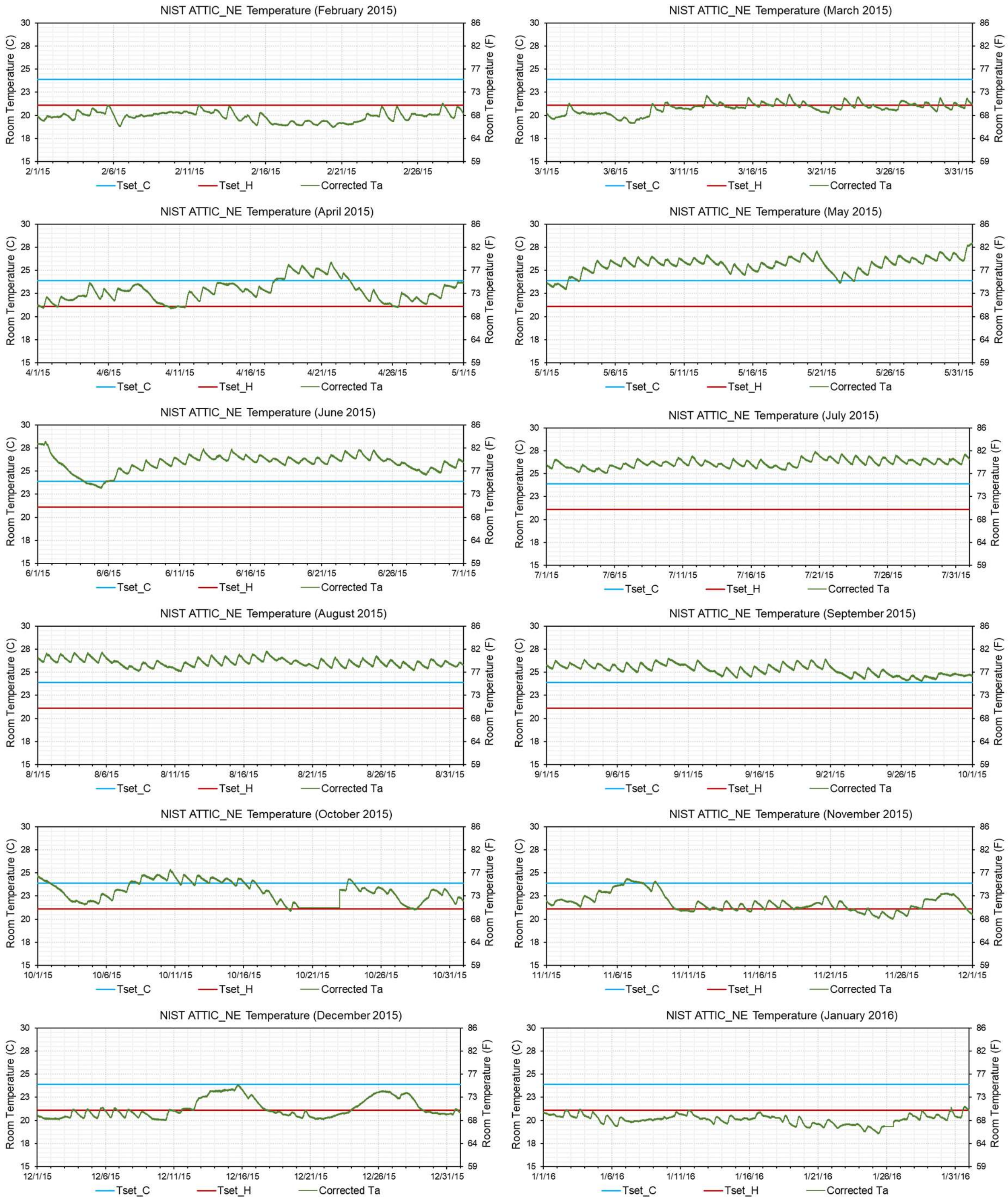

Figure C-26: Year 2 1-Min Attic Northeast Temperature.

- A_SE: Attic – Southeast

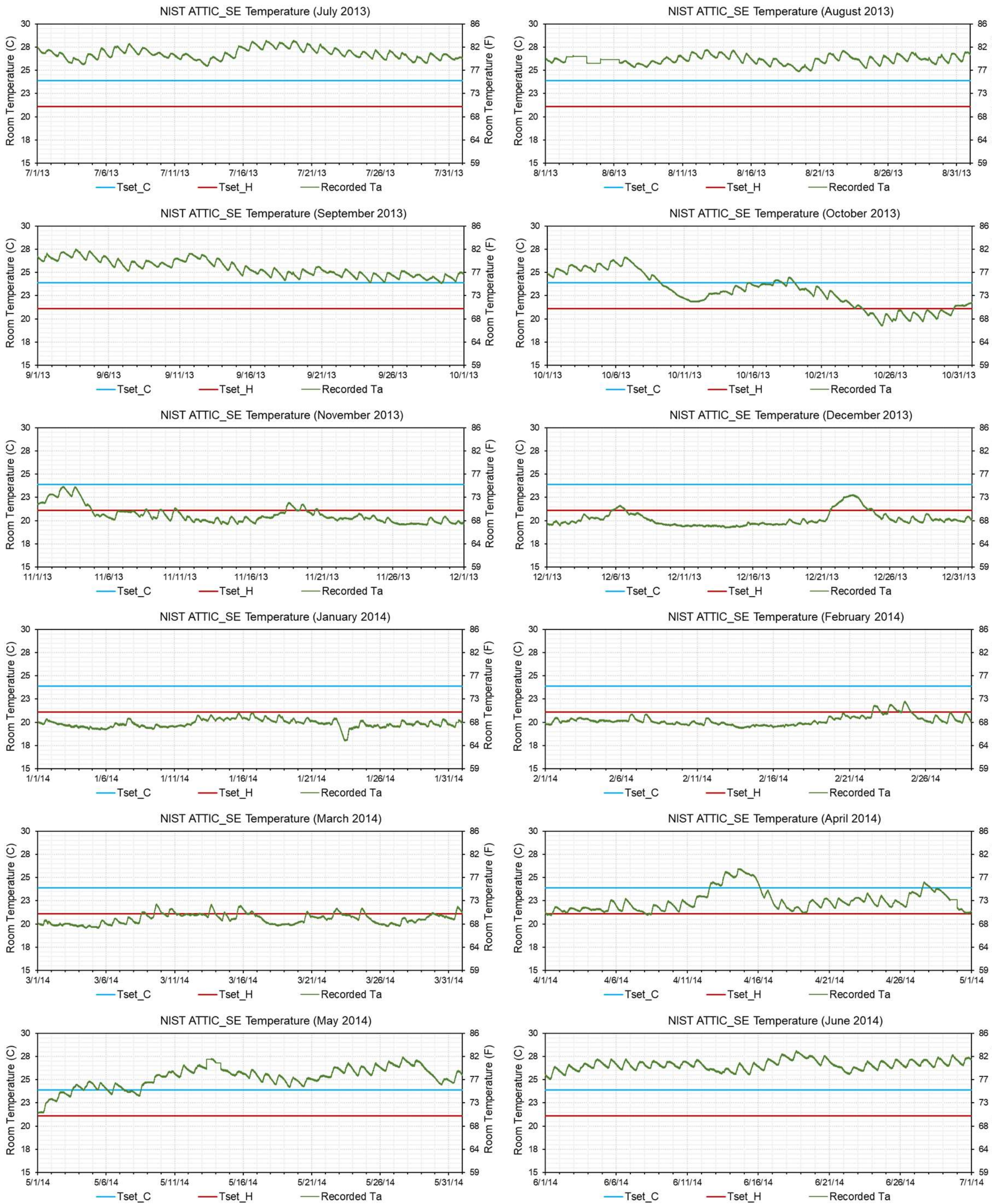

Figure C-27: Year 1 1-Min Attic Southeast Temperature.

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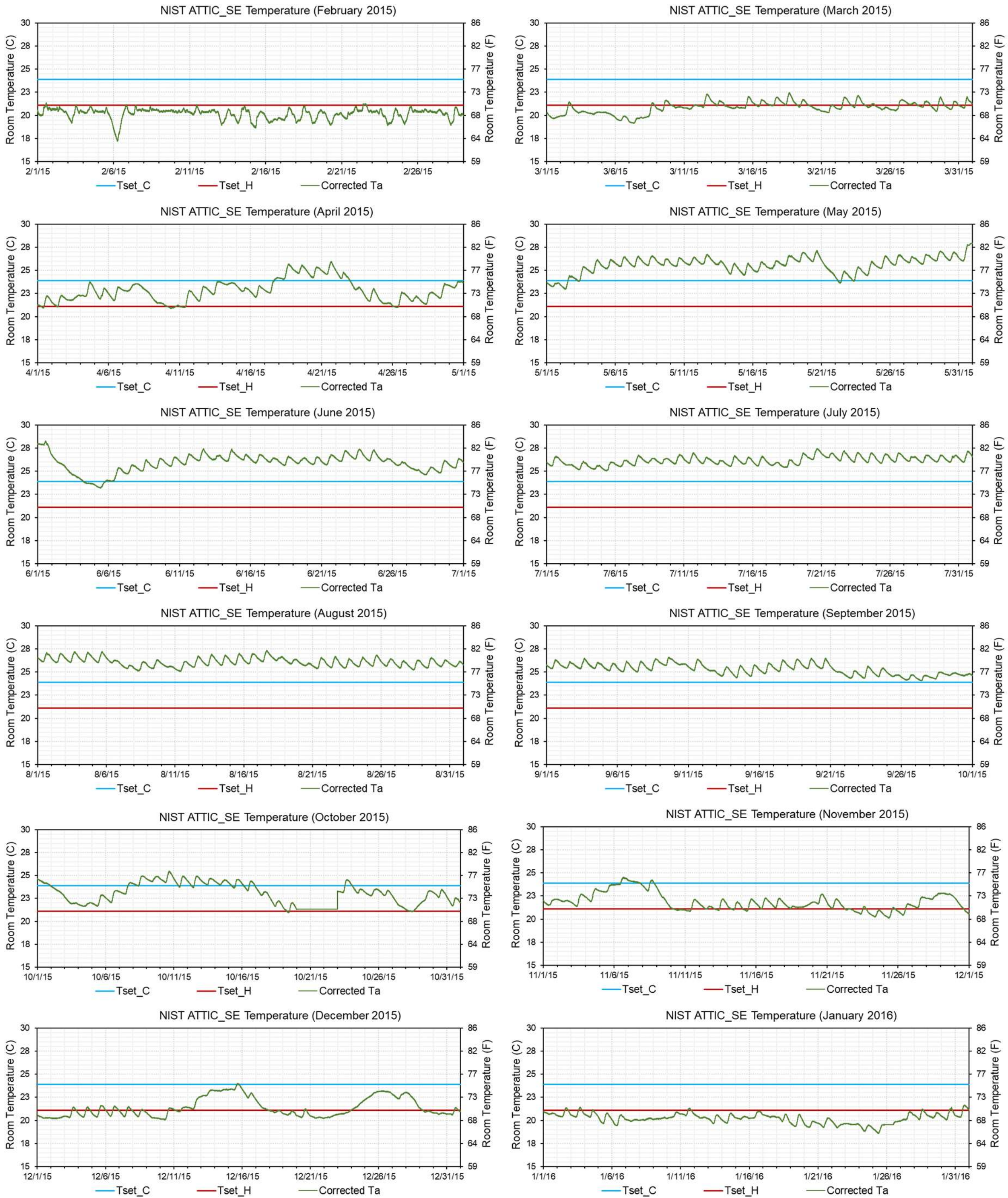

Figure C-28: Year 2 1-Min Attic Southeast Temperature.

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- A_SW: Attic – Southwest

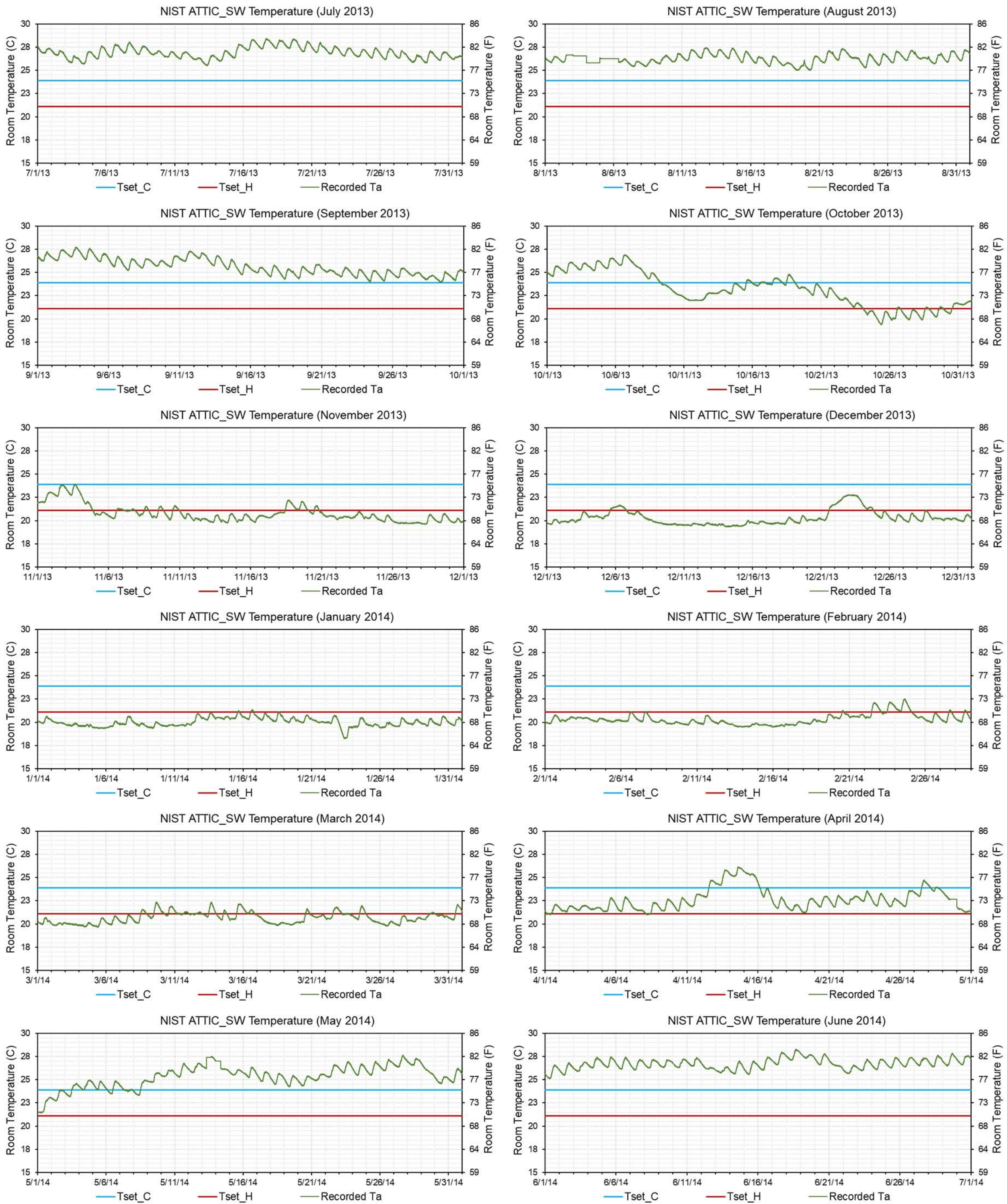

Figure C-29: Year 1 1-Min Attic Southwest Temperature.

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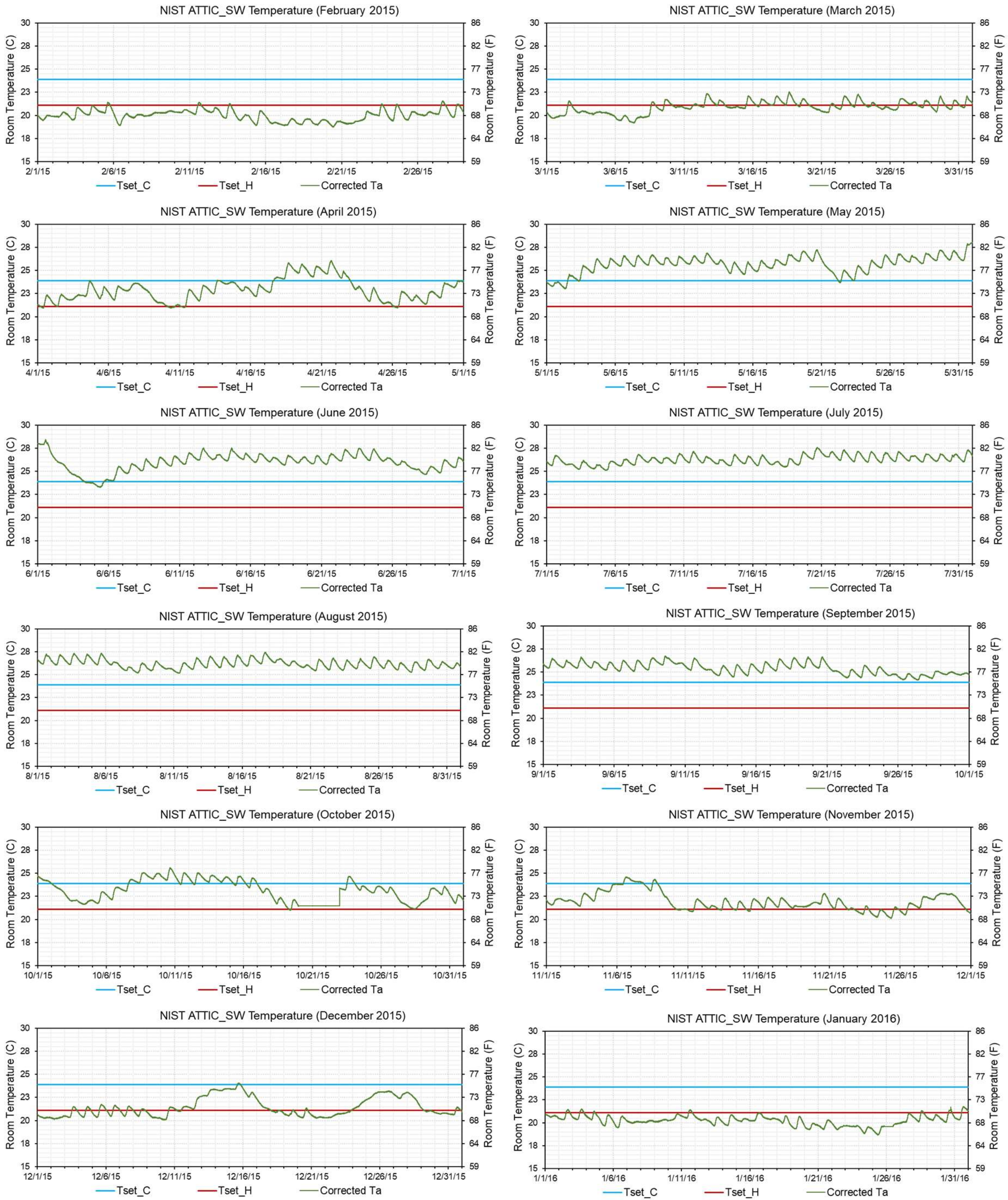

Figure C-30: Year 2 1-Min Attic Southwest Temperature.

BASEMENT

- B_NW: Basement – Northwest

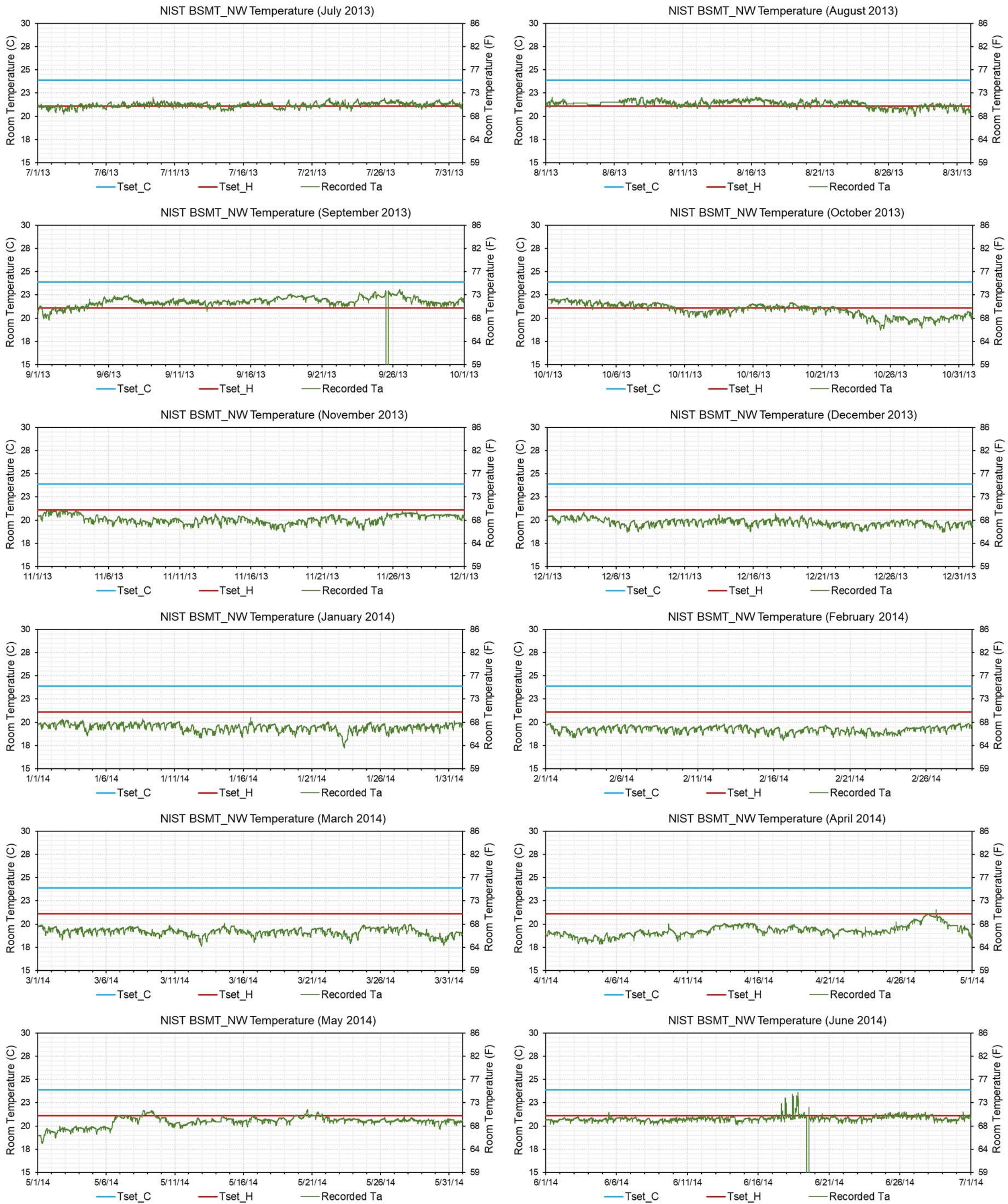

Figure C-31: Year 1 1-Min BSMT Northwest Temperature.

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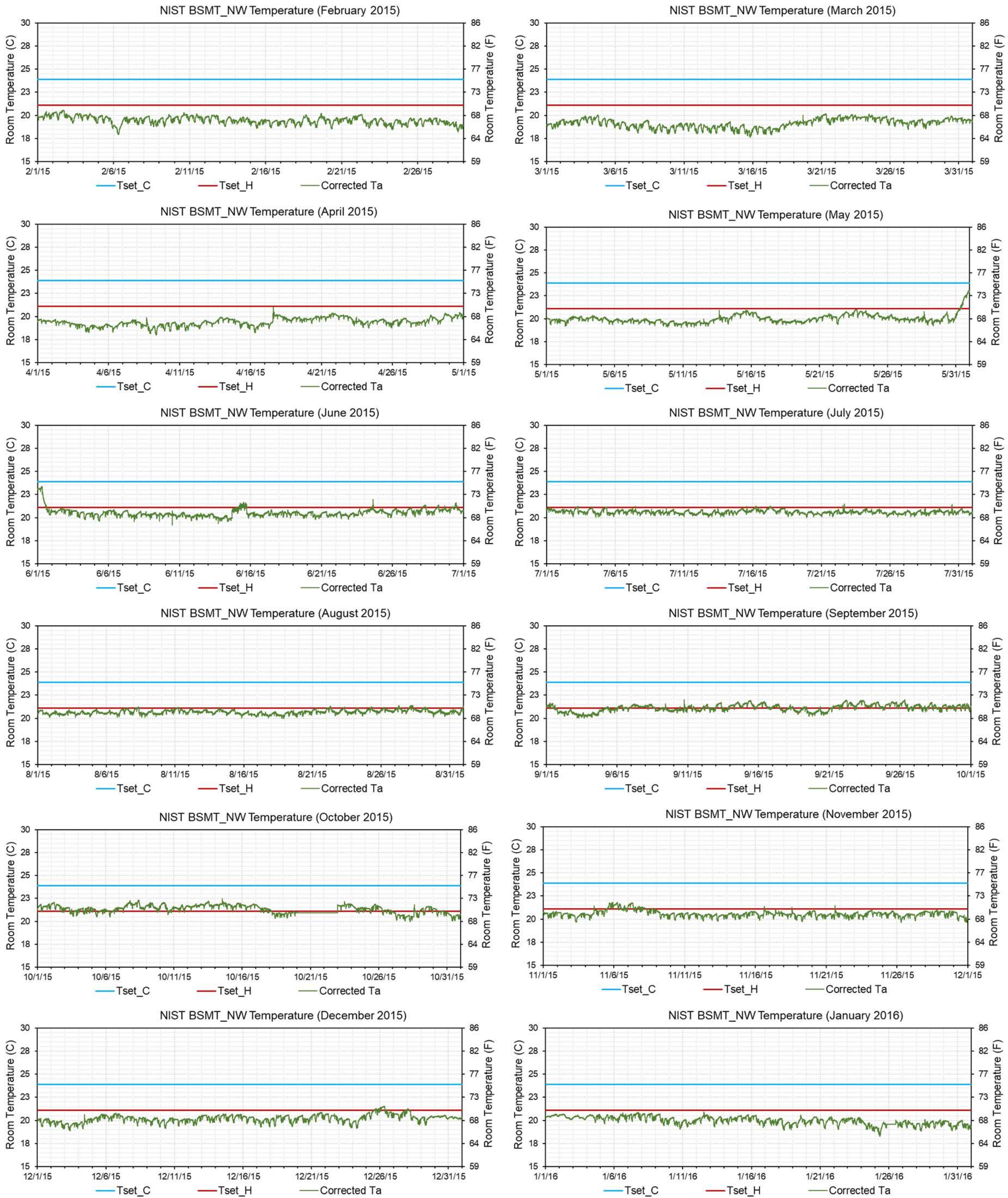

Figure C-32: Year 2 1-Min BSMT Northwest Temperature.

- B_NE: Basement – Northeast

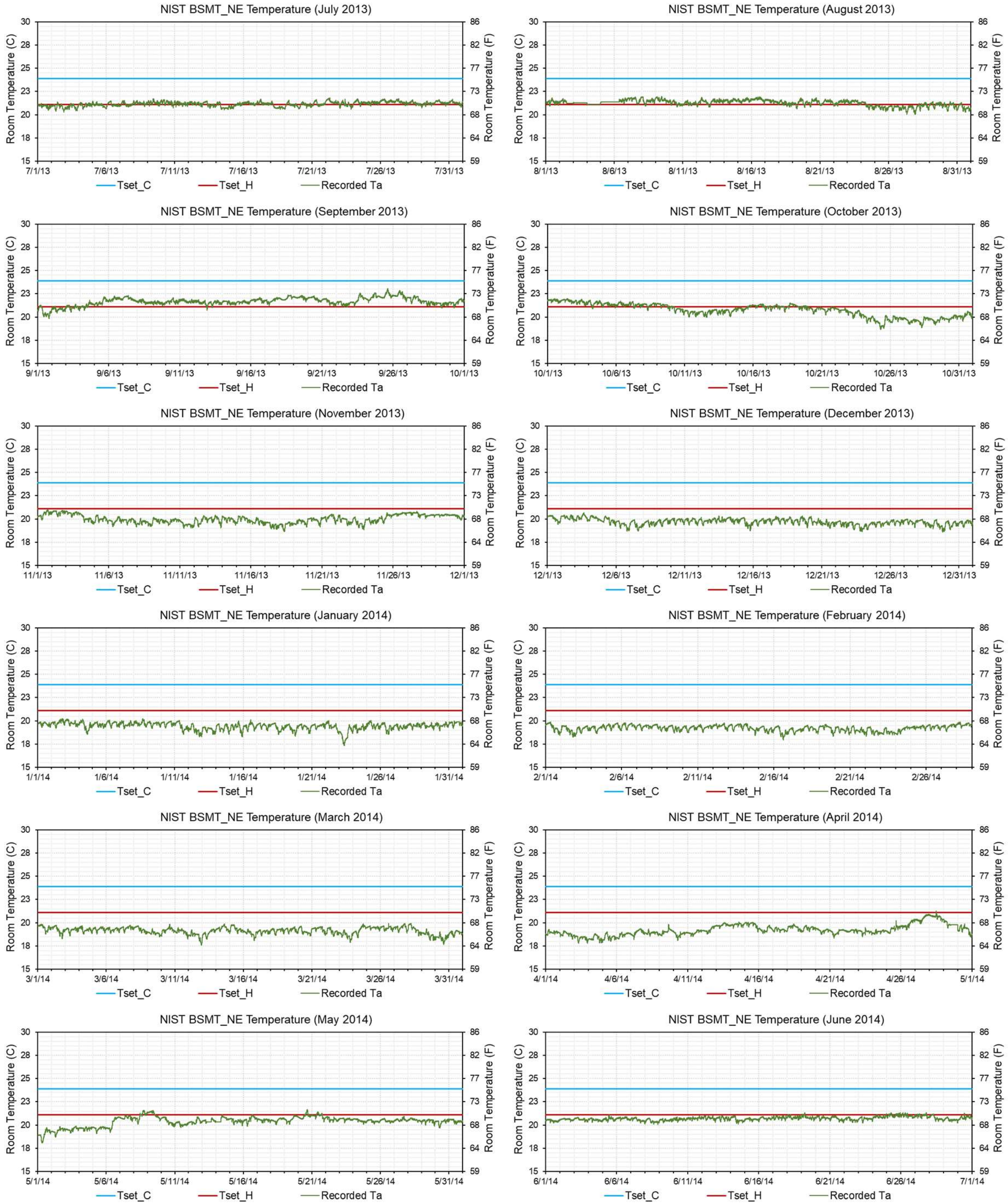

Figure C-33: Year 1 1-Min BSMT Northeast Temperature.

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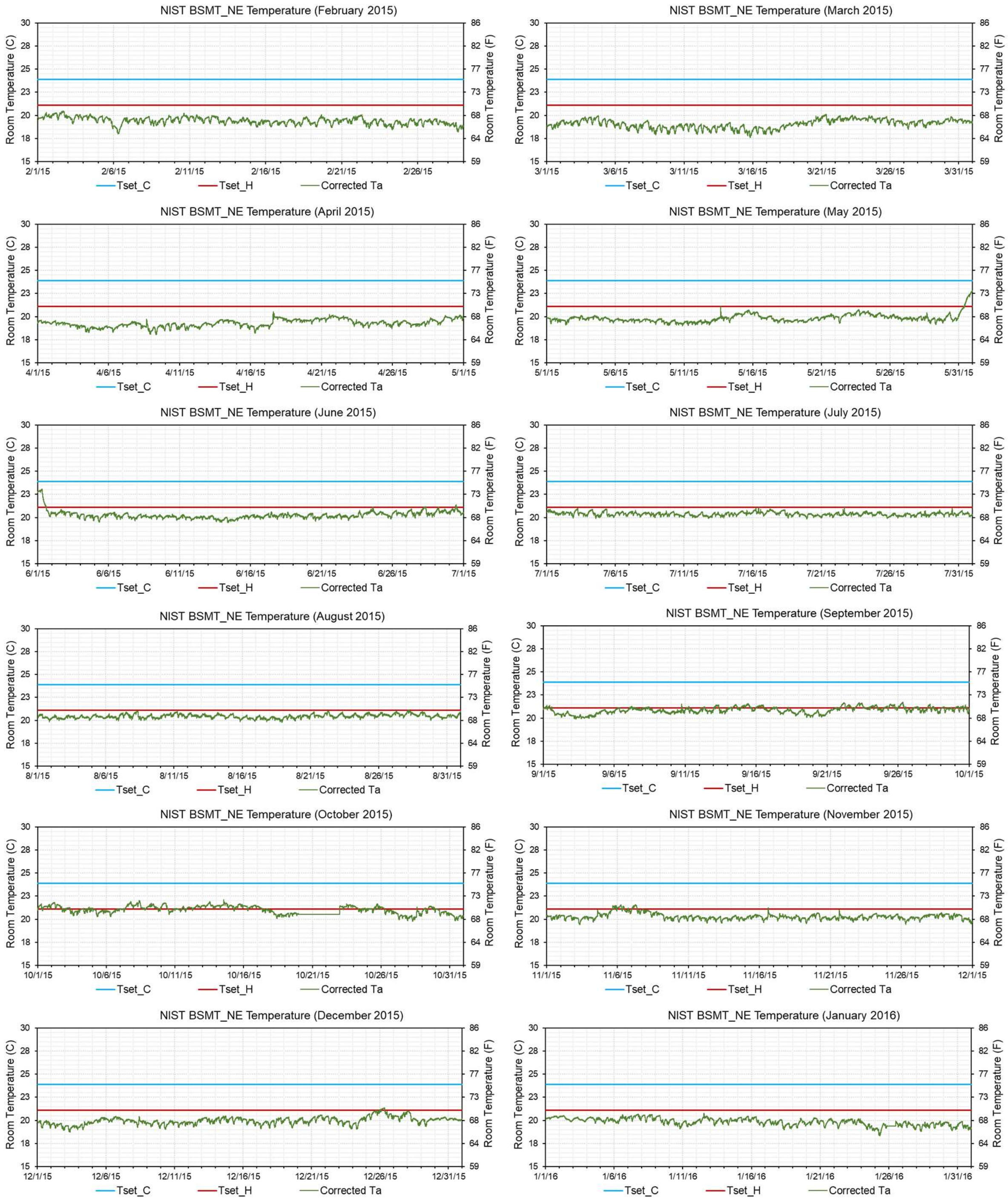

Figure C-34: Year 2 1-Min BSMT Northeast Temperature.

- B_SE: Basement – Southeast

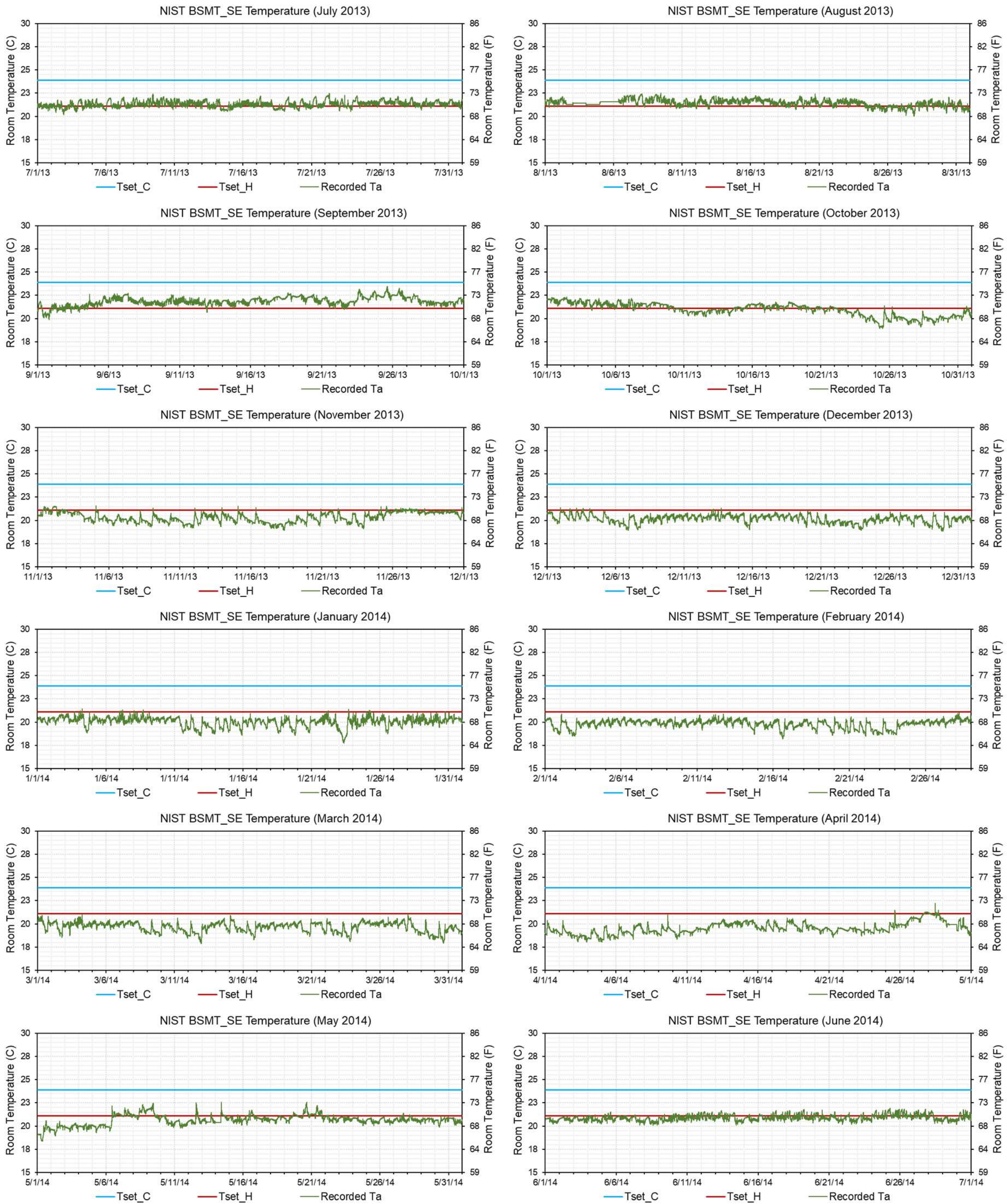

Figure C-35: Year 1 1-Min BSMT Southeast Temperature.

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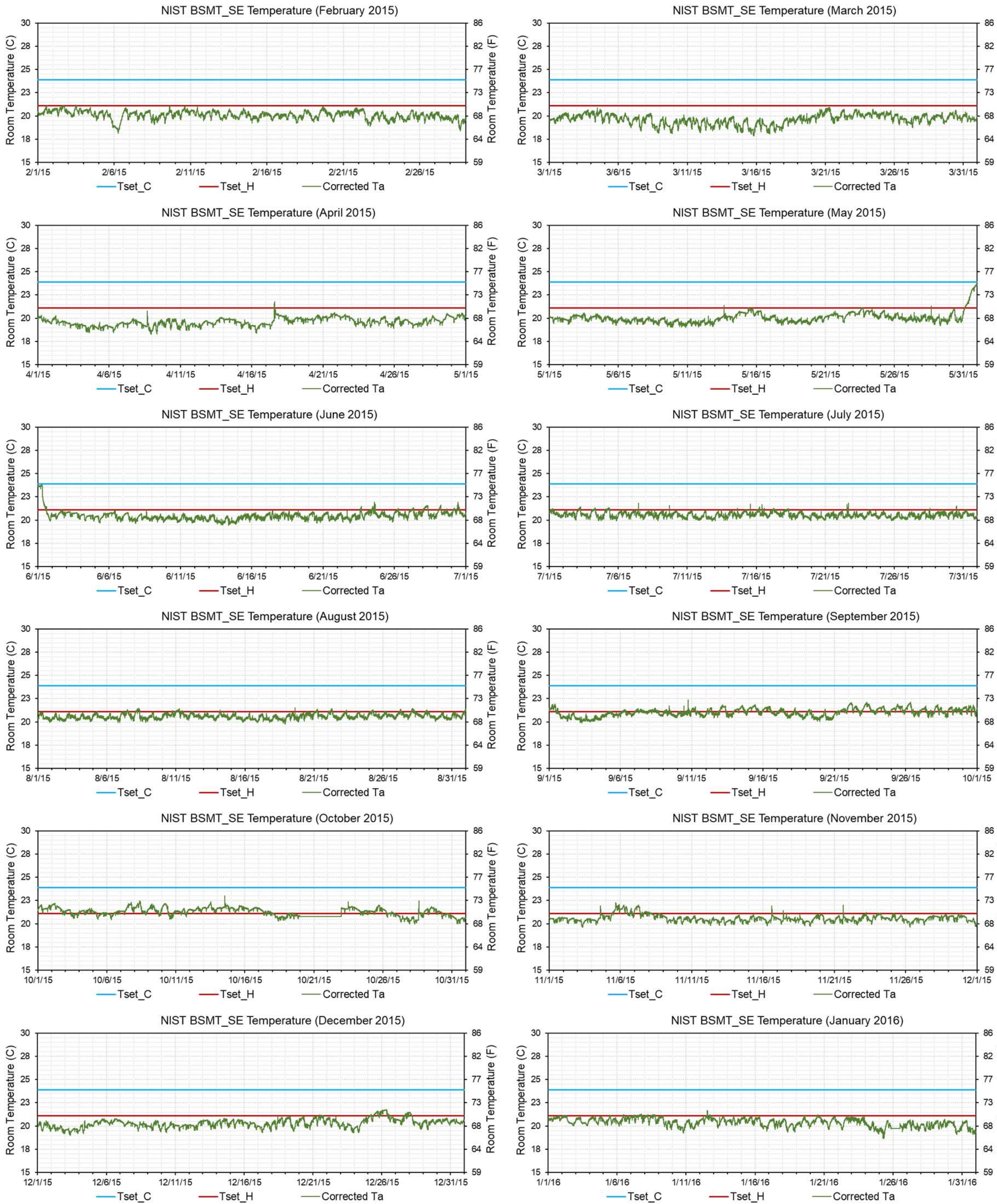

Figure C-36: Year 2 1-Min BSMT Southeast Temperature.

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- B_SW: Basement – Southwest

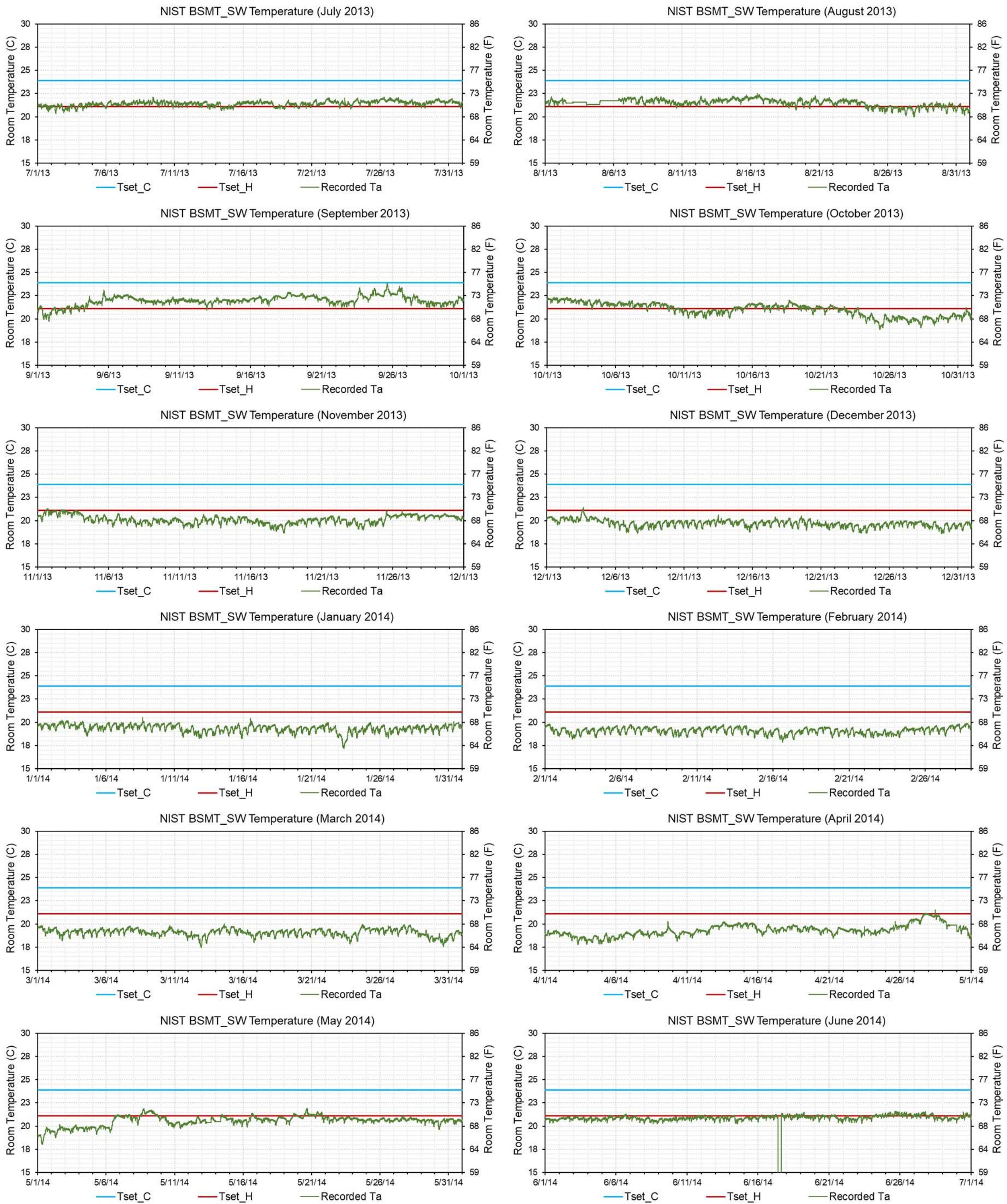

Figure C-37: Year 1 1-Min BSMT Southwest Temperature.

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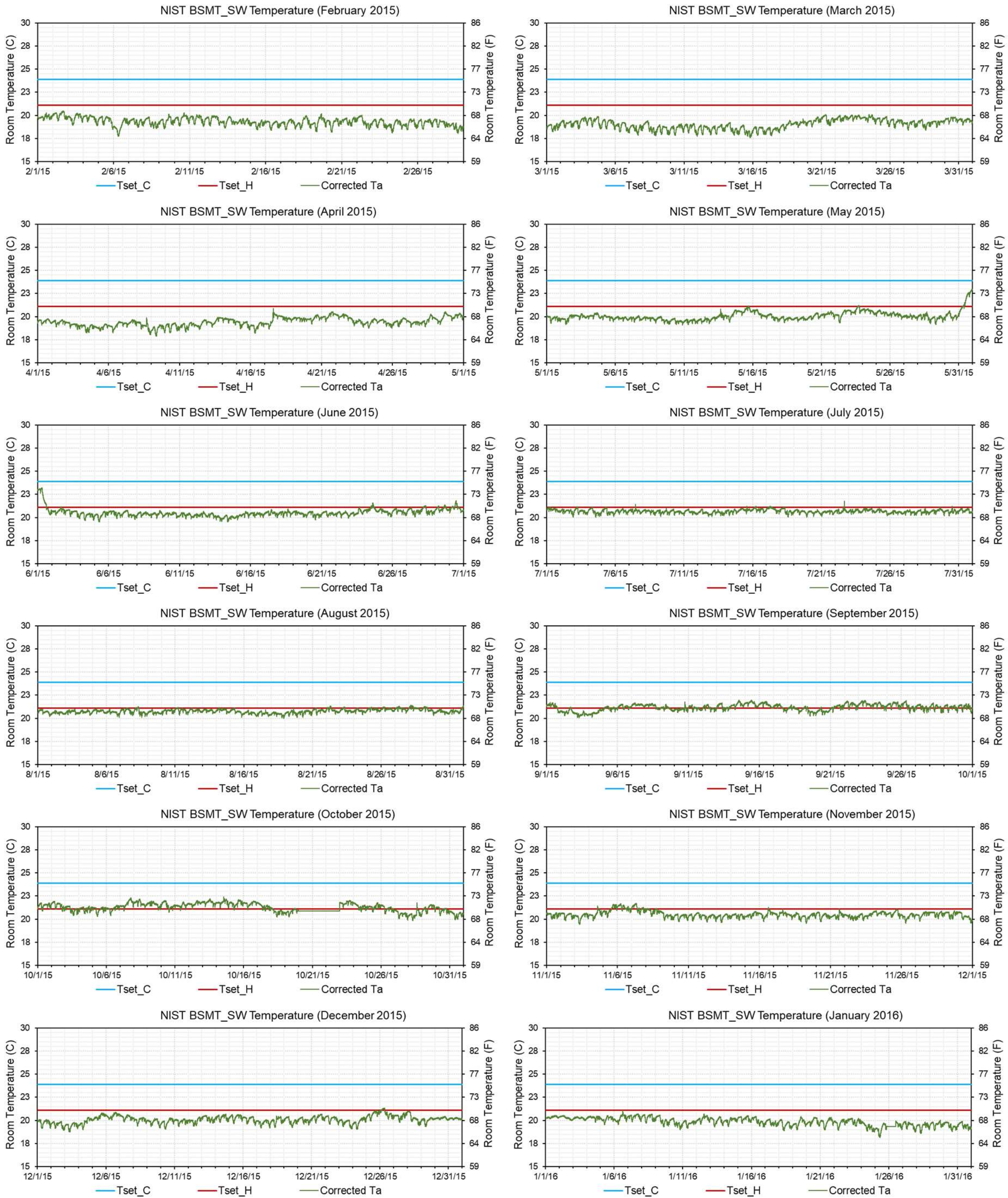

Figure C-38: Year 2 1-Min BSMT Southwest Temperature.

ENTRY HALLWAY (EH)

- EH Lowest: Entry Hallway Lowest at 0.6m (24 in.)

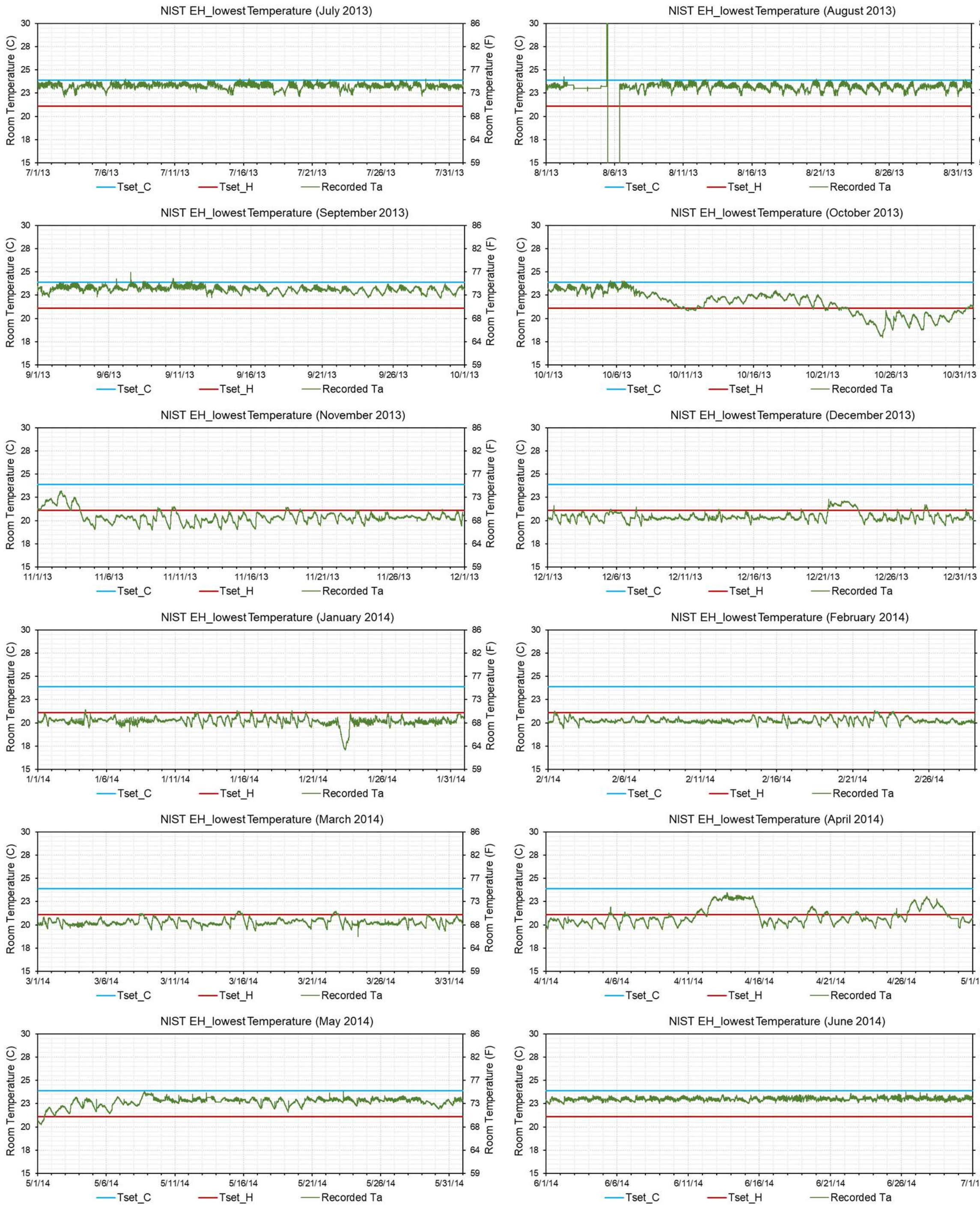

Figure C-39: Year 1 1-Min EH Lowest Temperature.

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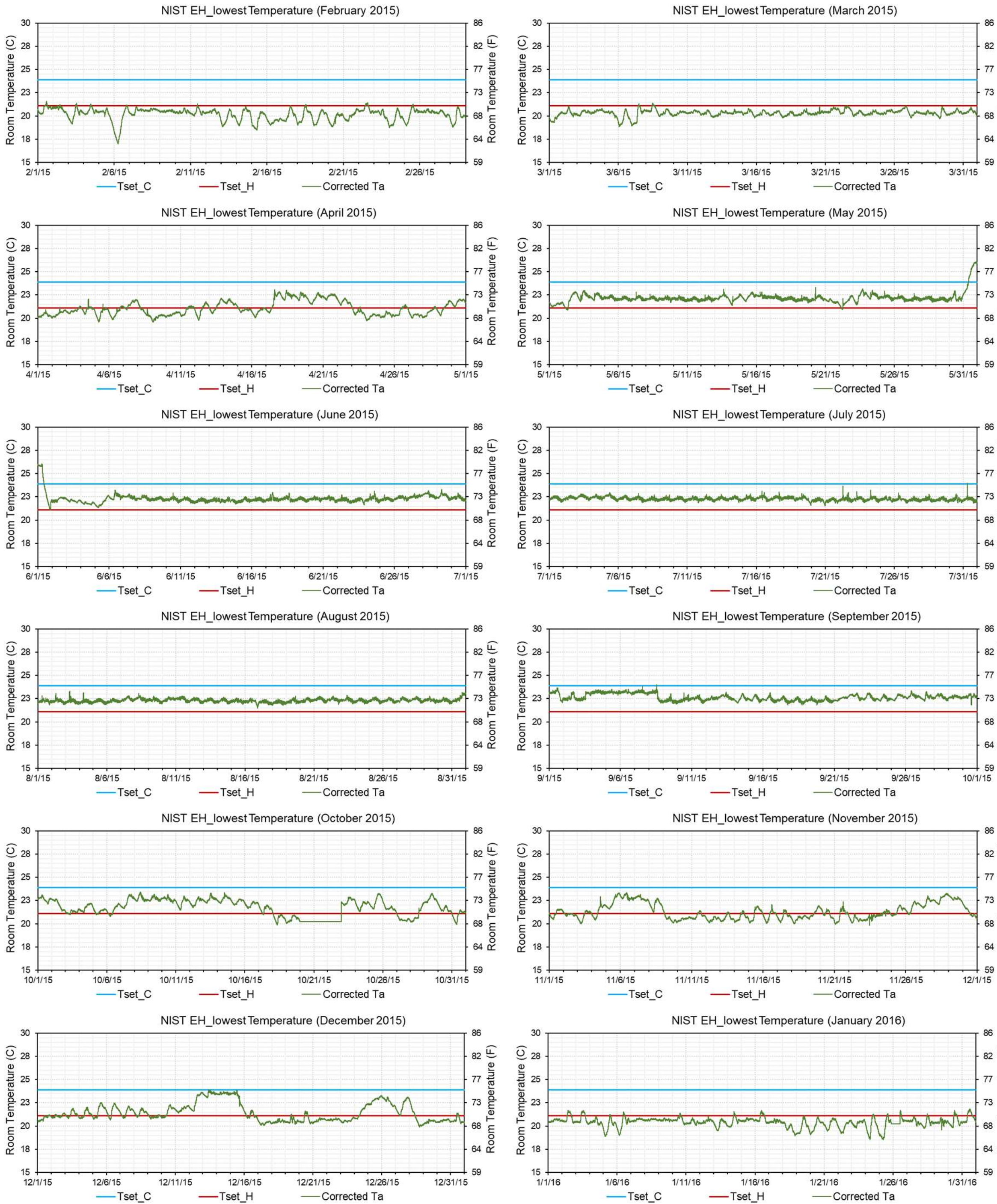

Figure C-40: Year 2 1-Min EH Lowest Temperature.

- EH LowerMid: Entry Hallway Lower Middle at 1.8m (71 in.)

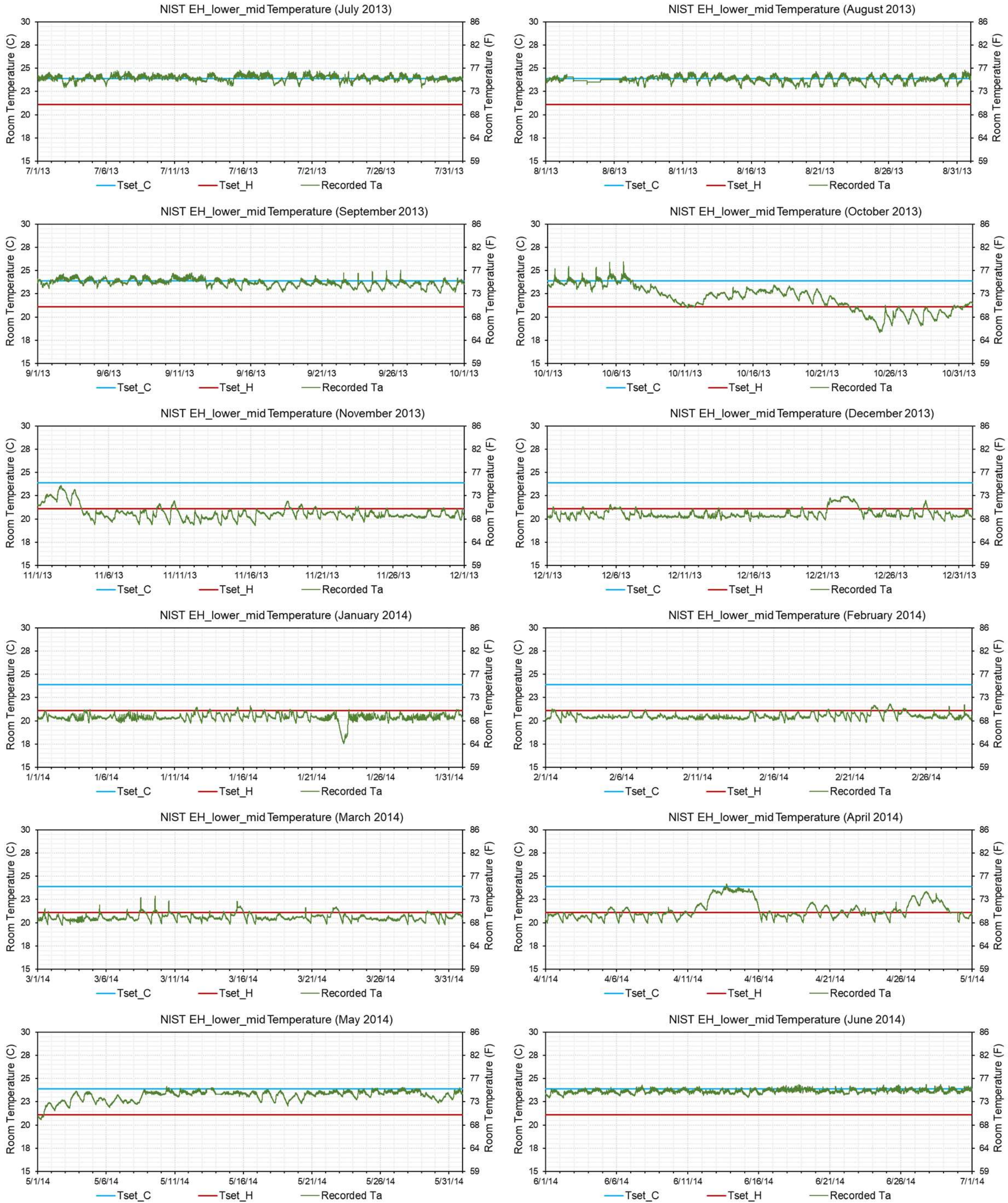

Figure C-41: Year 1 1-Min EH Lower Middle Temperature.

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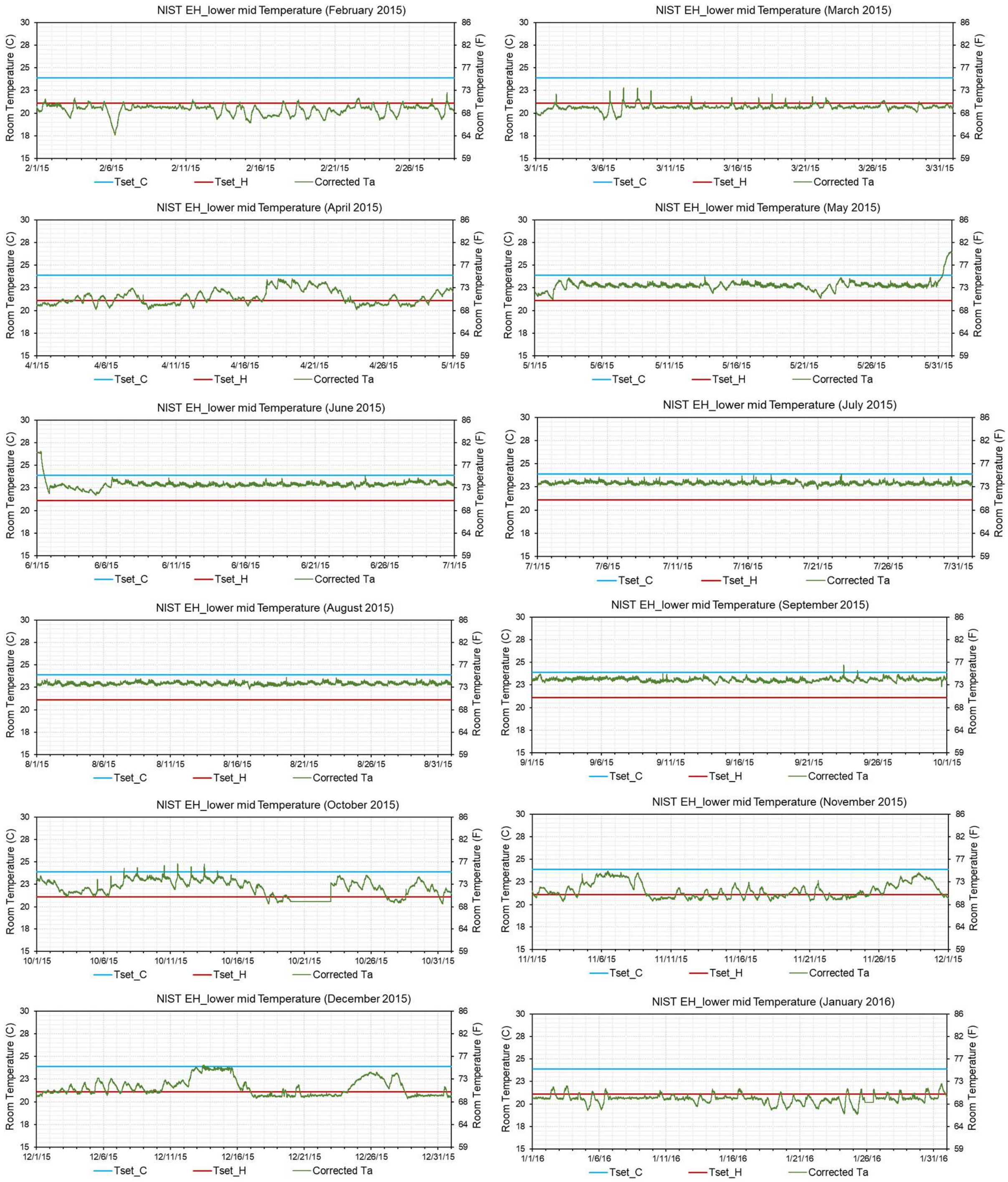

Figure C-42: Year 2 1-Min EH Lower Middle Temperature.

- EH Middle: Entry Hallway Middle at 3.0 m (118 in.)

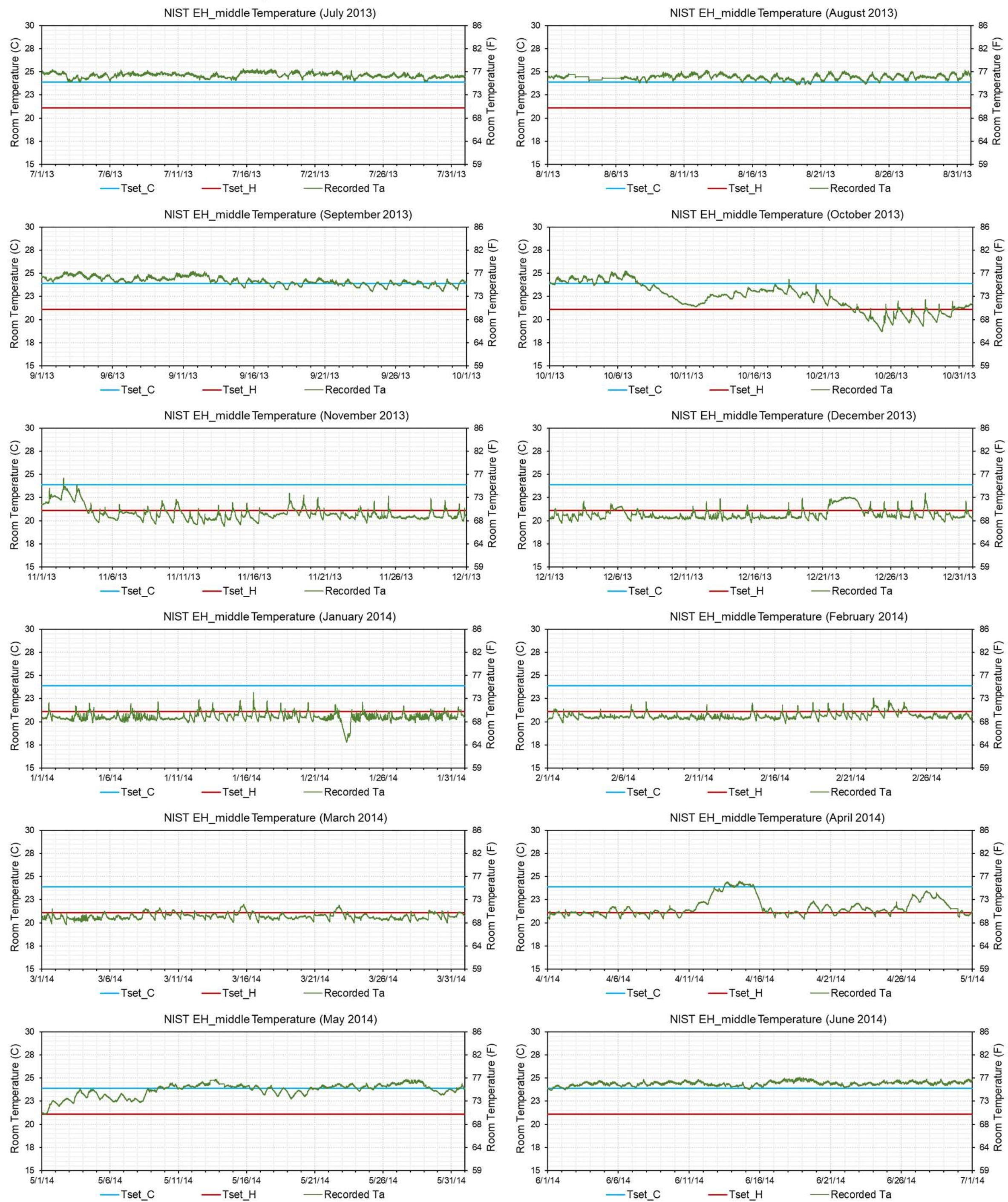

Figure C-43: Year 1 1-Min EH Middle Temperature.

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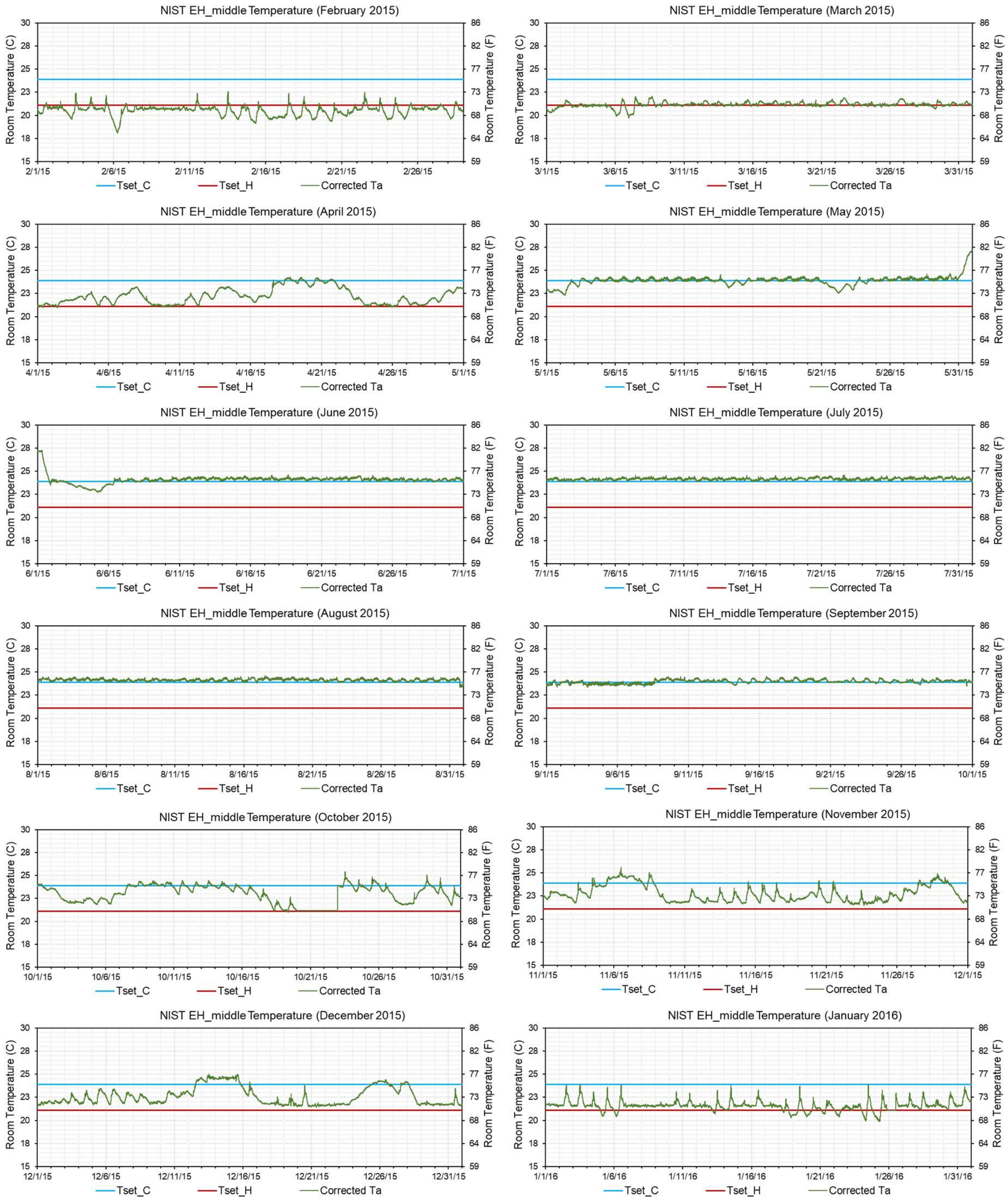

Figure C-44: Year 2 1-Min EH Middle Temperature.

- EH UpperMid: Entry Hallway Upper Middle at 4.3 m (169 in.)

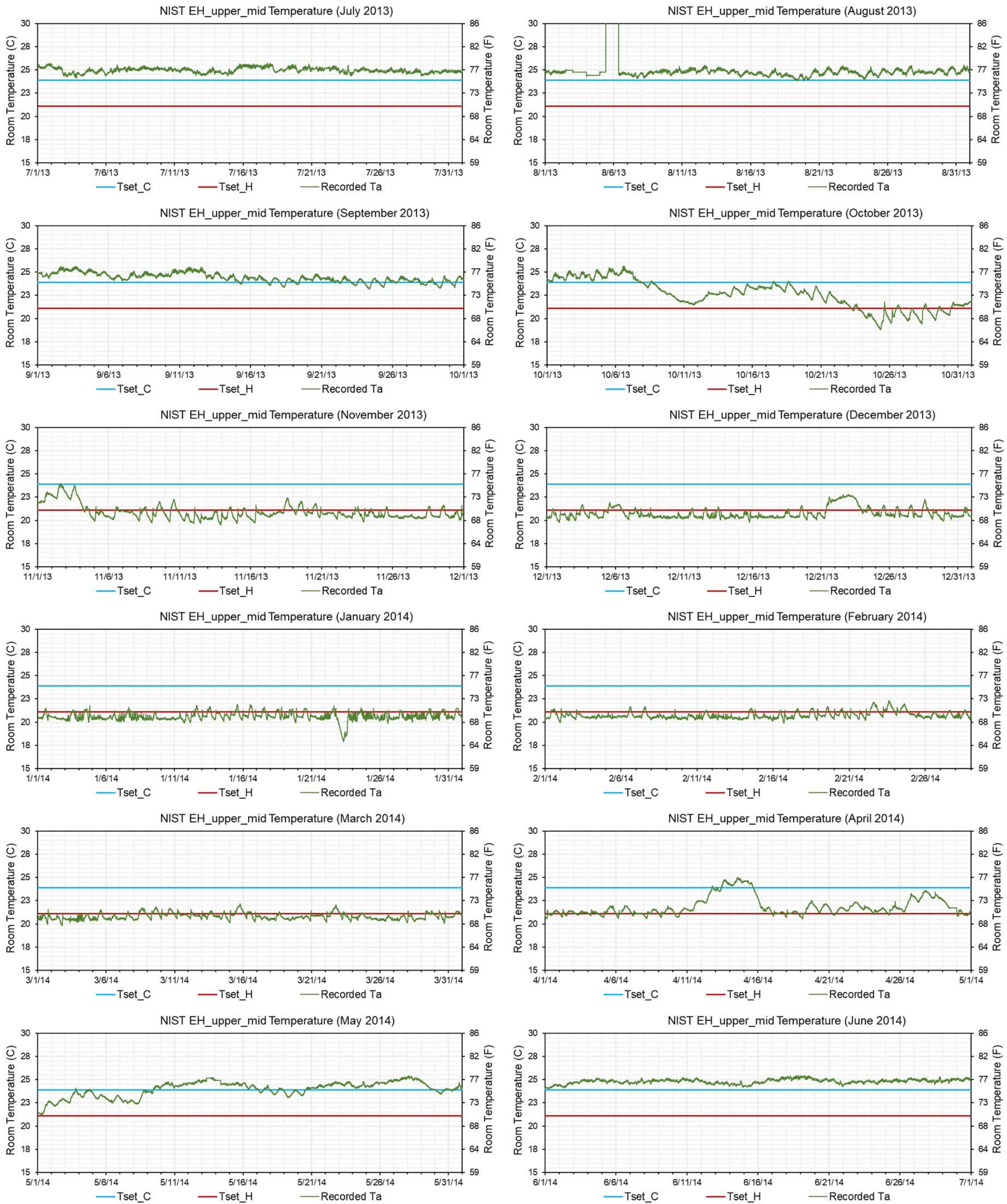

Figure C-45: Year 1 1-Min EH Upper Middle Temperature.

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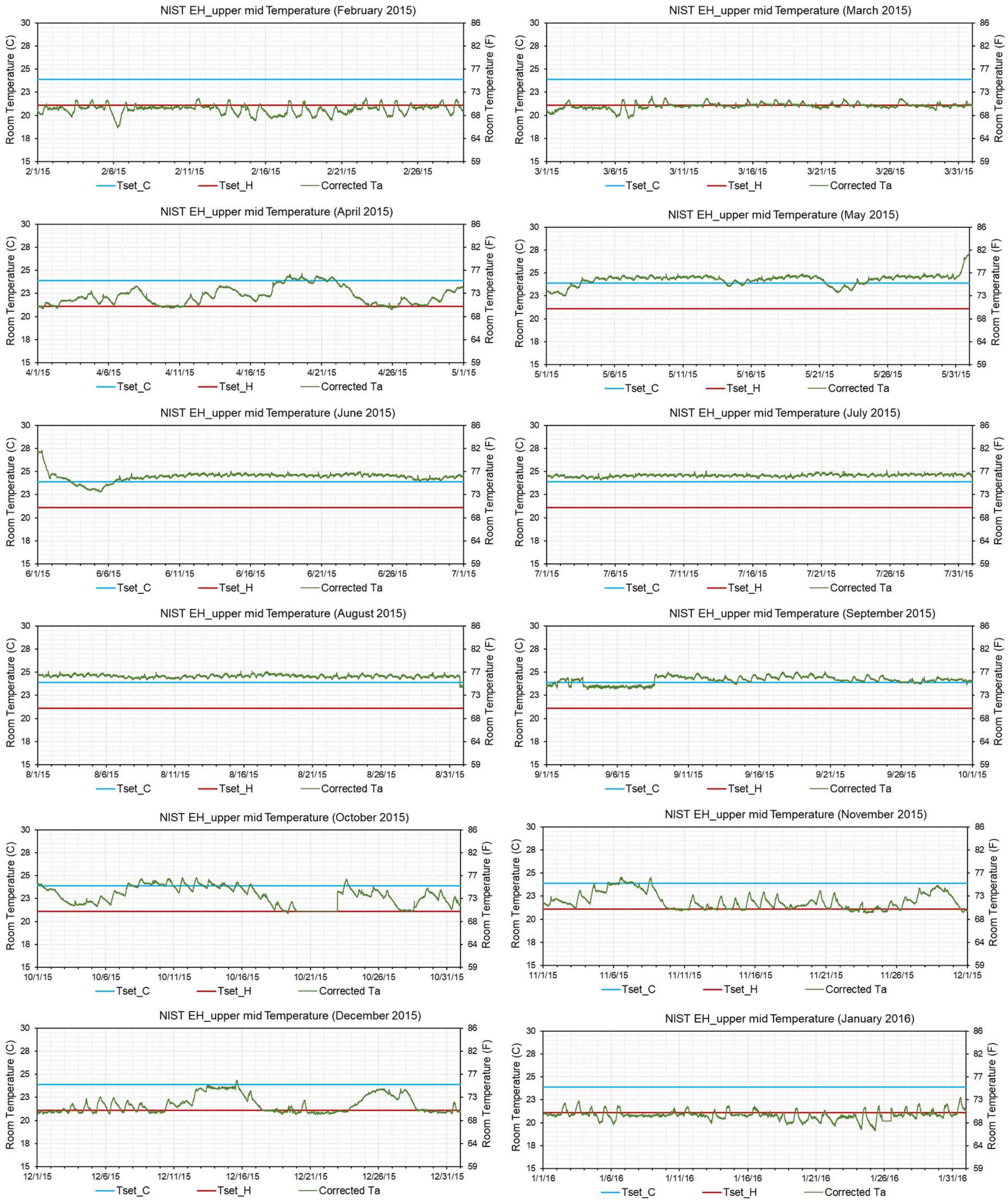

Figure C-46: Year 2 1-Min EH Upper Middle Temperature.

- EH Upper: Entry Hallway Upper at 5.5 m (217 in.)

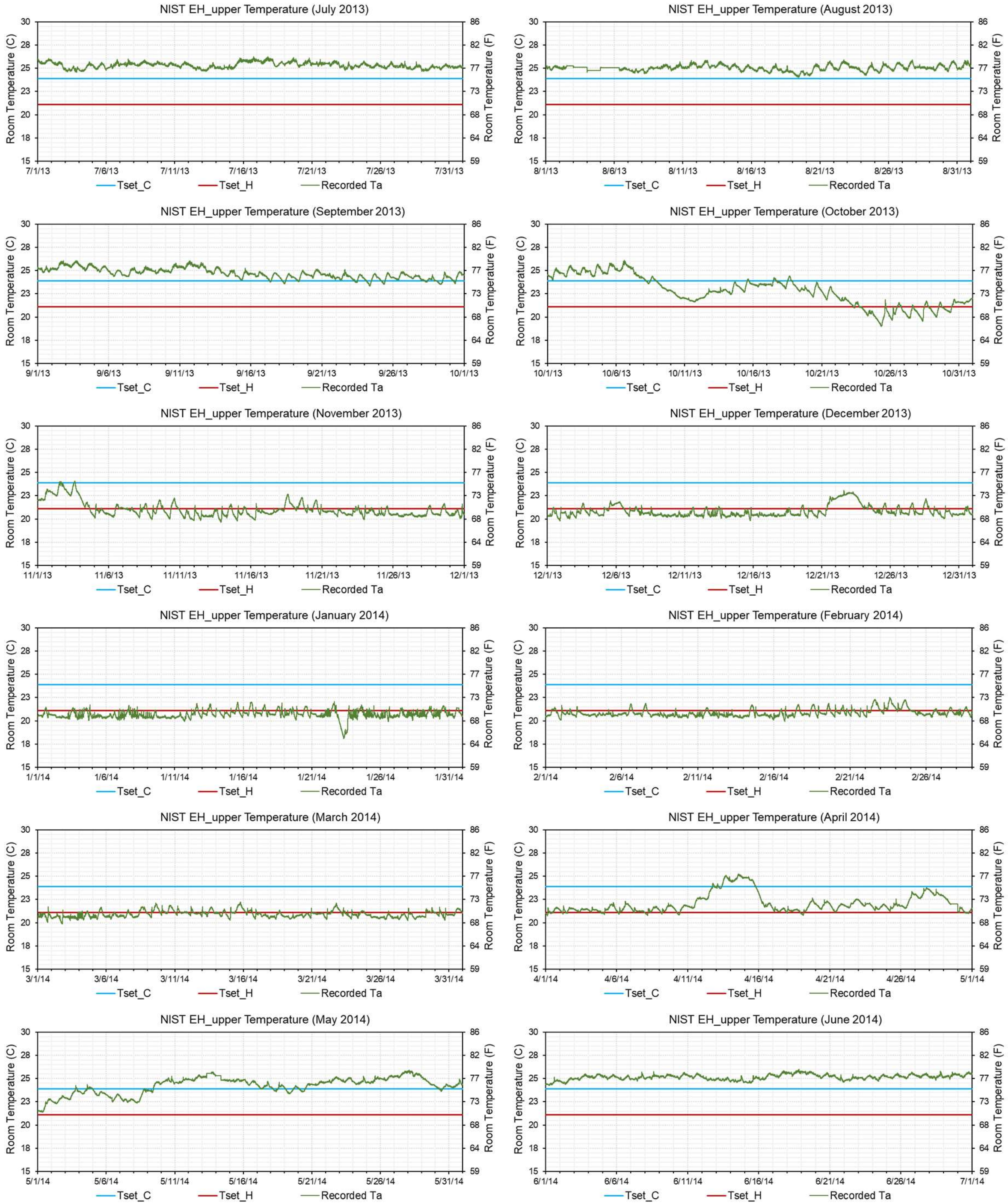

Figure C-47: Year 1 1-Min EH Upper Temperature.

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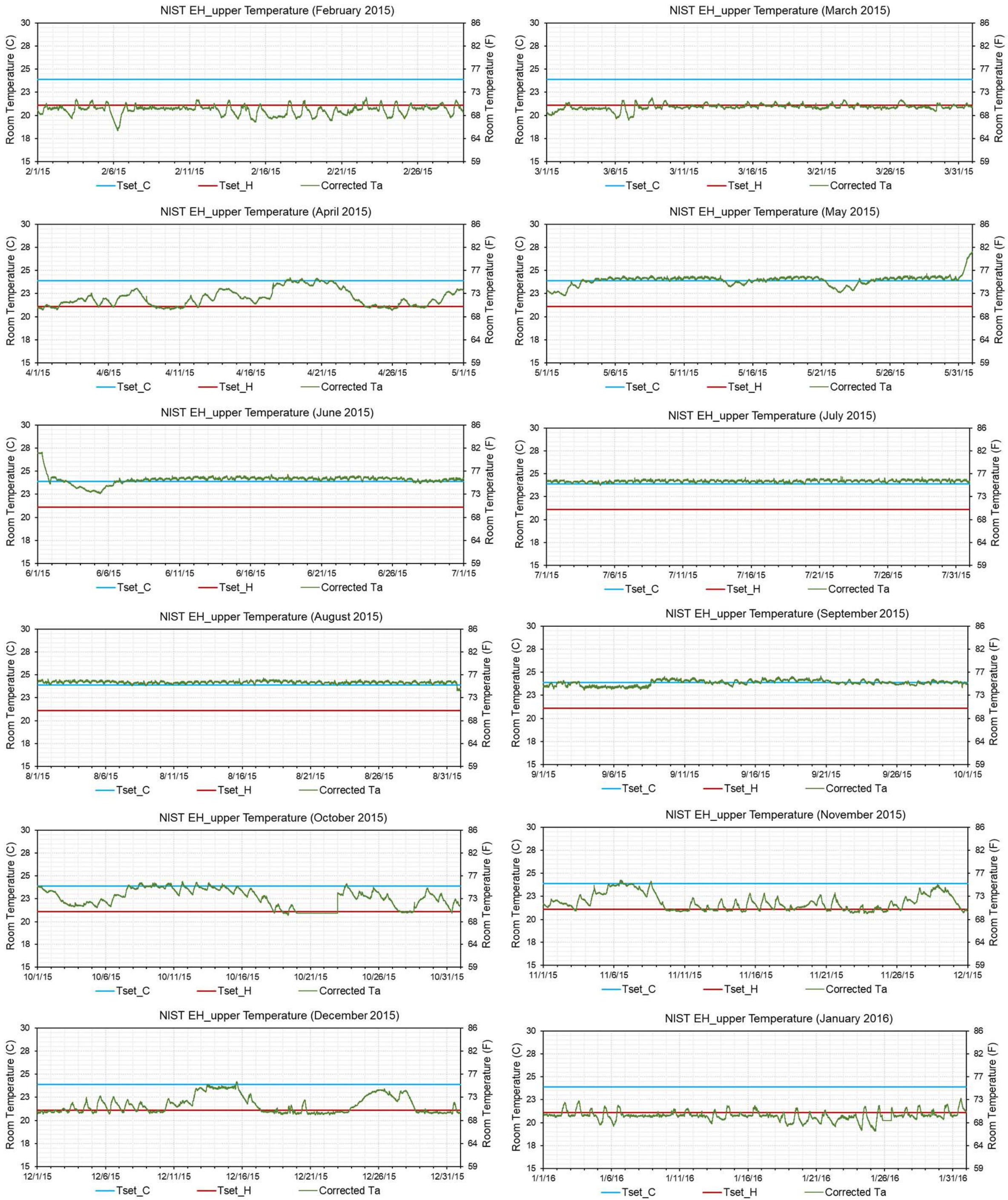

Figure C-48: Year 2 1-Min EH Upper Temperature.

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APPENDIX C-2: 1-MIN GLOBE TEMPERATURE BY ROOM
ROOMS ON THE FIRST FLOOR

- LR: Living Room

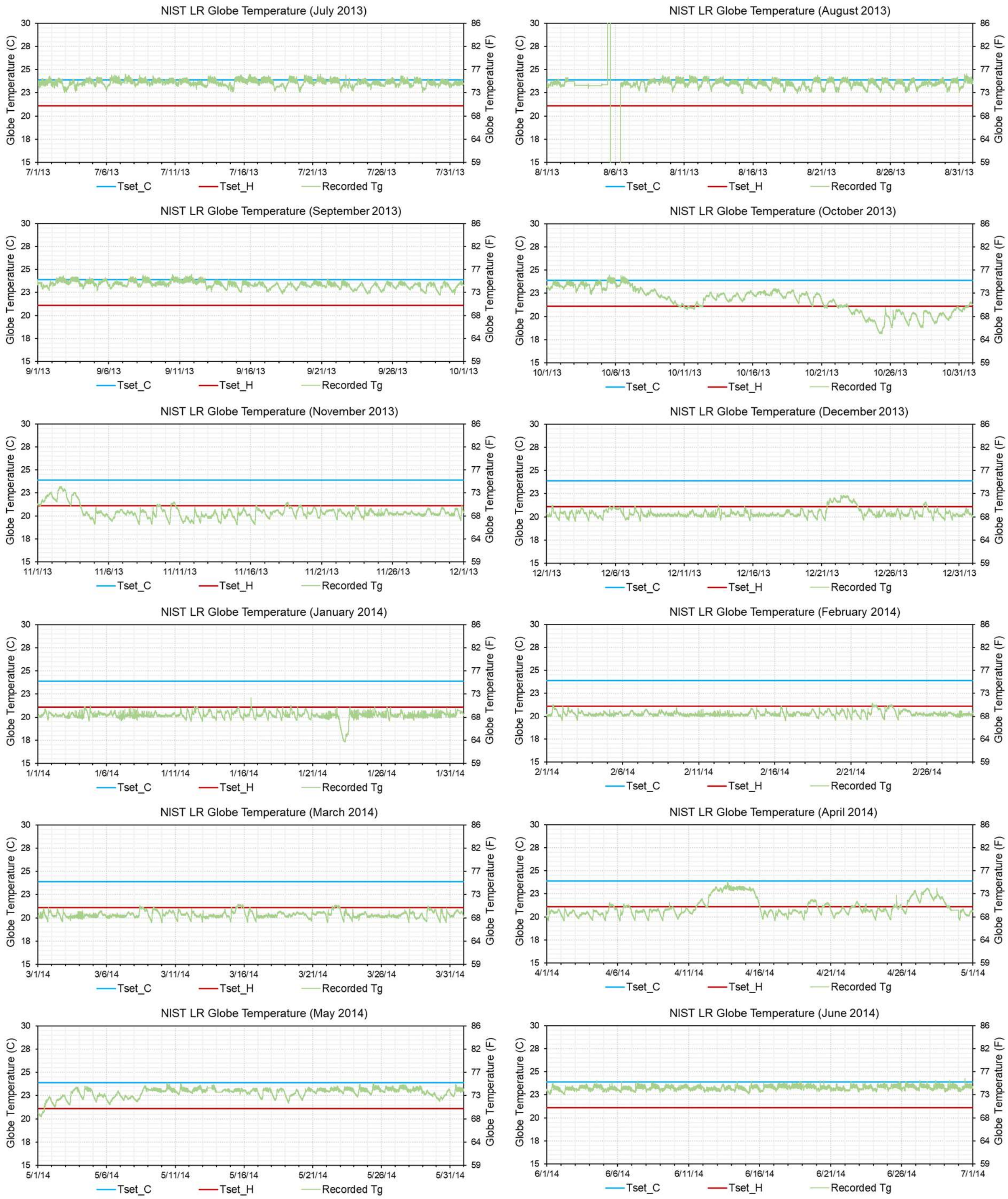

Figure C-49: Year 1 1-Min LR Globe Temperature.

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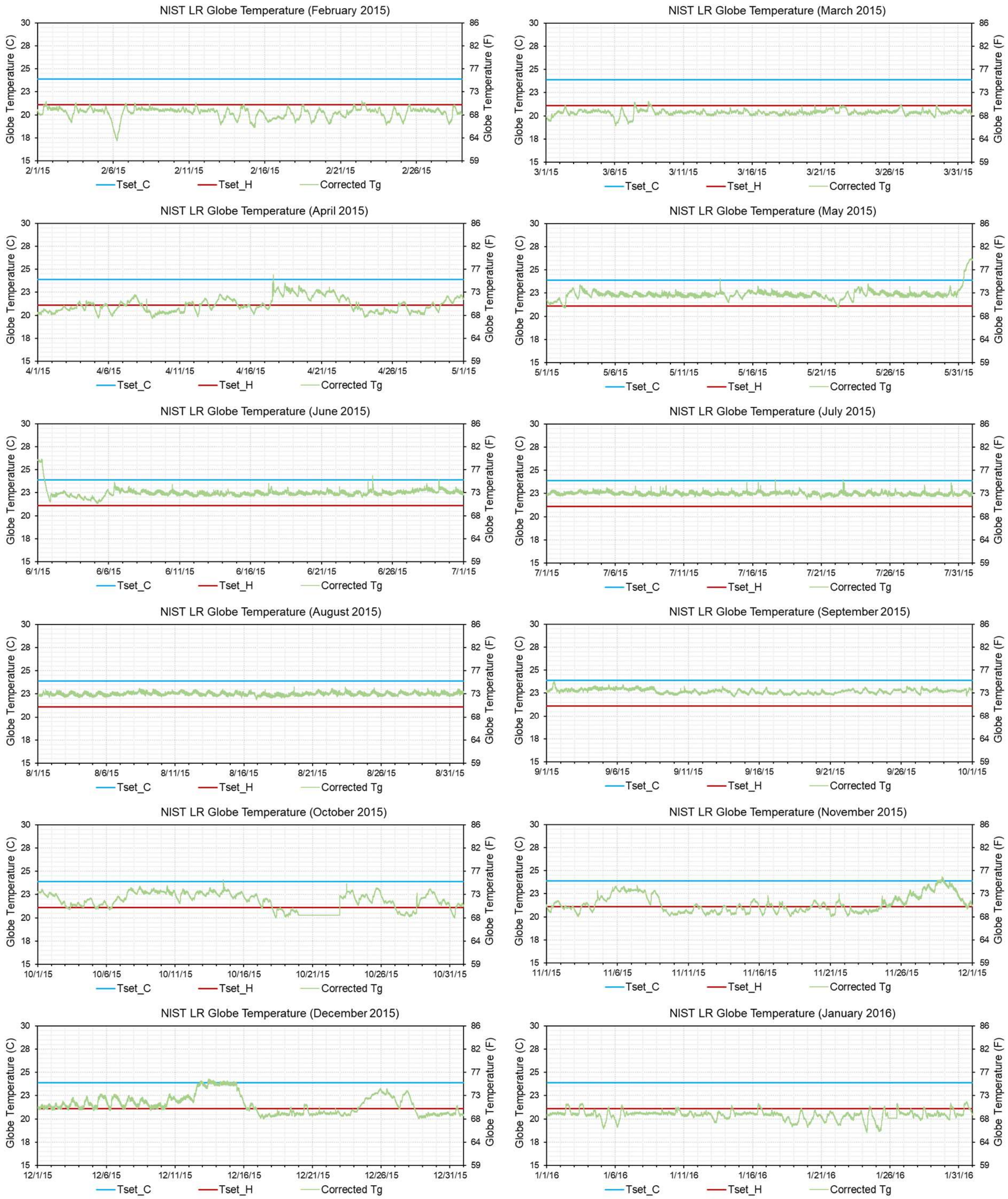

Figure C-50: Year 2 1-Min LR Globe Temperature.

- KIT: Kitchen

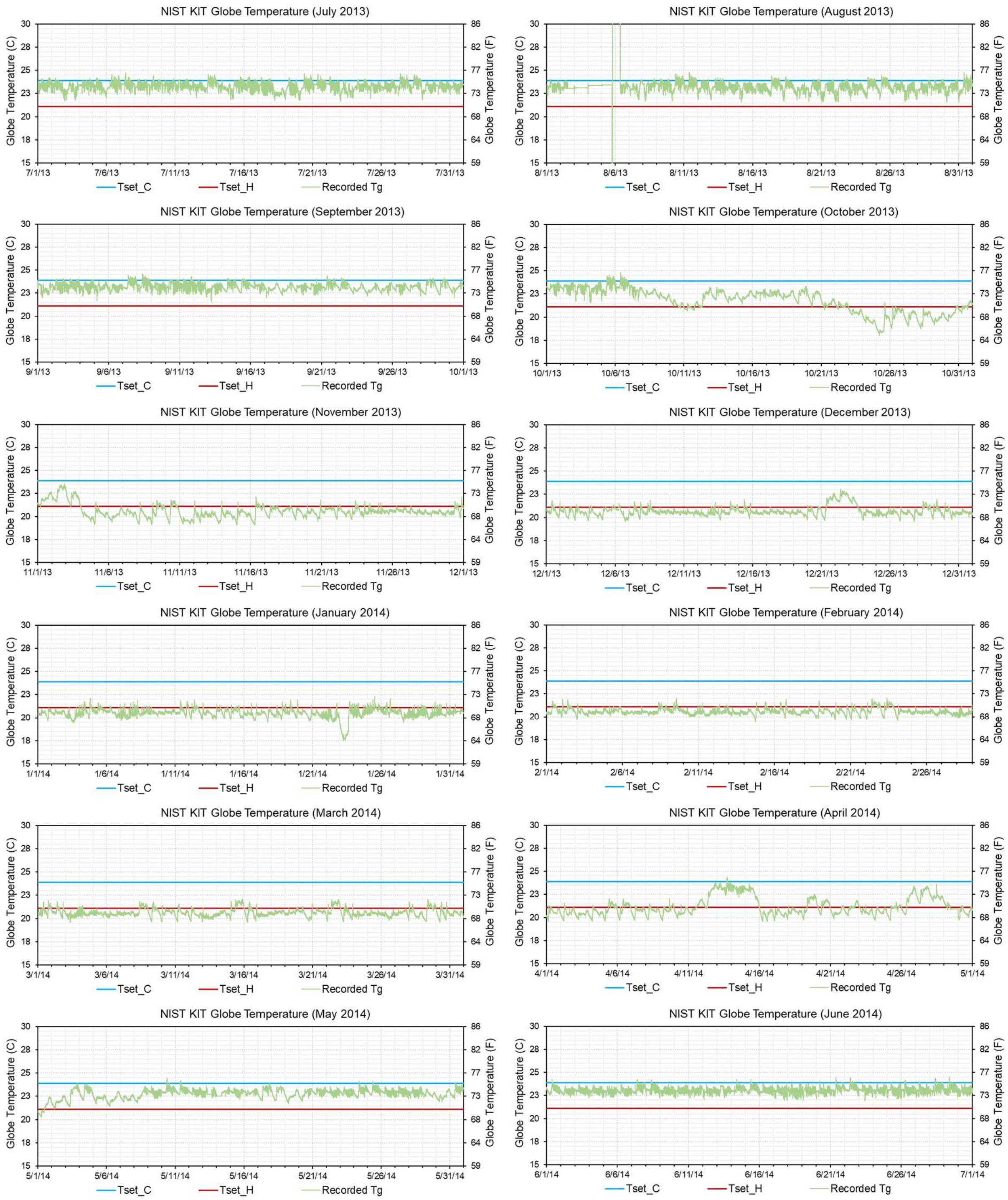

Figure C-51: Year 1 1-Min KIT Globe Temperature.

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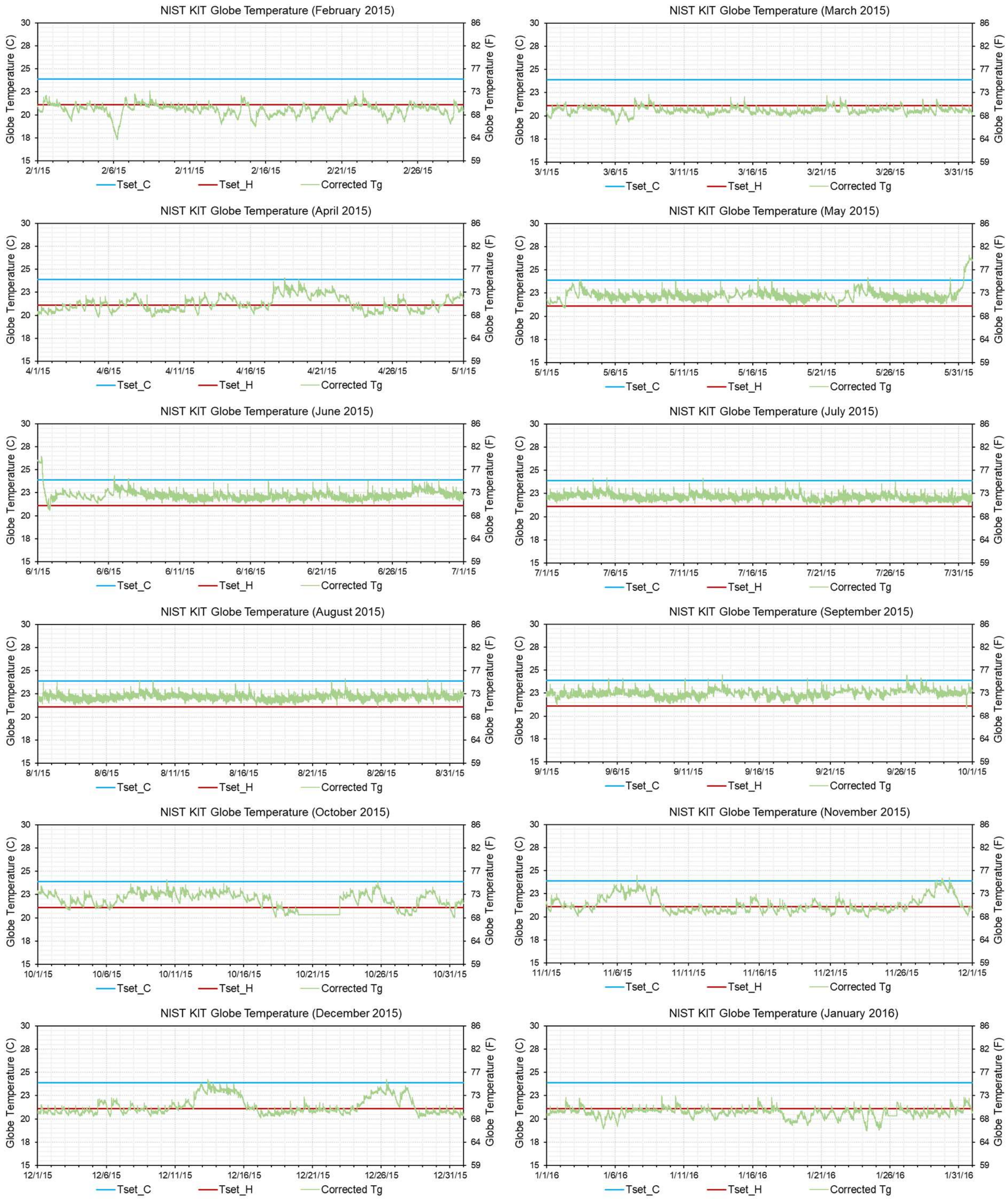

Figure C-52: Year 2 1-Min KIT Globe Temperature.

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ROOMS ON THE SECOND FLOOR

- MBR: Master Bedroom

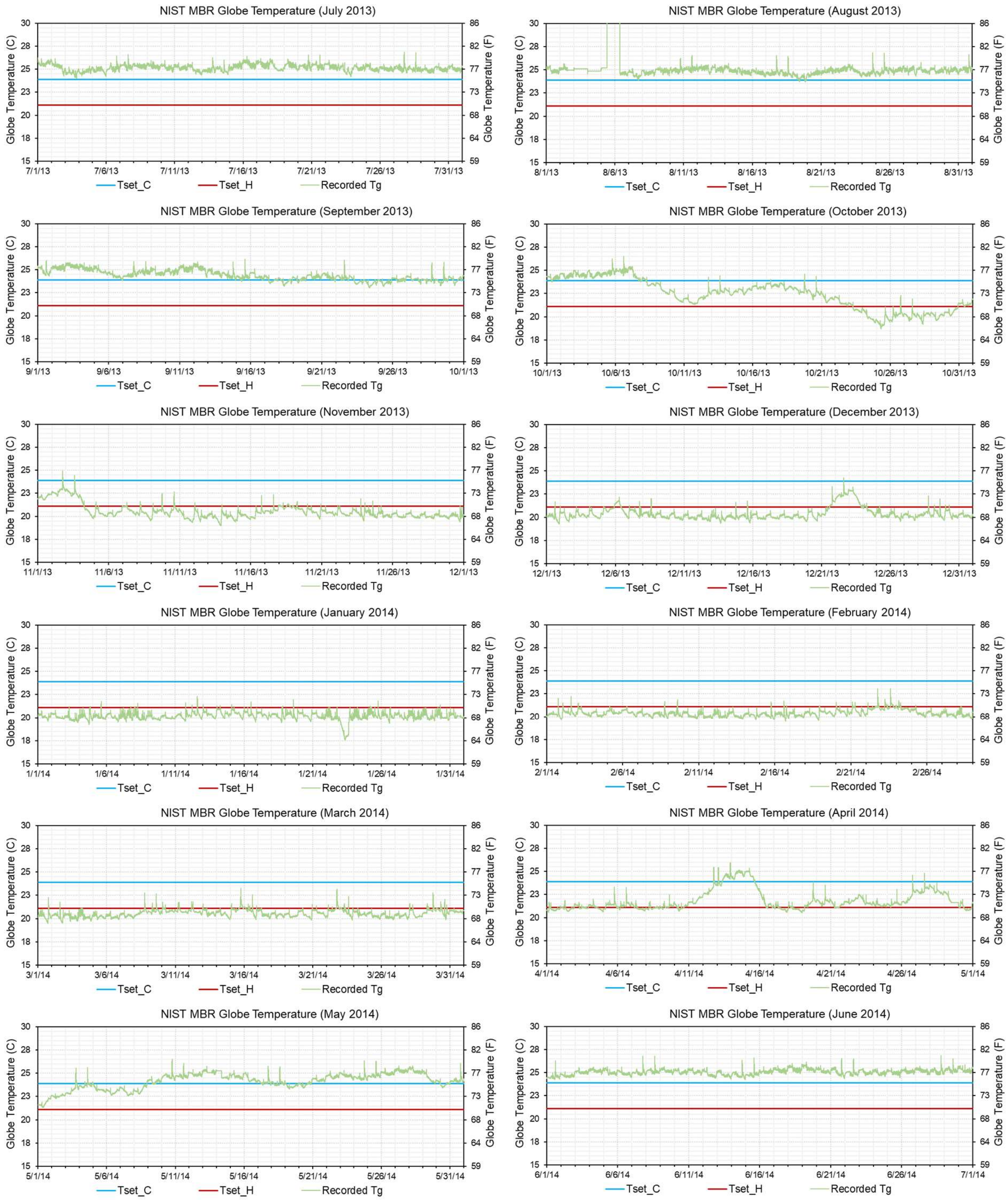

Figure C-53: Year 1 1-Min MBR Globe Temperature.

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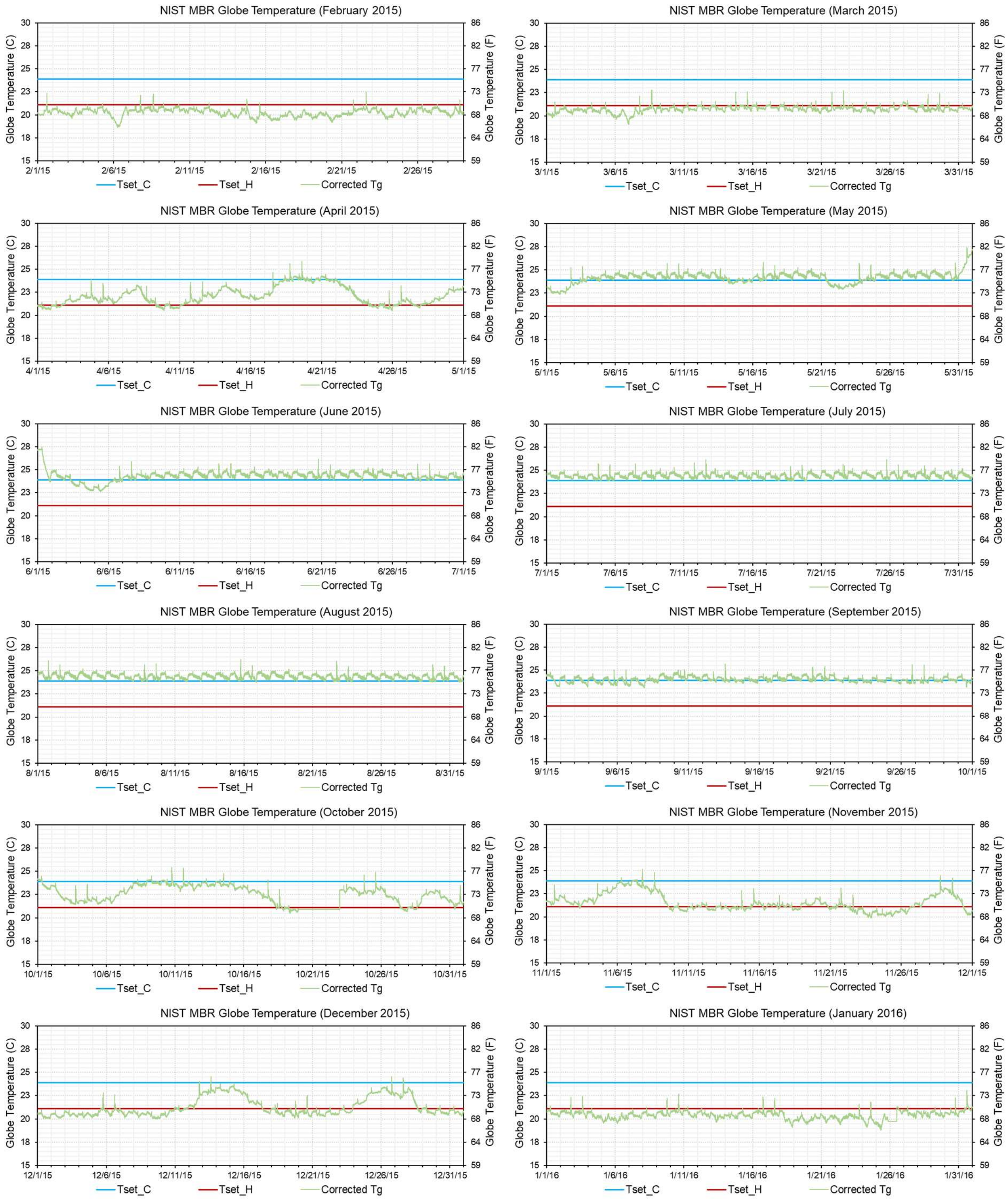

Figure C-54: Year 2 1-Min MBR Globe Temperature.

- BR2: Bedroom 2

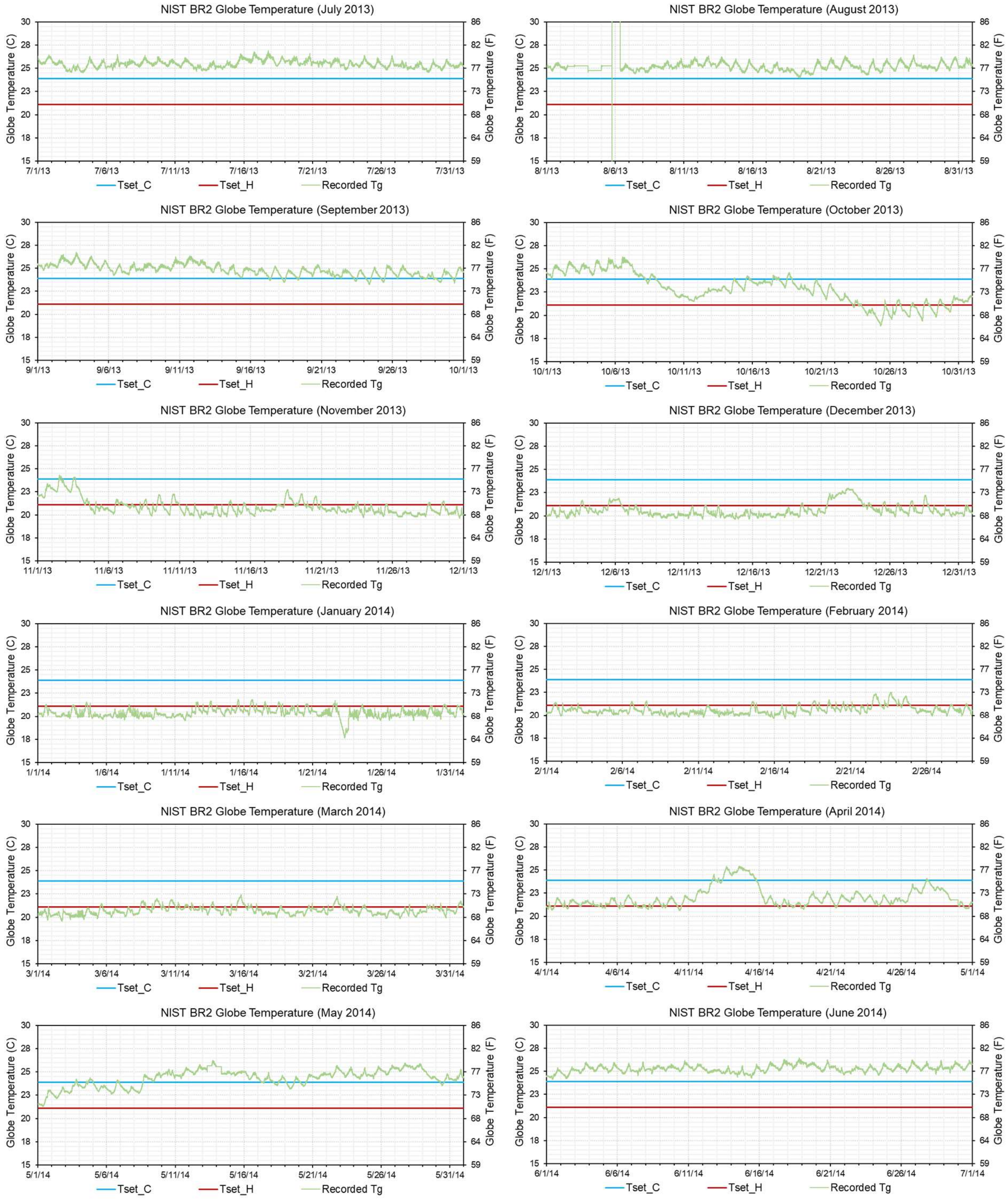

Figure C-55: Year 1 1-Min BR2 Globe Temperature.

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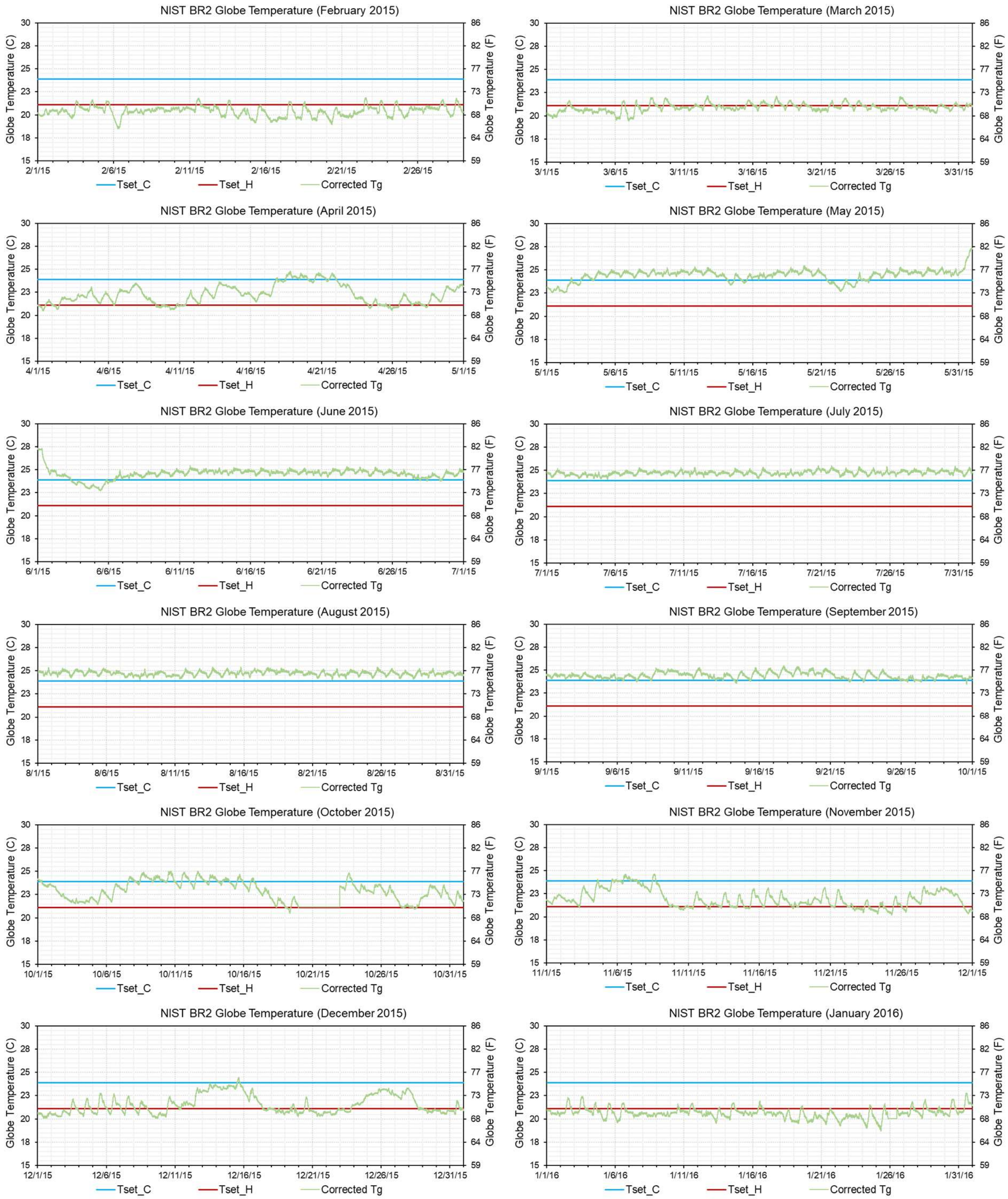

Figure C-56: Year 2 1-Min BR2 Globe Temperature.

- BR3: Bedroom 3

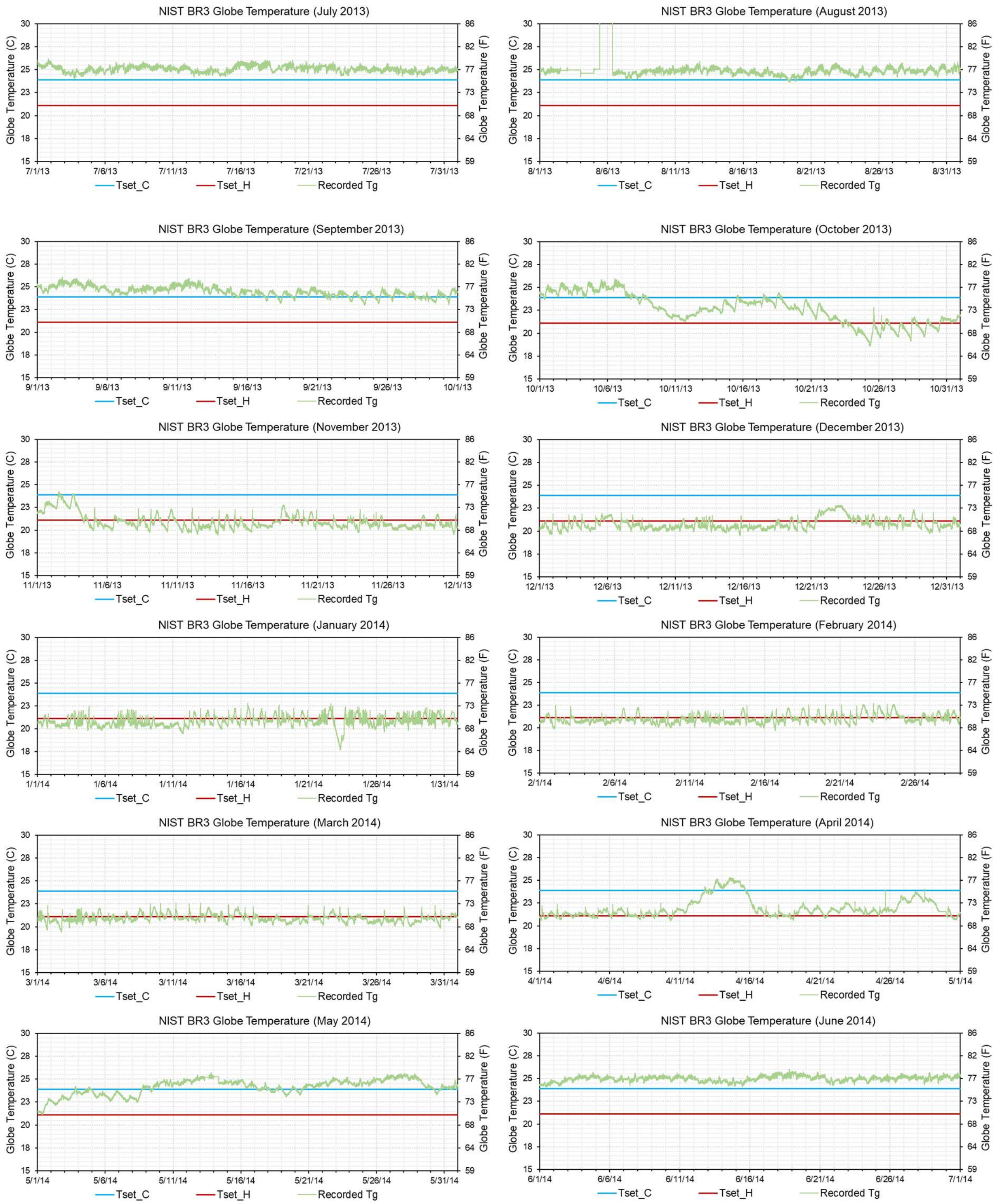

Figure C-57: Year 1 1-Min BR3 Globe Temperature.

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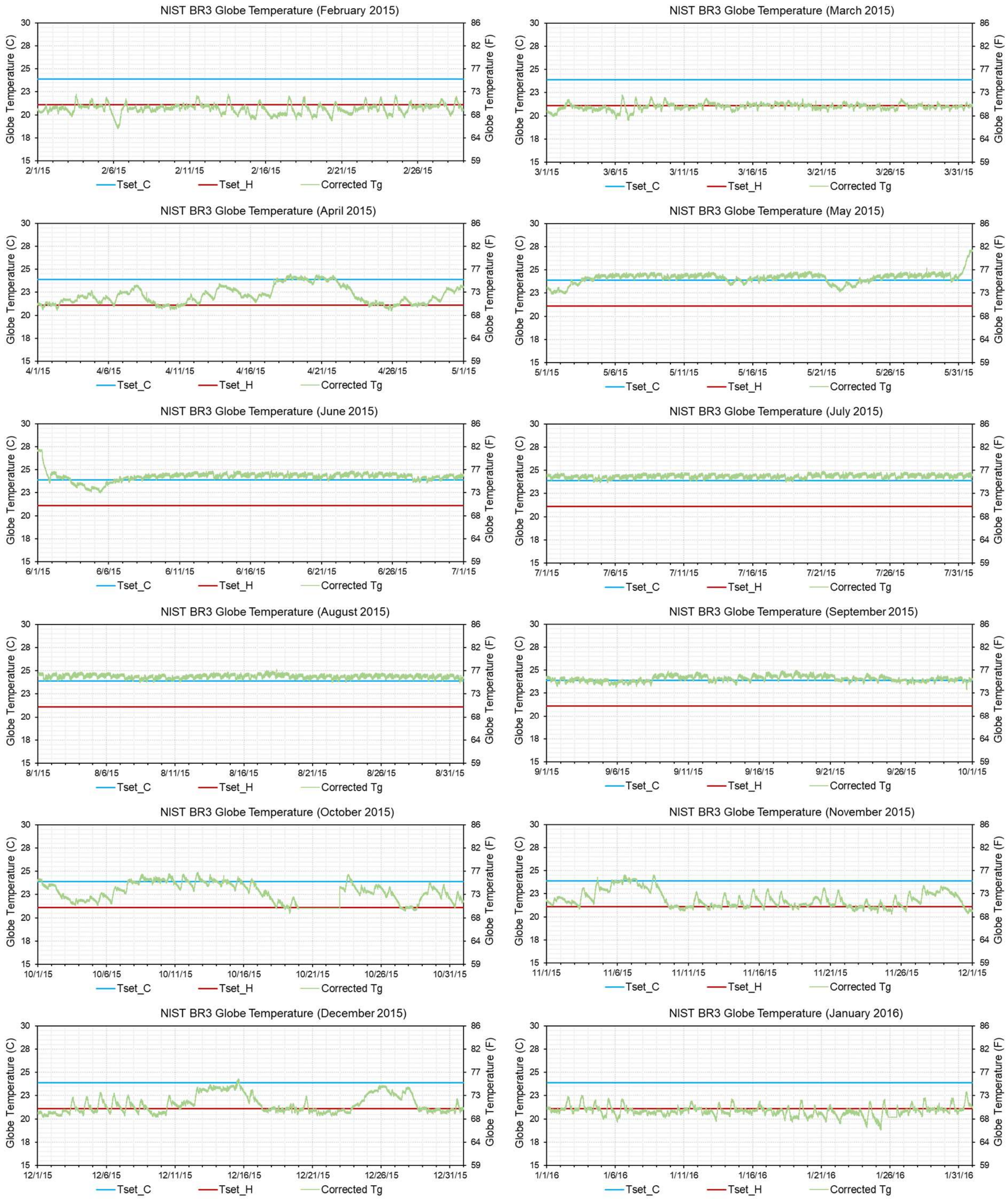

Figure C-58: Year 2 1-Min BR3 Globe Temperature.

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APPENDIX C-3: 1-MIN OUTDOOR AIR (OA) TEMPERATURES

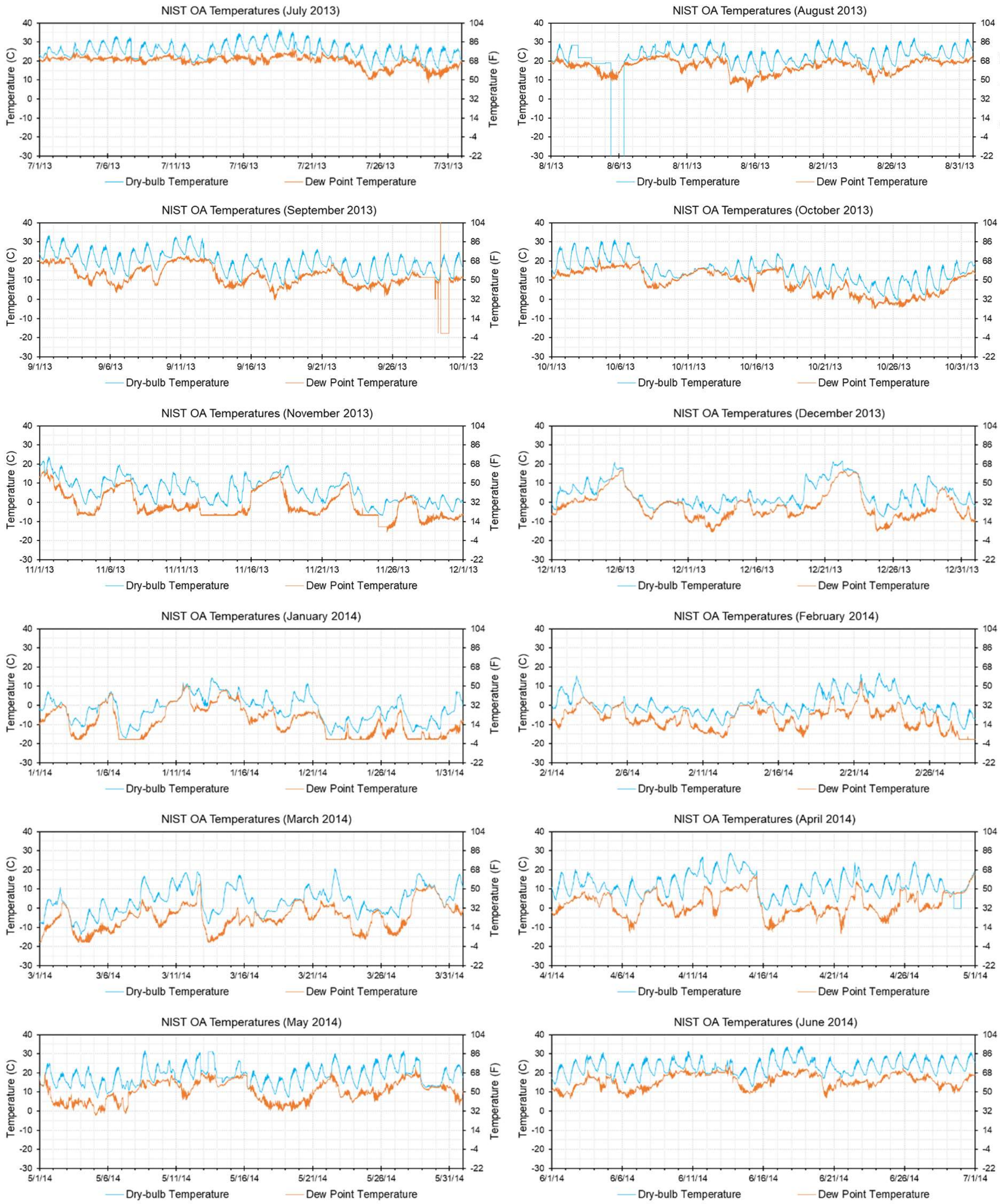

Figure C-59: Year 1 1-Min Outdoor Air Dry-Bulb and Dew Point Temperatures.

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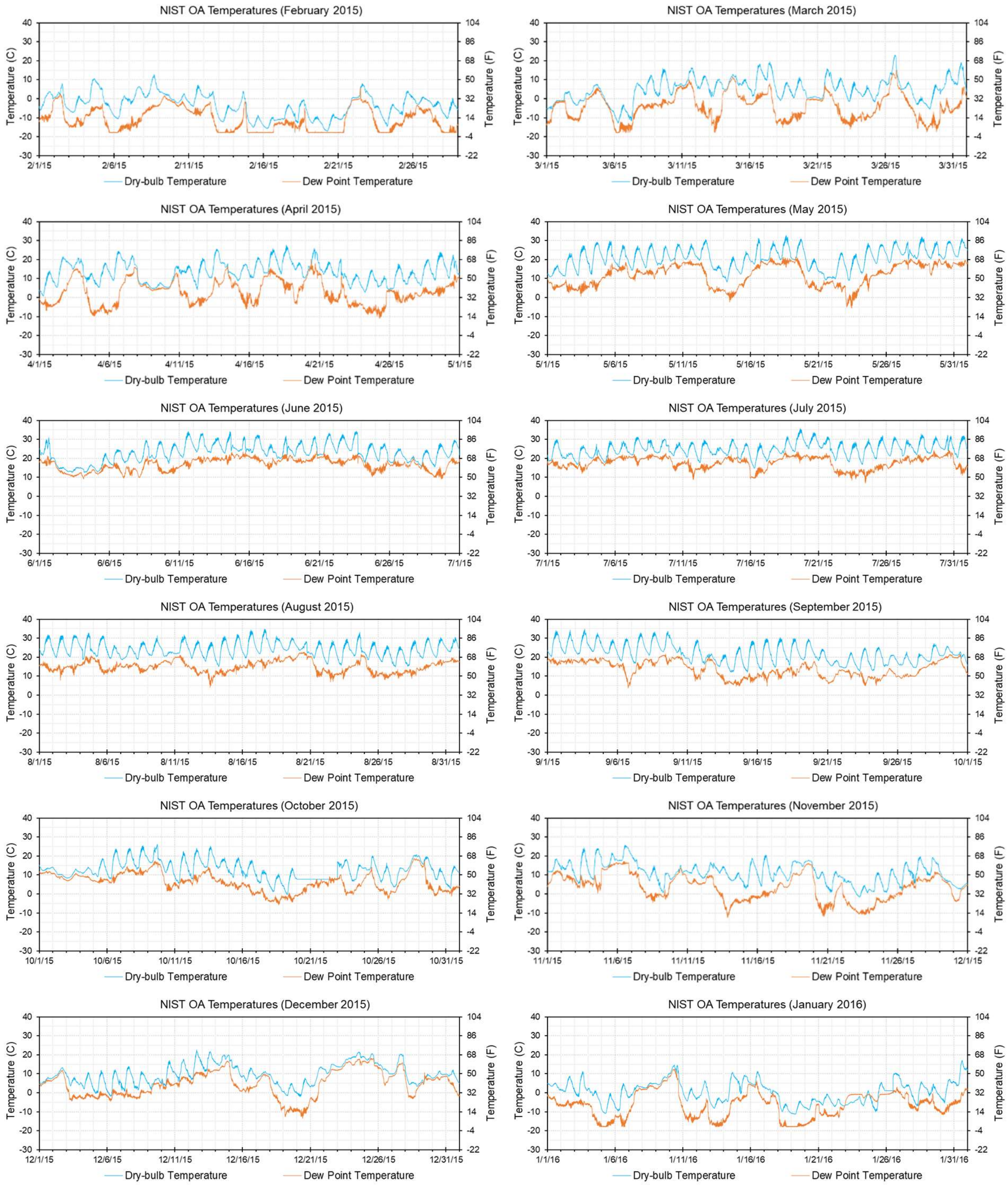

Figure C-60: Year 2 1-Min Outdoor Air Dry-Bulb and Dew Point Temperatures.

APPENDIX C-4: 1-MIN RELATIVE HUMIDITY BY ROOM

ROOMS ON THE FIRST FLOOR

- LR: Living Room

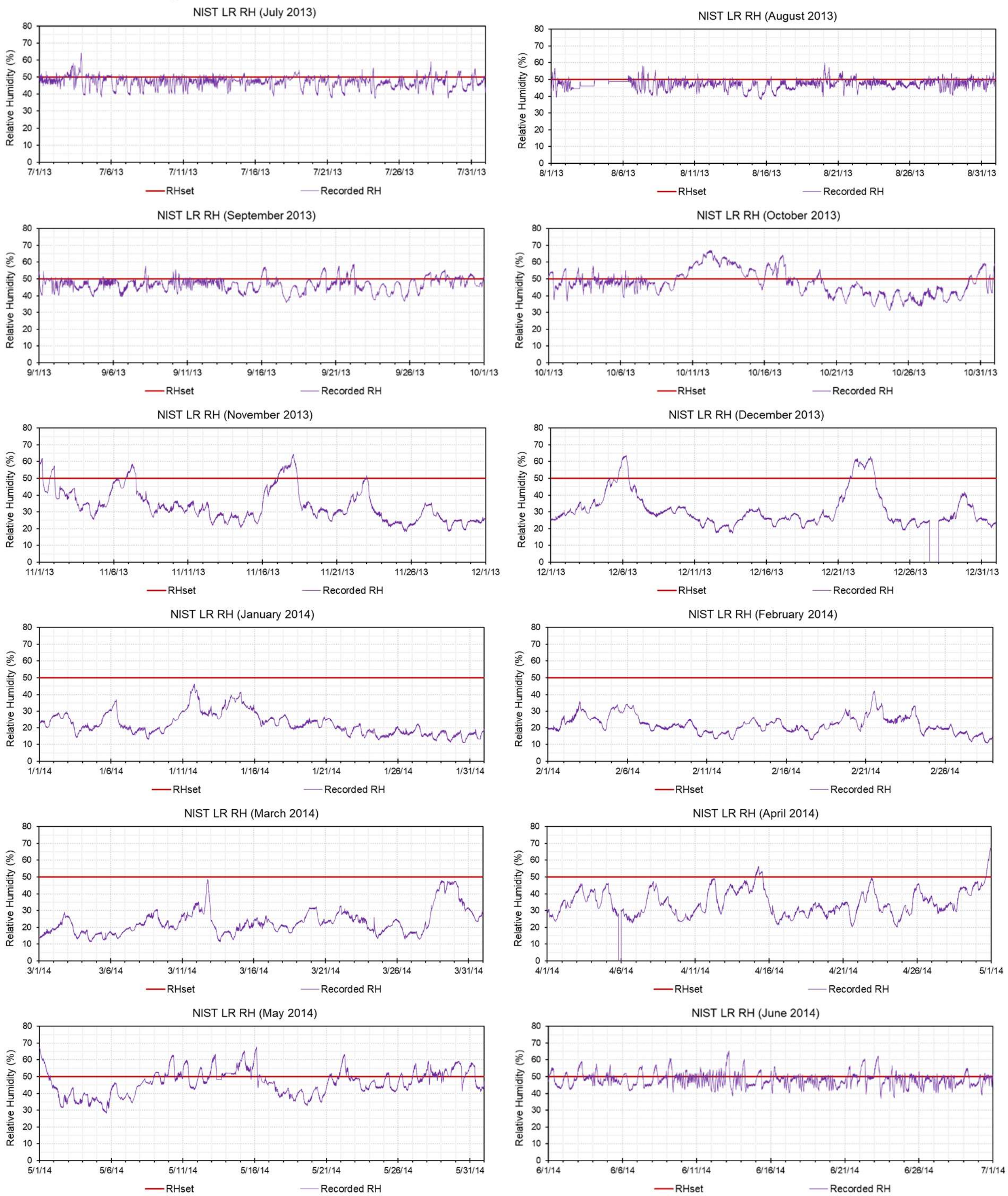

Figure C-61: Year 1 1-Min LR Relative Humidity.

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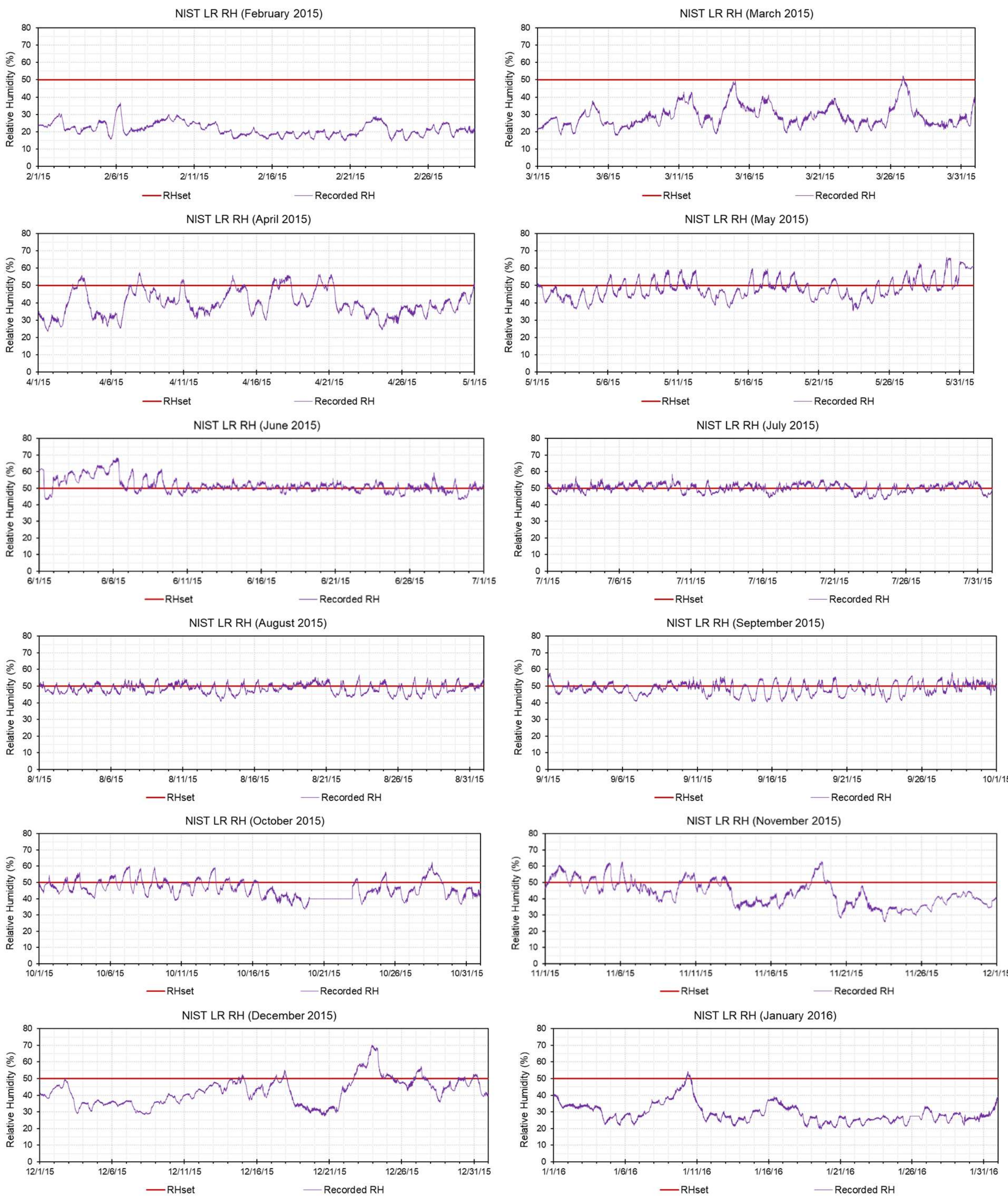

Figure C-62: Year 2 1-Min LR Relative Humidity.

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- KIT: Kitchen

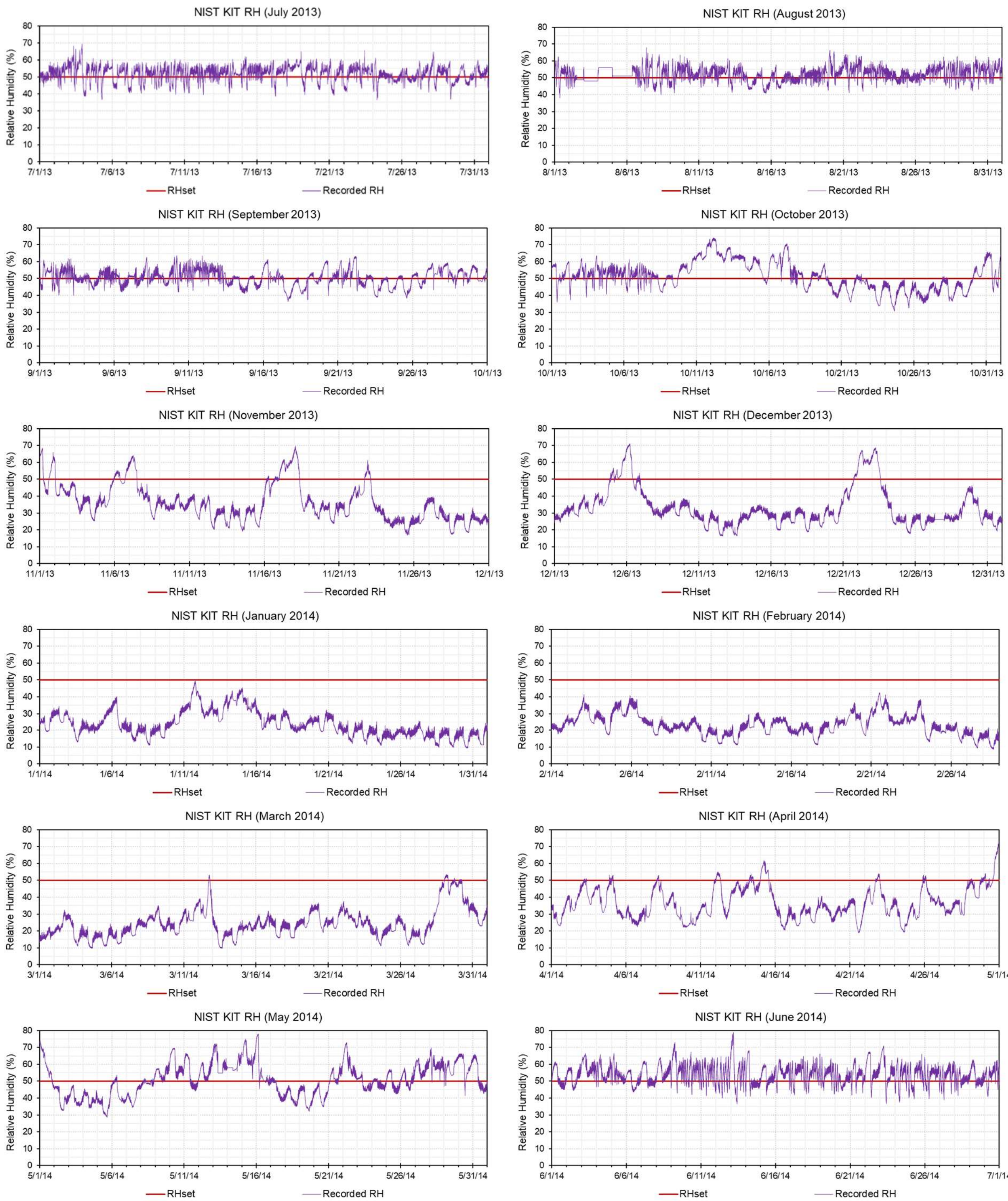

Figure C-63: Year 1 1-Min KIT Relative Humidity.

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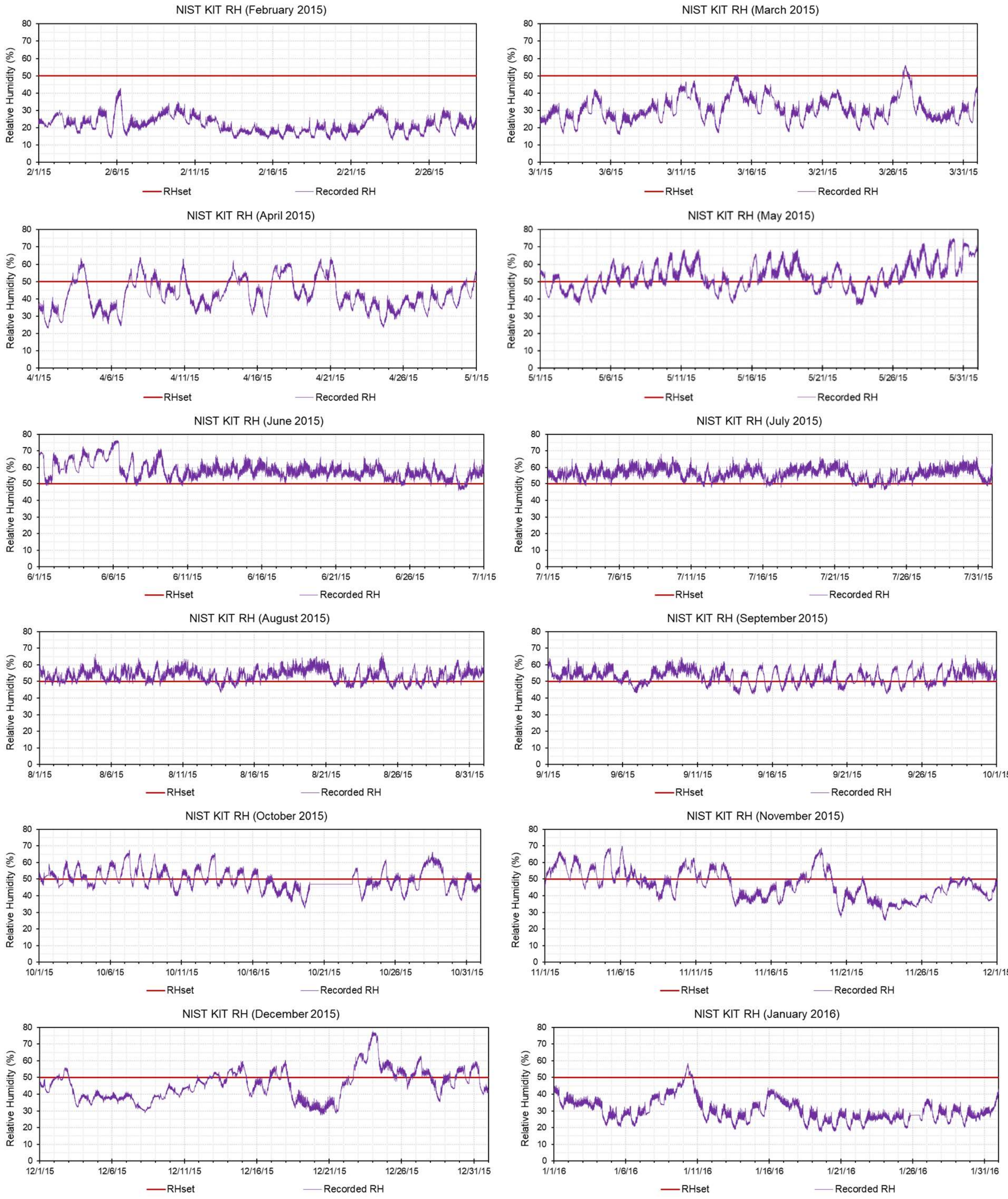

Figure C-64: Year 2 1-Min KIT Relative Humidity.

ROOMS ON THE SECOND FLOOR

- MBR: Master Bedroom

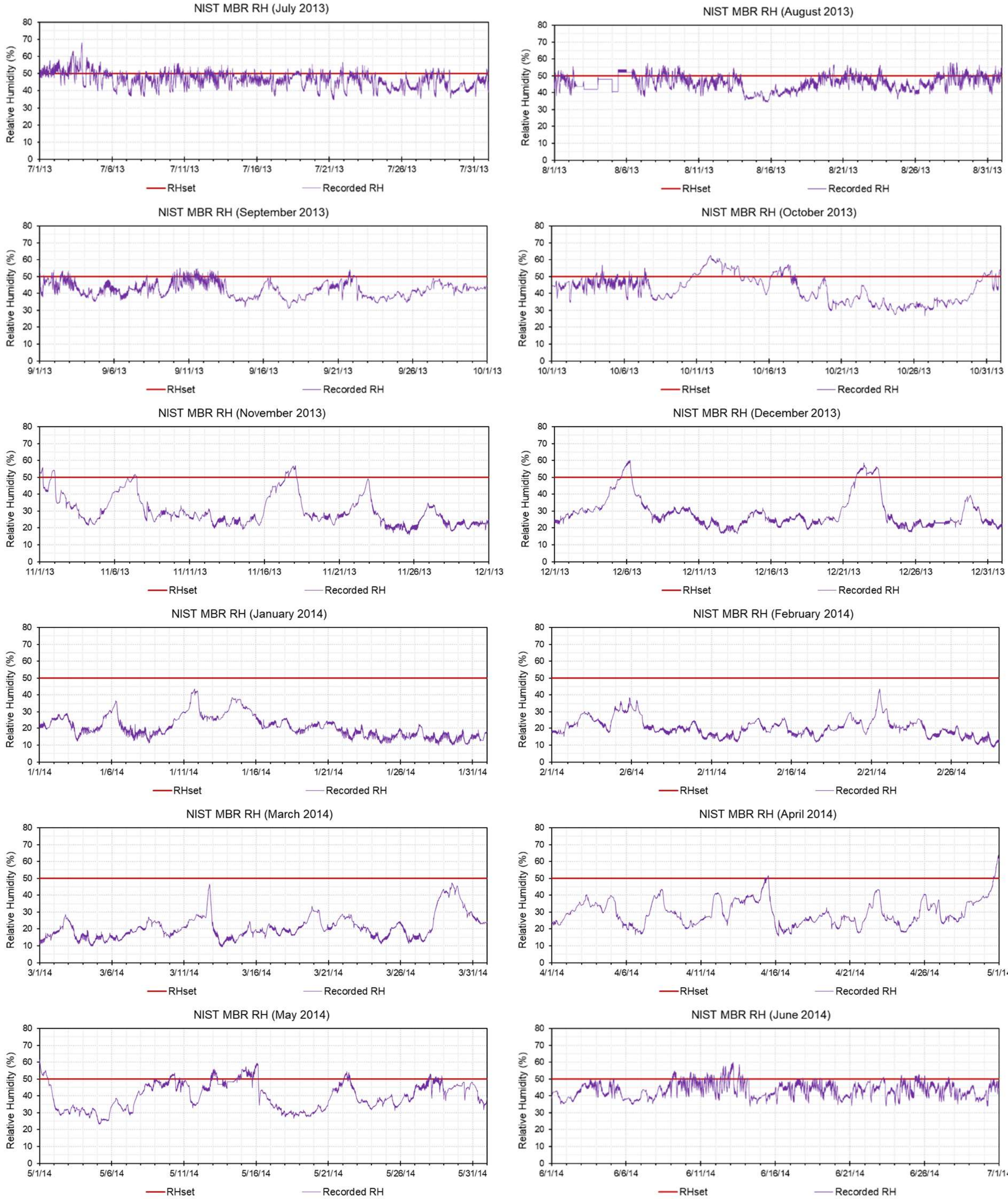

Figure C-65: Year 1 1-Min MBR Relative Humidity.

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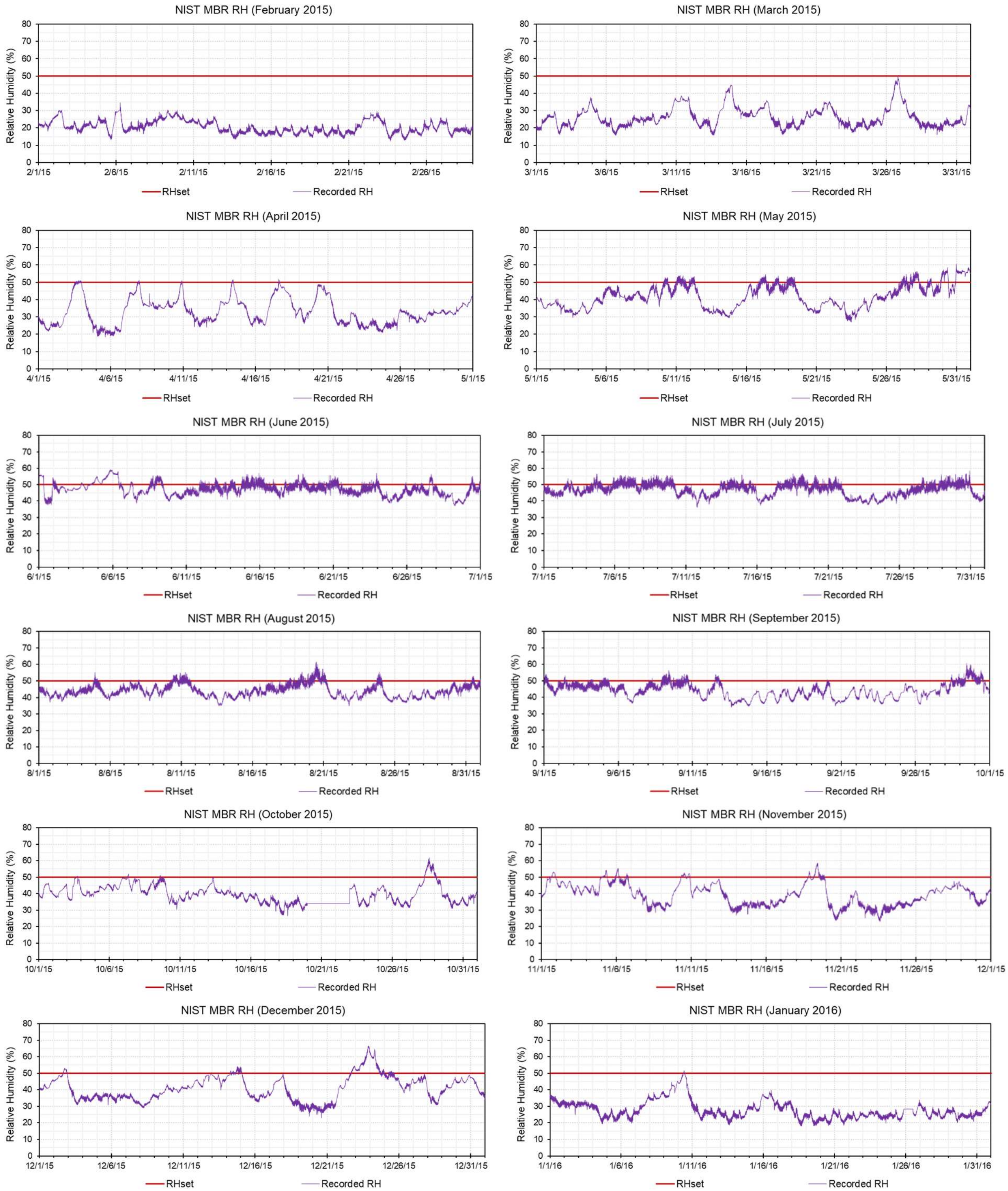

Figure C-66: Year 2 1-Min MBR Relative Humidity.

- BR2: Bedroom 2

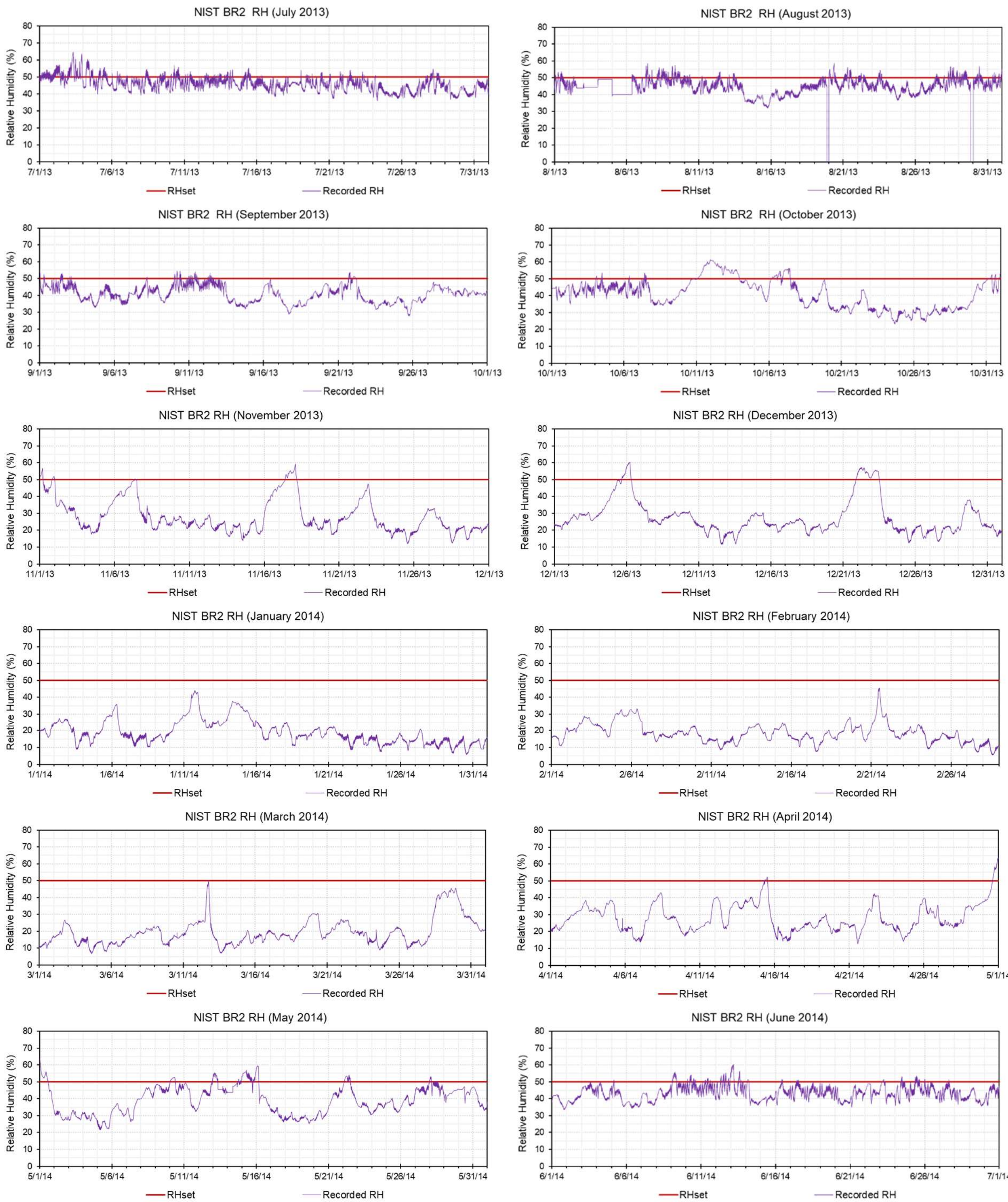

Figure C-67: Year 1 1-Min BR2 Relative Humidity.

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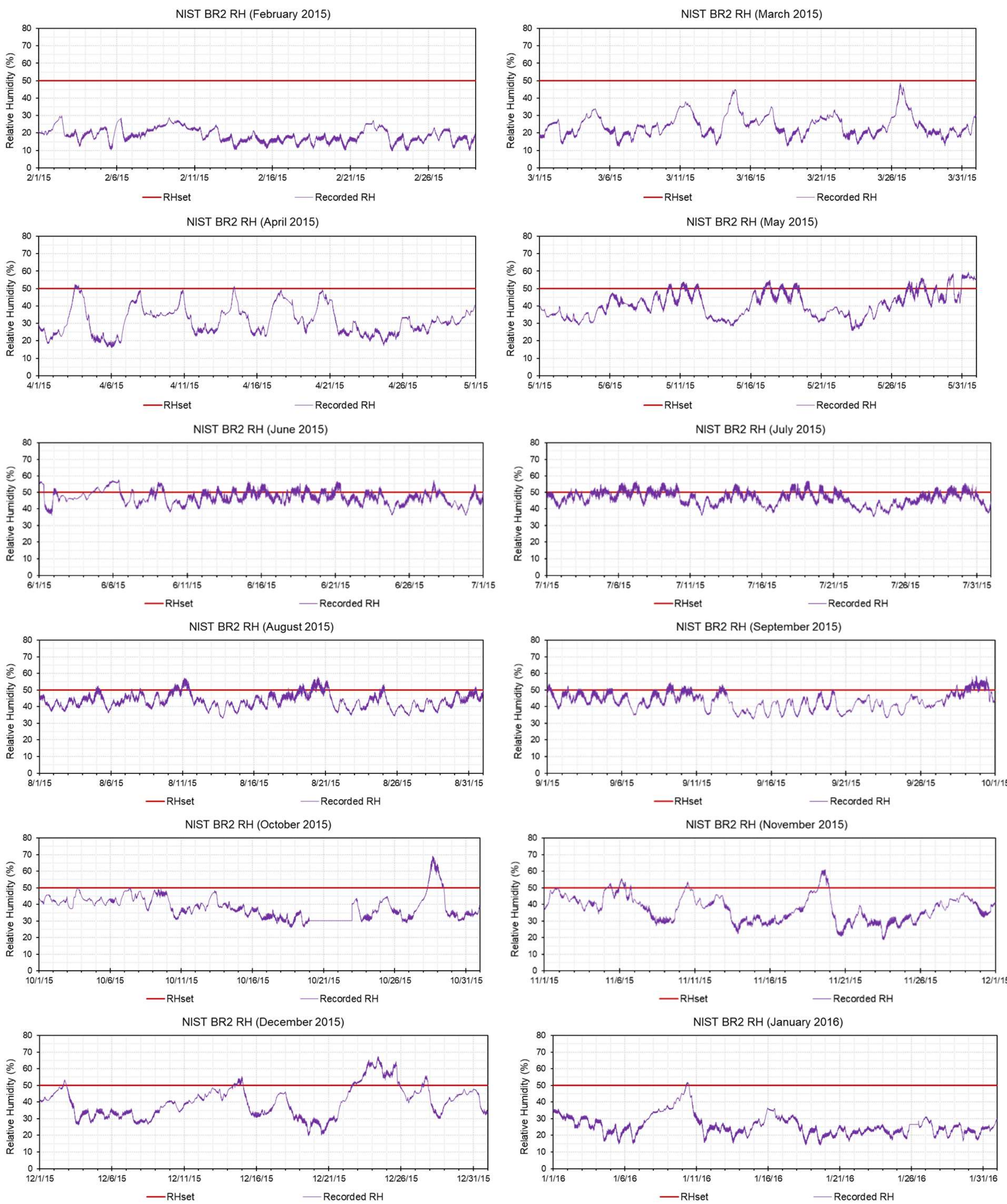

Figure C-68: Year 2 1-Min BR2 Relative Humidity.

- BR3: Bedroom 3

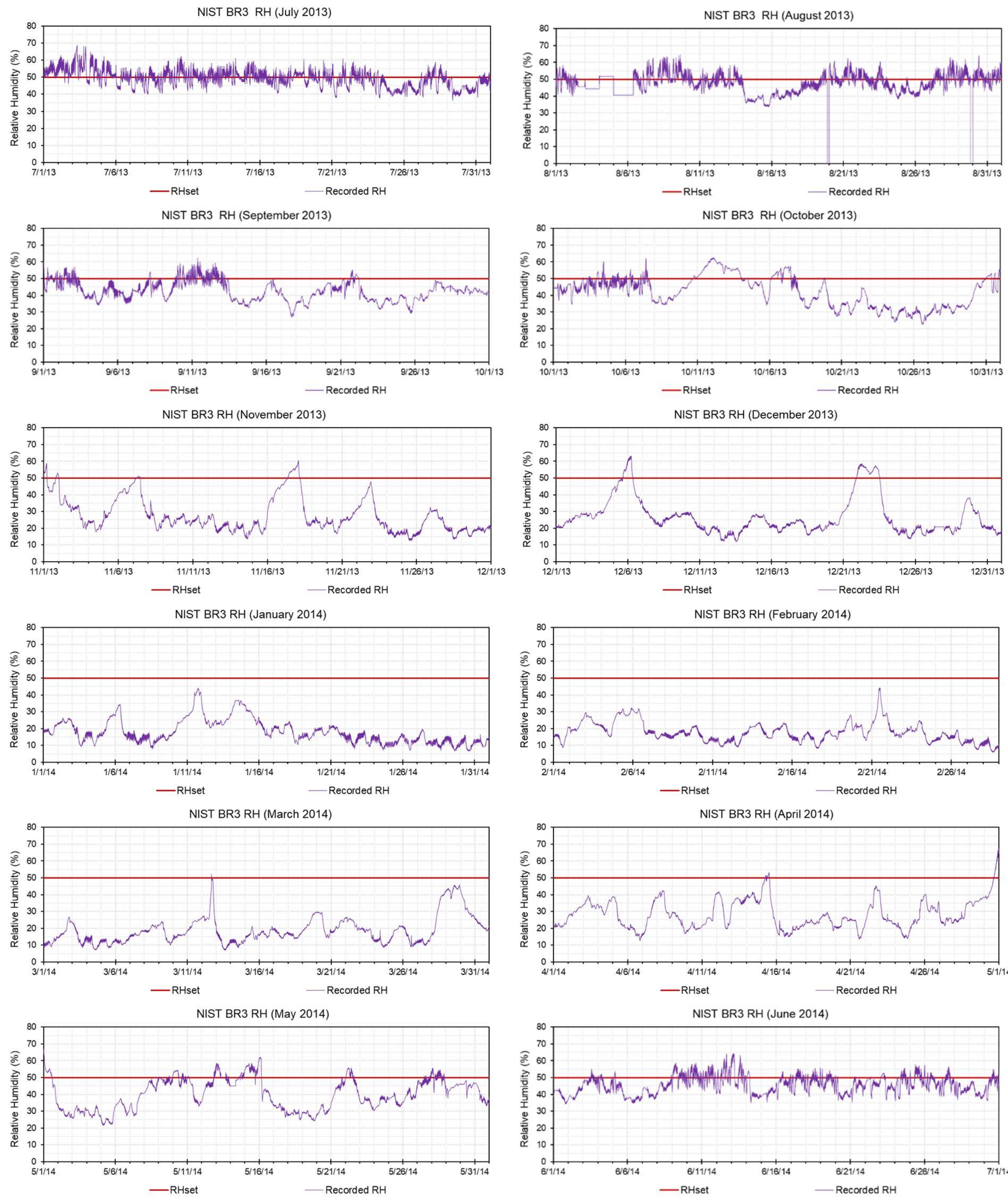

Figure C-69: Year 1 1-Min BR3 Relative Humidity.

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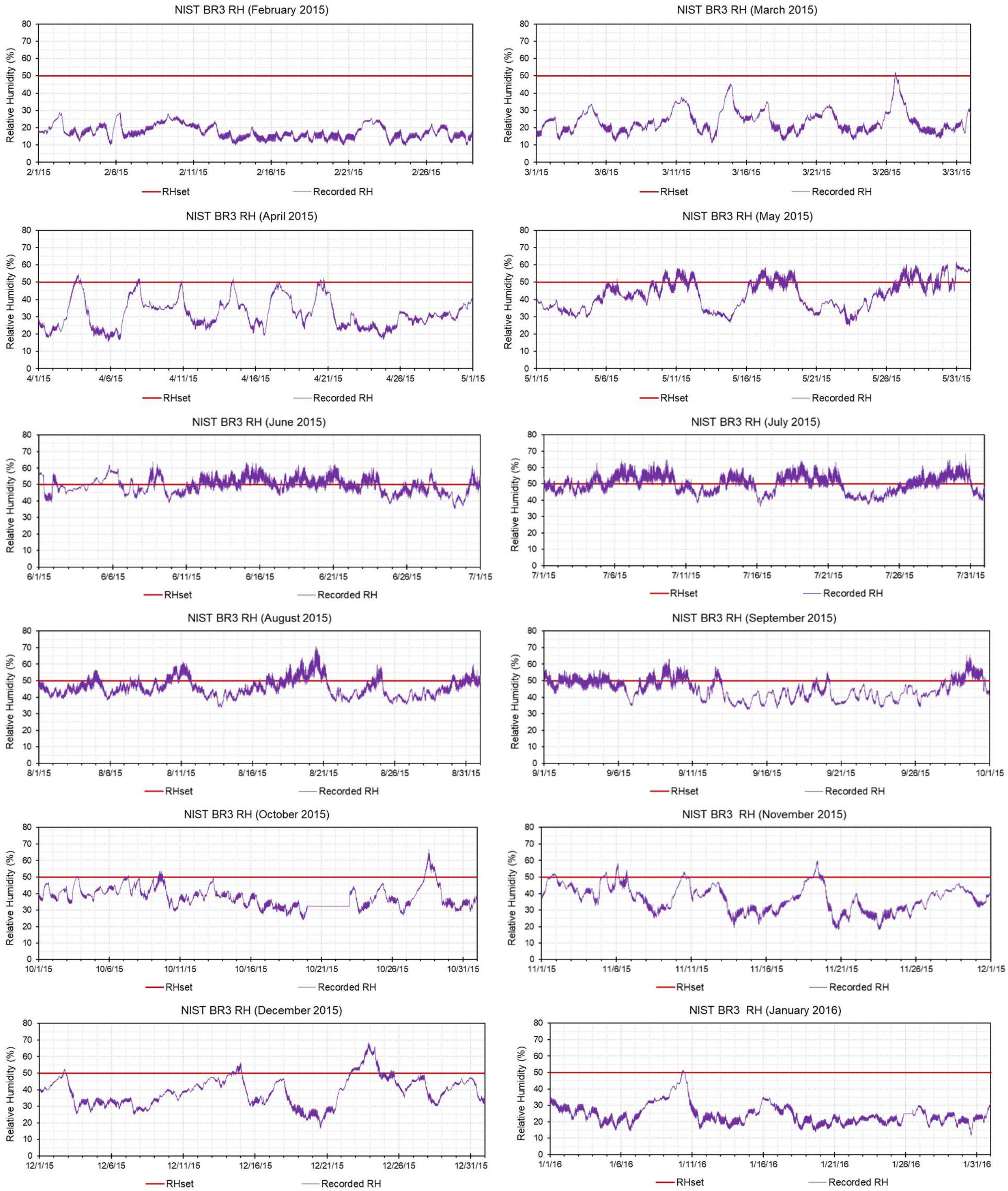

Figure C-70: Year 2 1-Min BR3 Relative Humidity.

- MBA: Master Bathroom

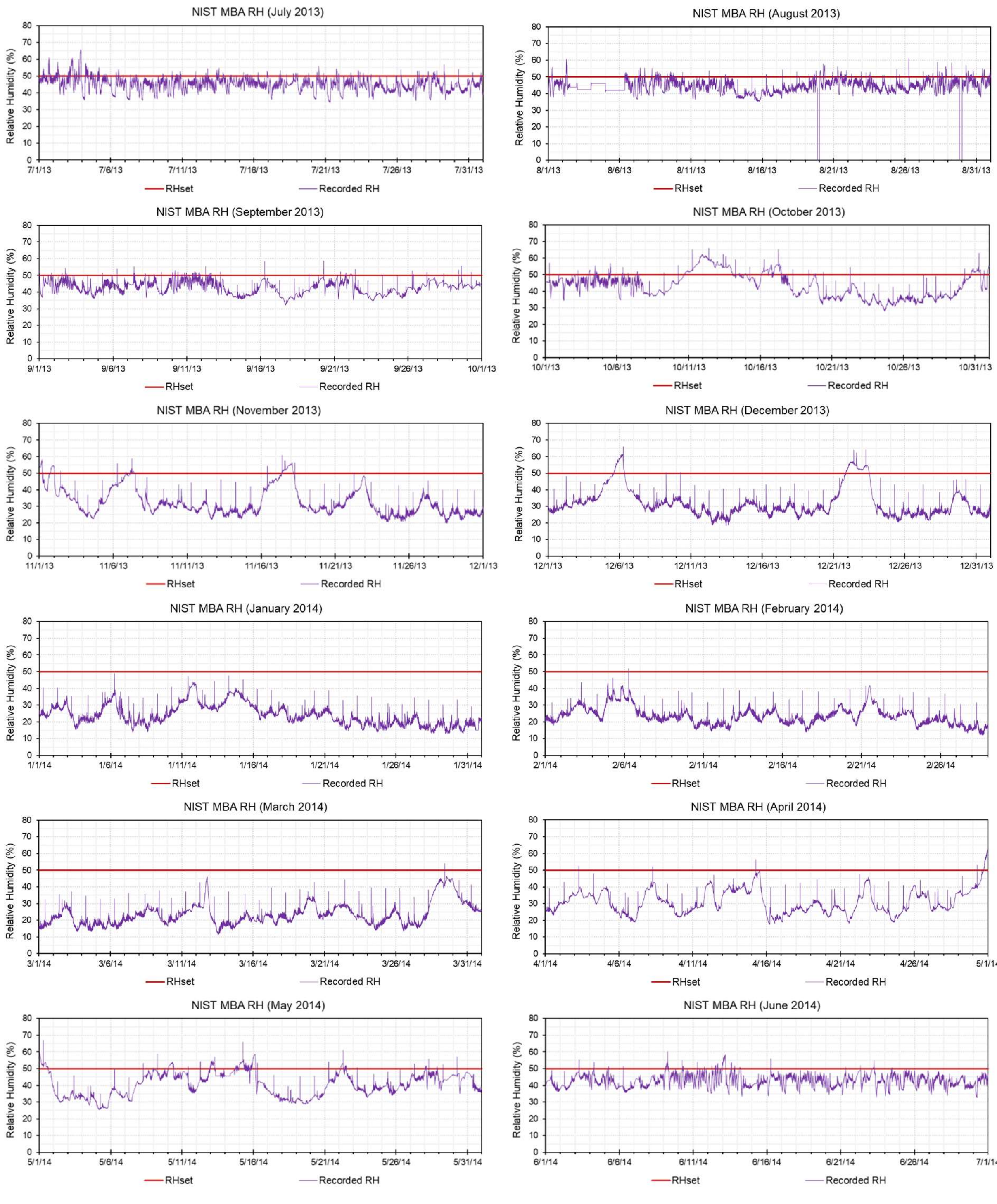

Figure C-71: Year 1 1-Min MBA Relative Humidity.

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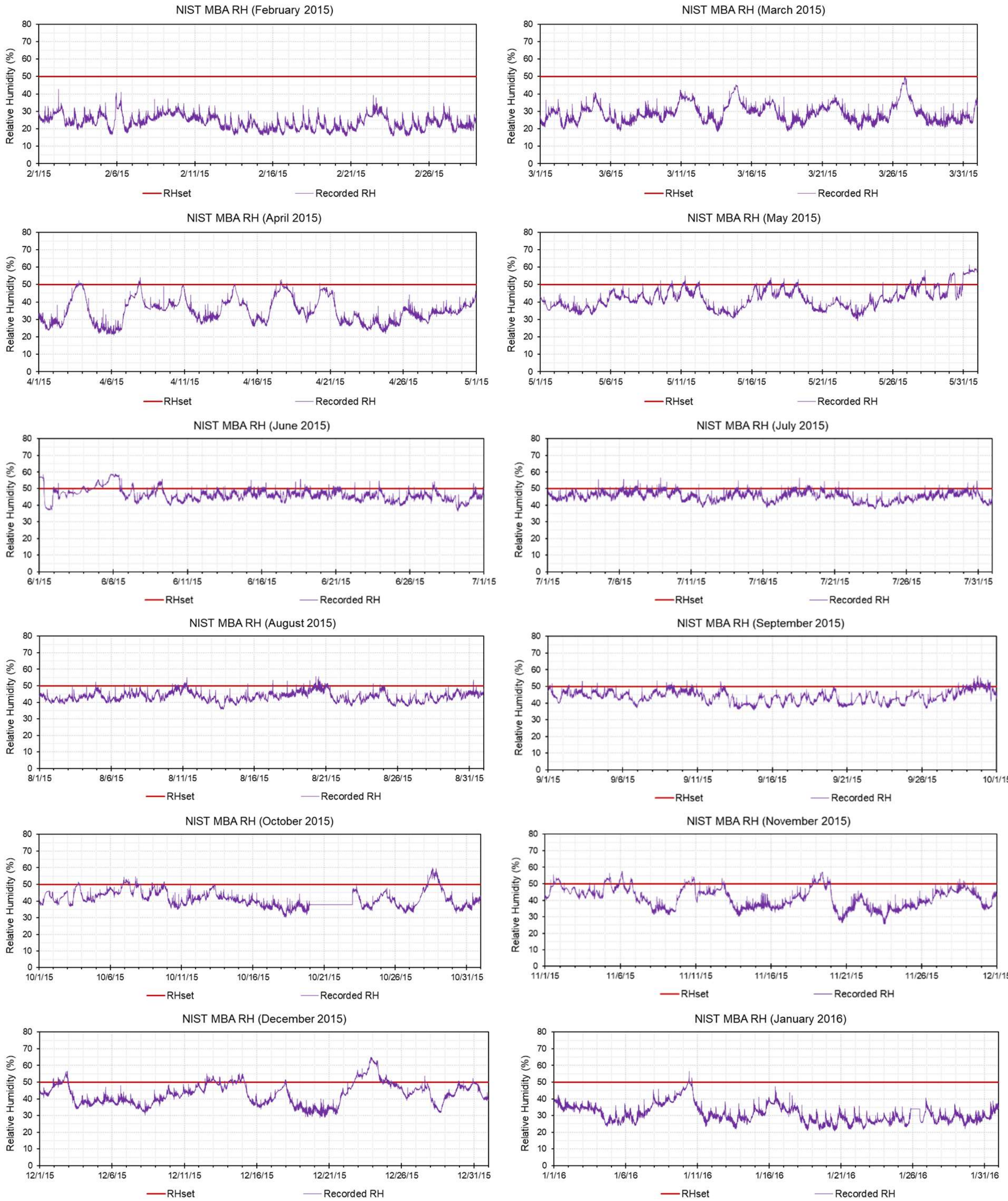

Figure C-72: Year 2 1-Min MBA Relative Humidity.

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BASEMENT

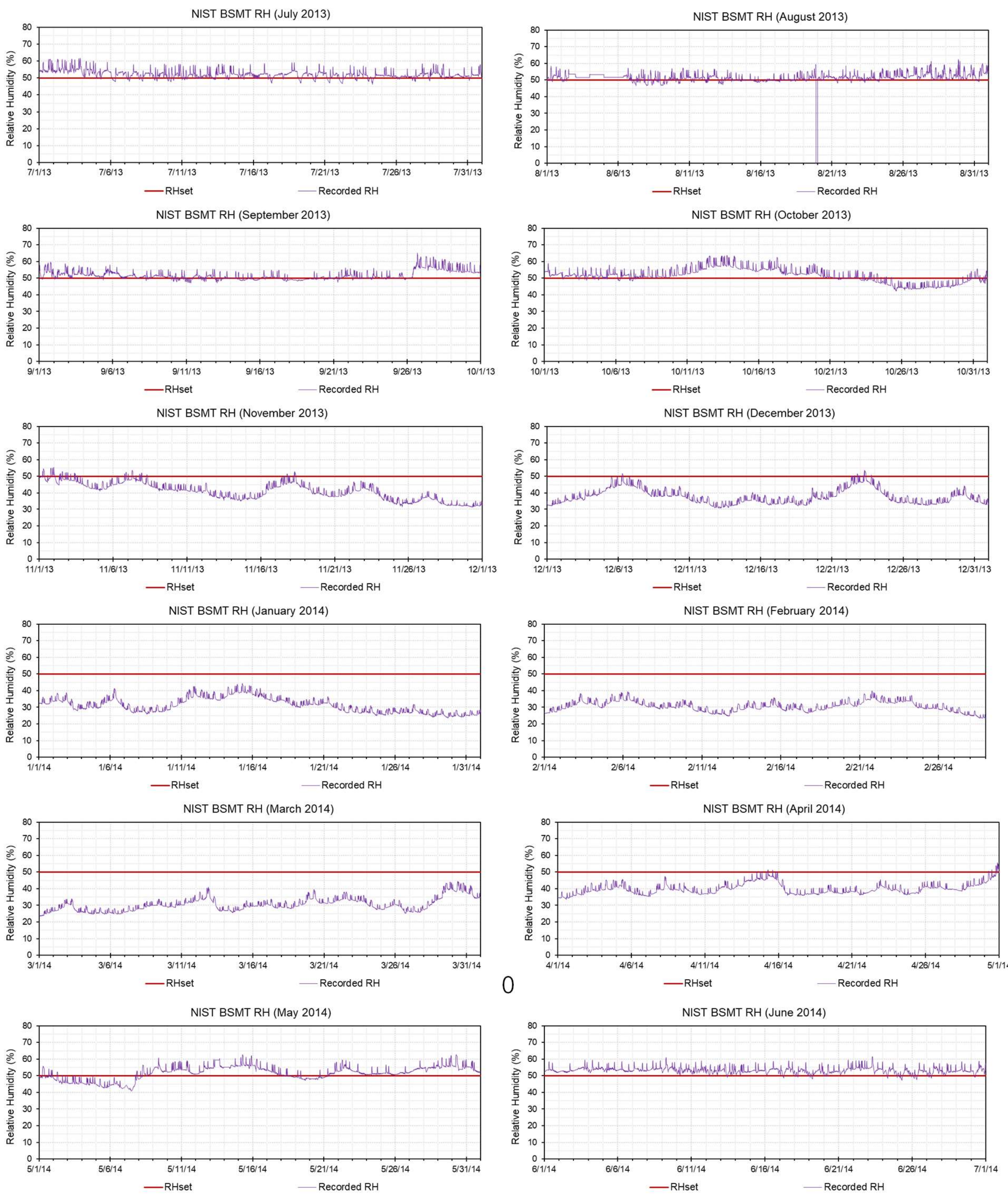

Figure C-73: Year 1 1-Min BSMT Relative Humidity.

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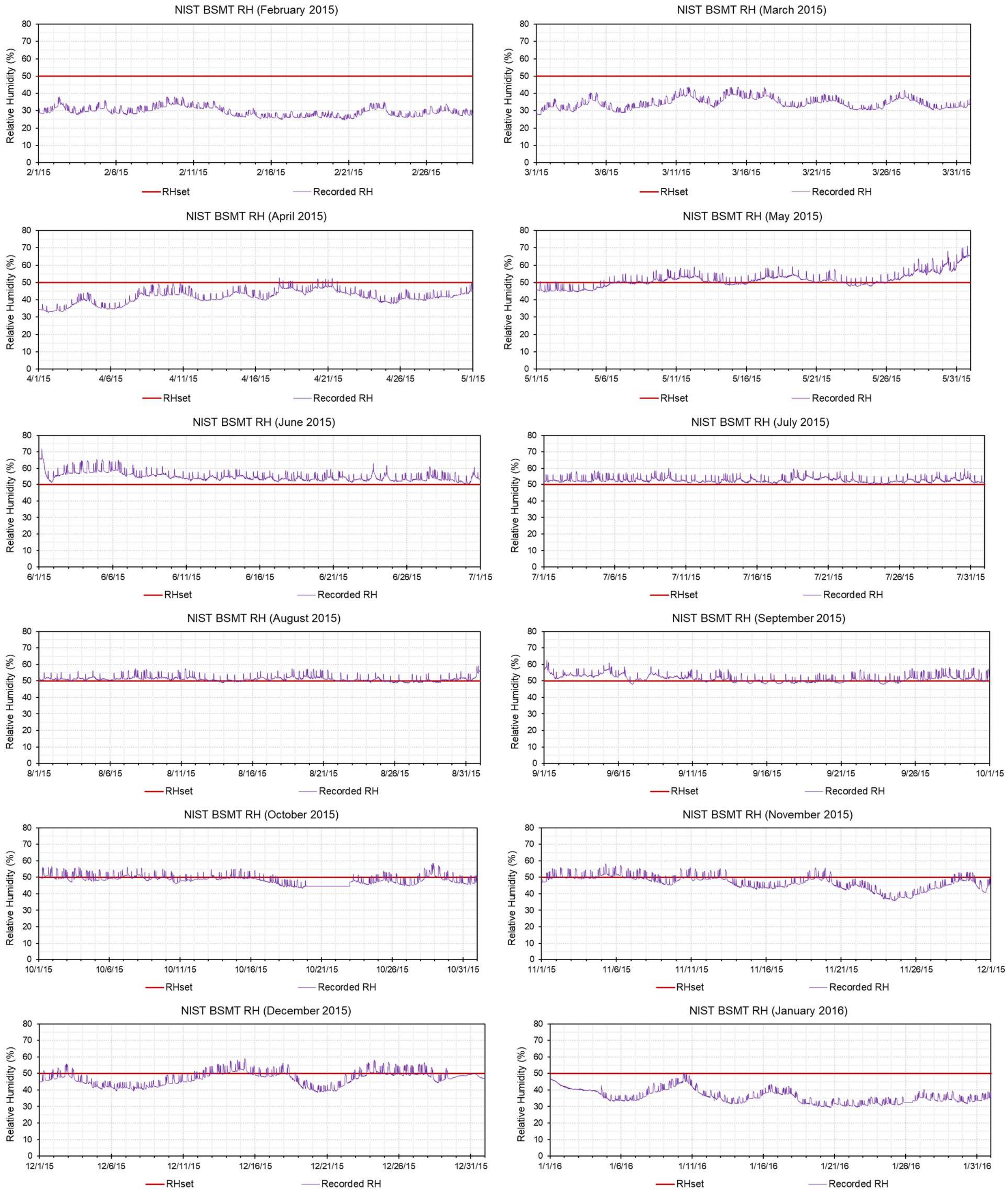

Figure C-74: Year 2 1-Min BSMT Relative Humidity.

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APPENDIX C-5: 1-MIN OUTDOOR AIR (OA) RELATIVE HUMIDITY

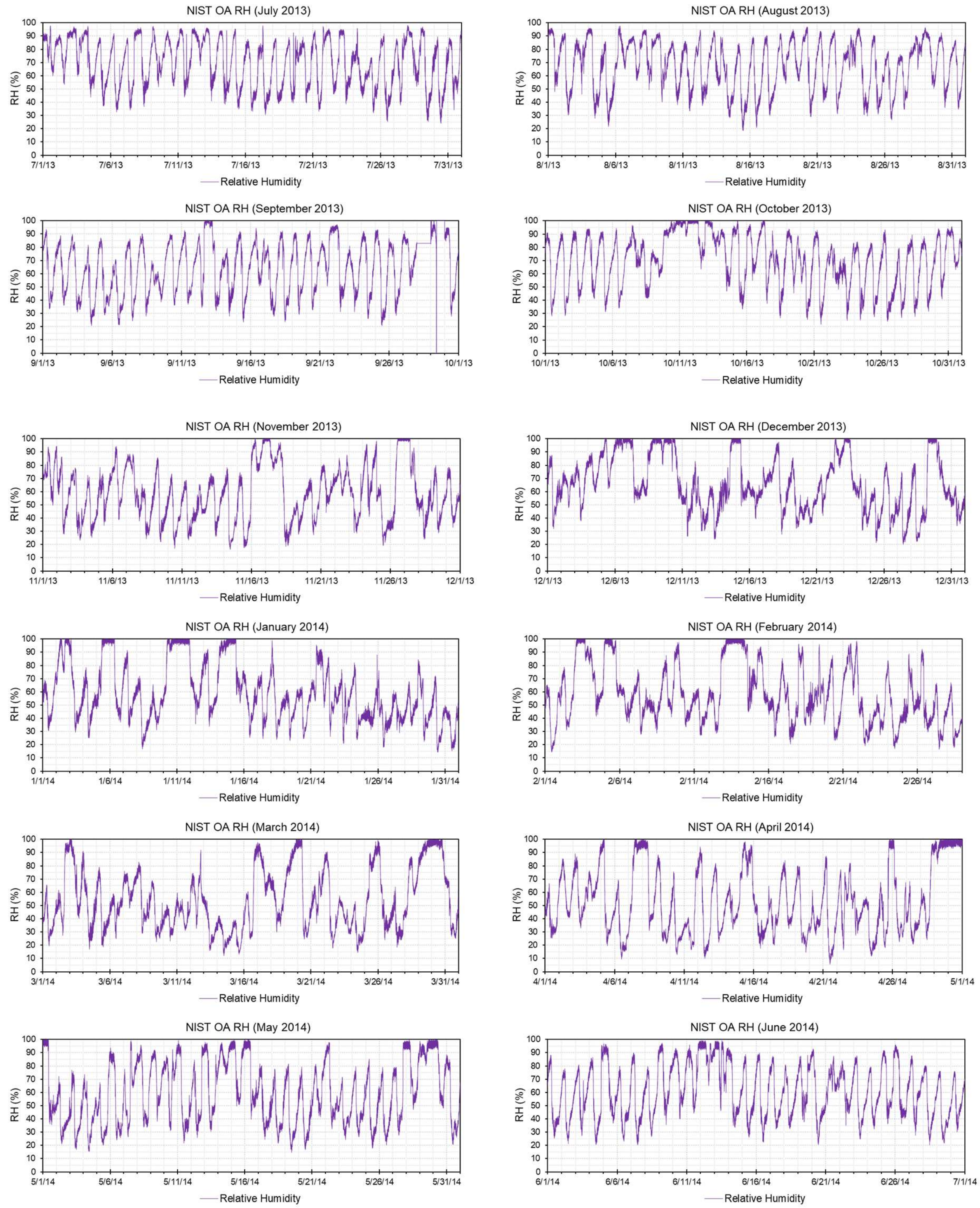

Figure C-75: Year 1 1-Min Outdoor Air Relative Humidity.

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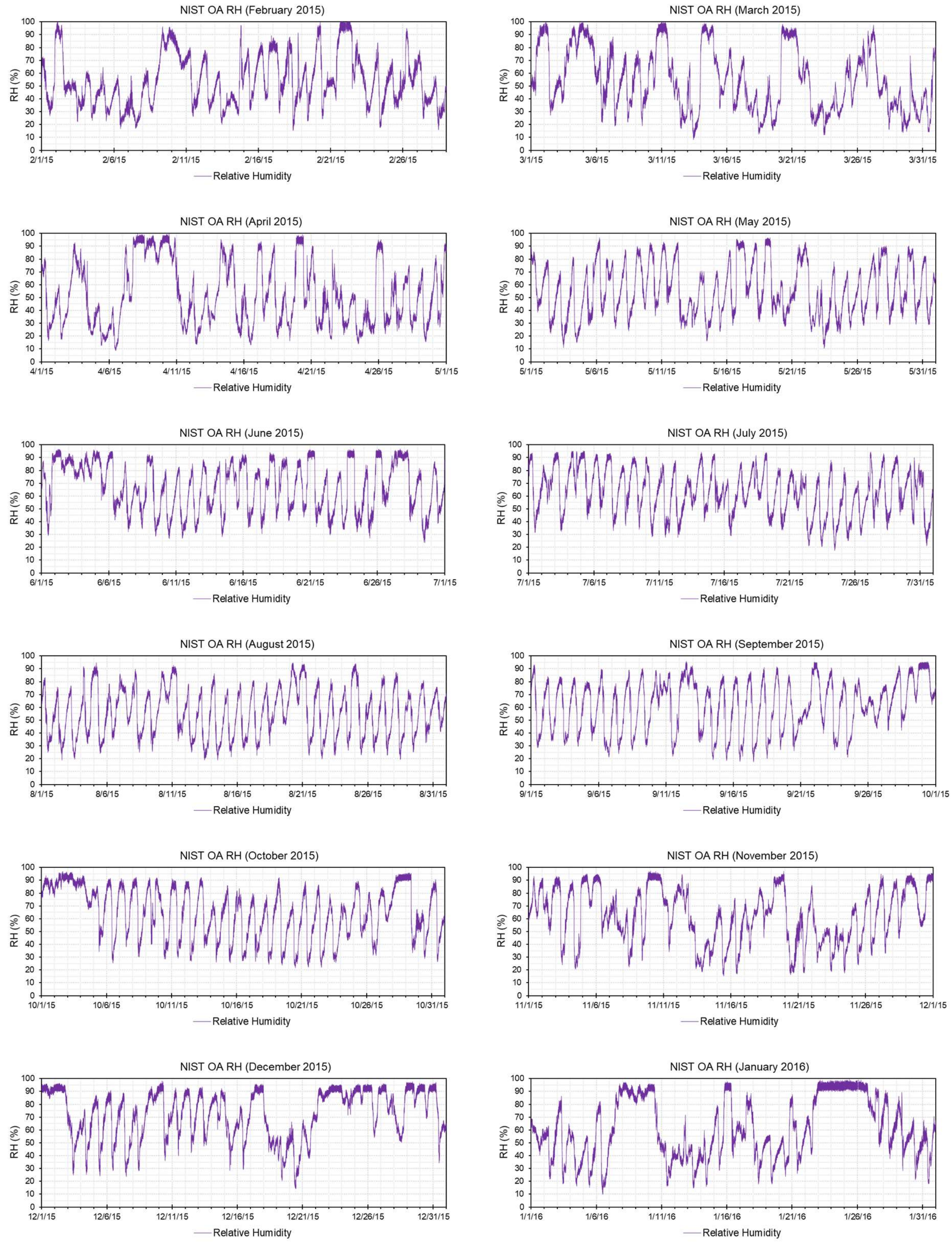

Figure C-76: Year 2 1-Min Outdoor Air Relative Humidity.

APPENDIX C-6: 1-MIN HEAT PUMP (HP) ELECTRICITY POWER

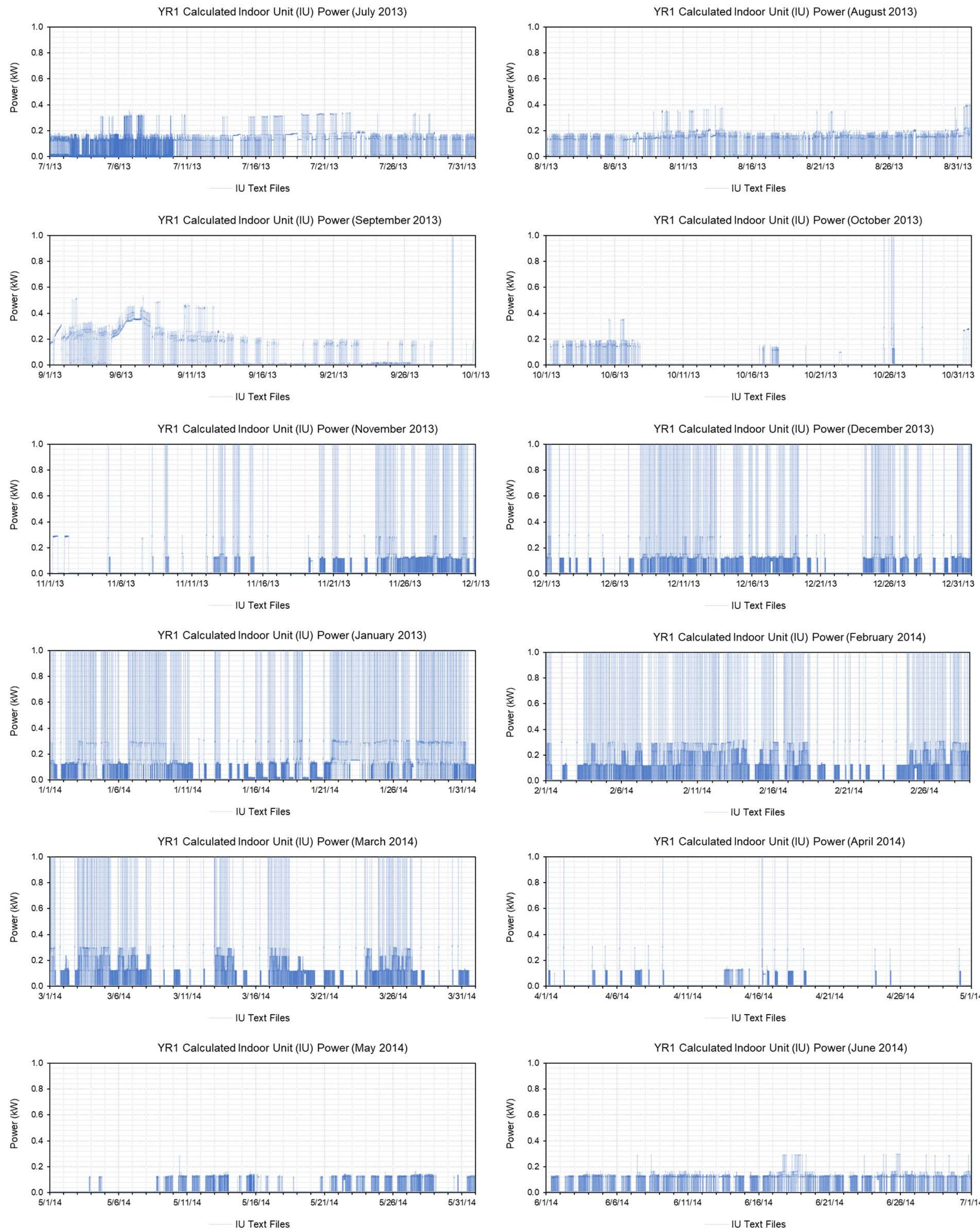

Figure C-77: Year 1 1-Min Heat Pump Indoor Unit Power.

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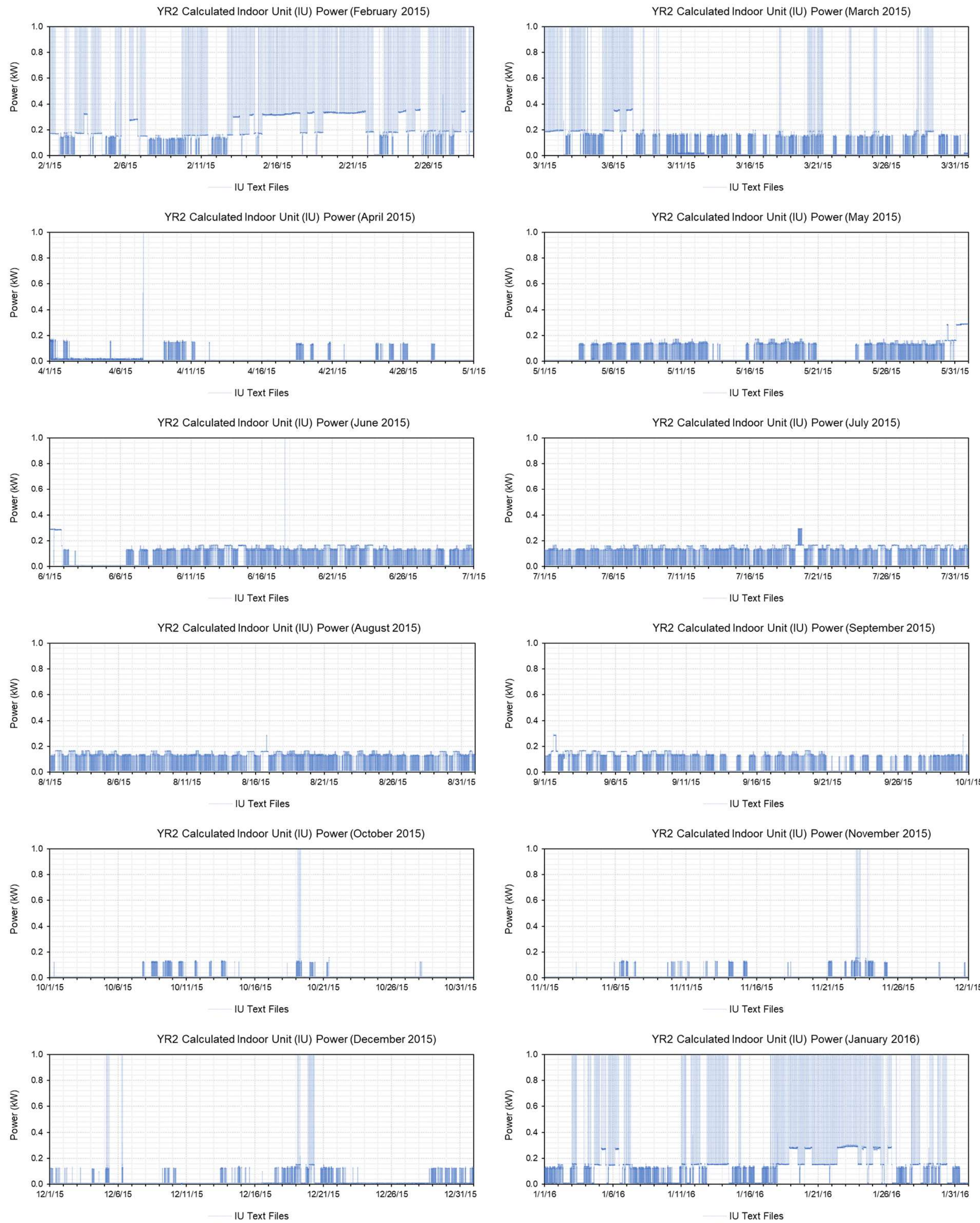

Figure C-78: Year 2 1-Min Heat Pump Indoor Unit Power.

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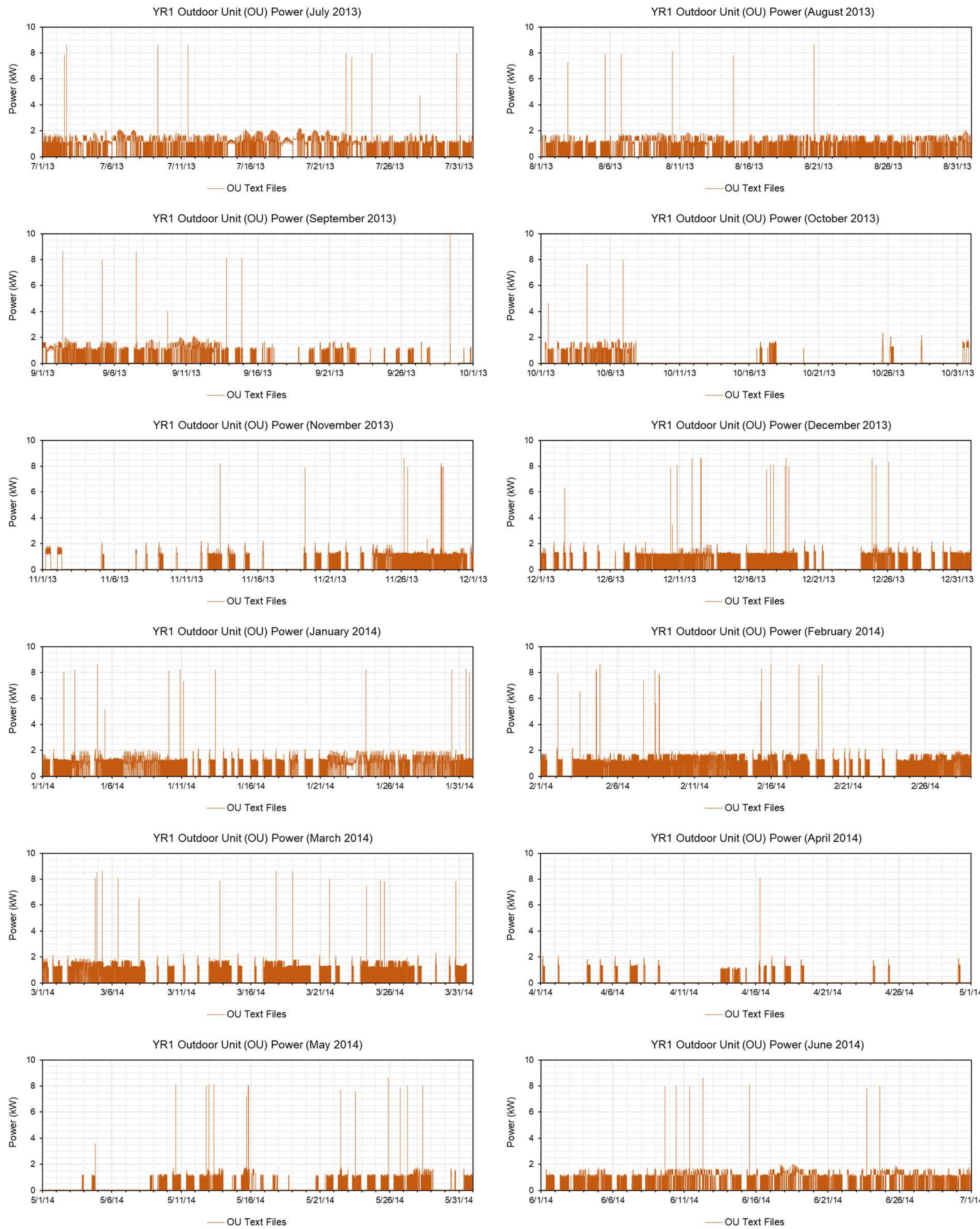

Figure C-79: Year 1 1-Min Heat Pump Outdoor Unit Power.

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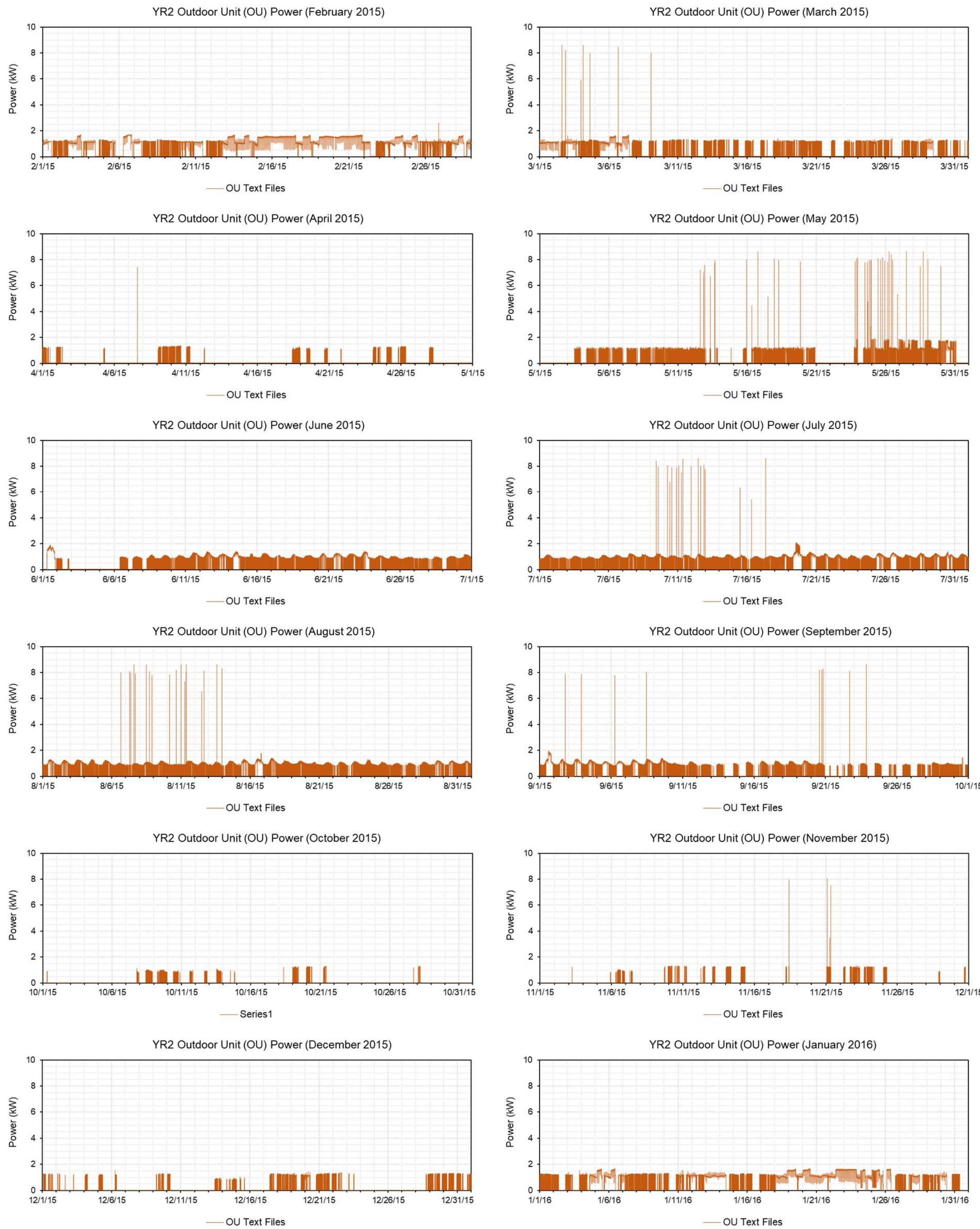

Figure C-80: Year 2 1-Min Heat Pump Outdoor Unit Power.

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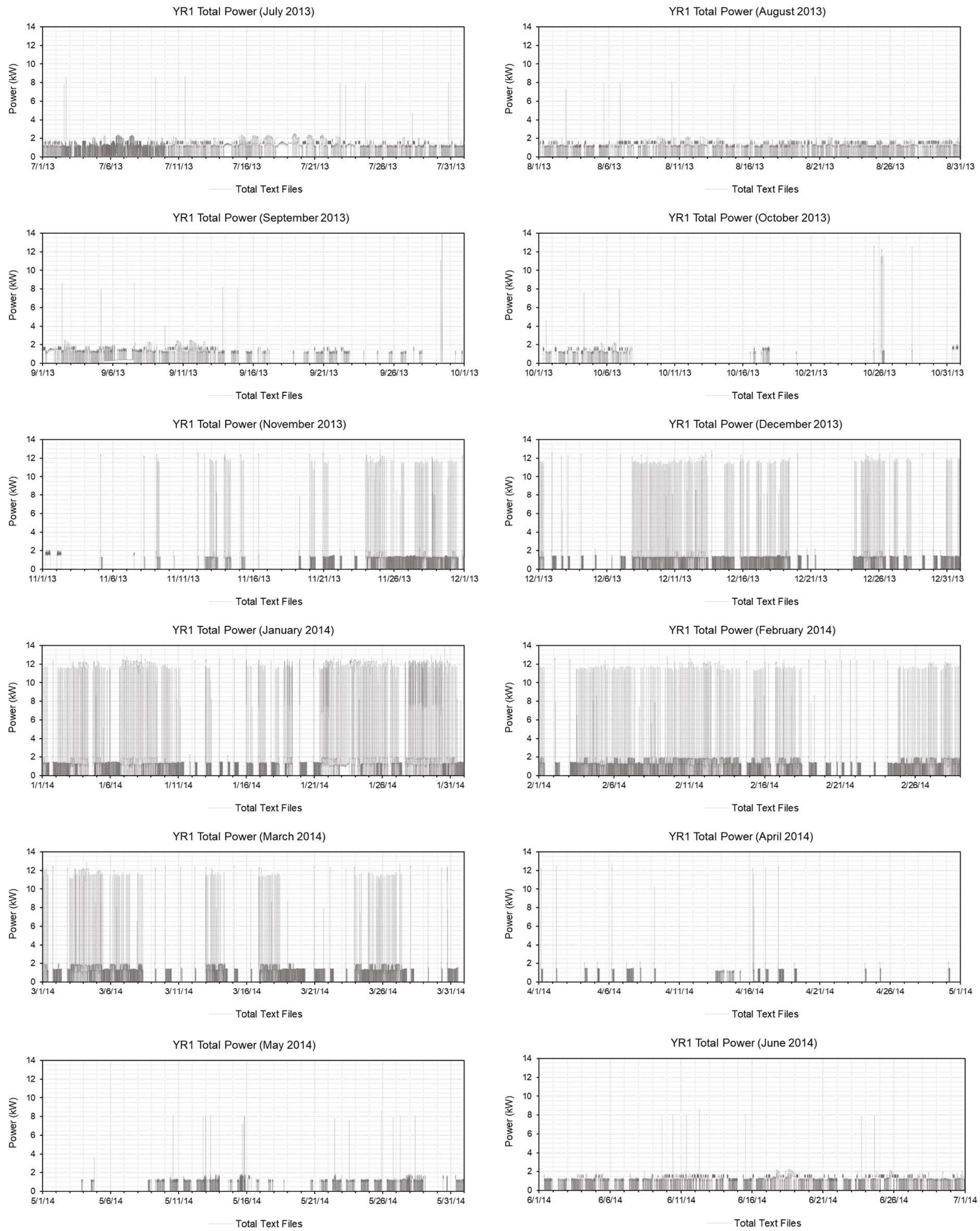

Figure C-81: Year 1 1-Min Heat Pump Total Power.

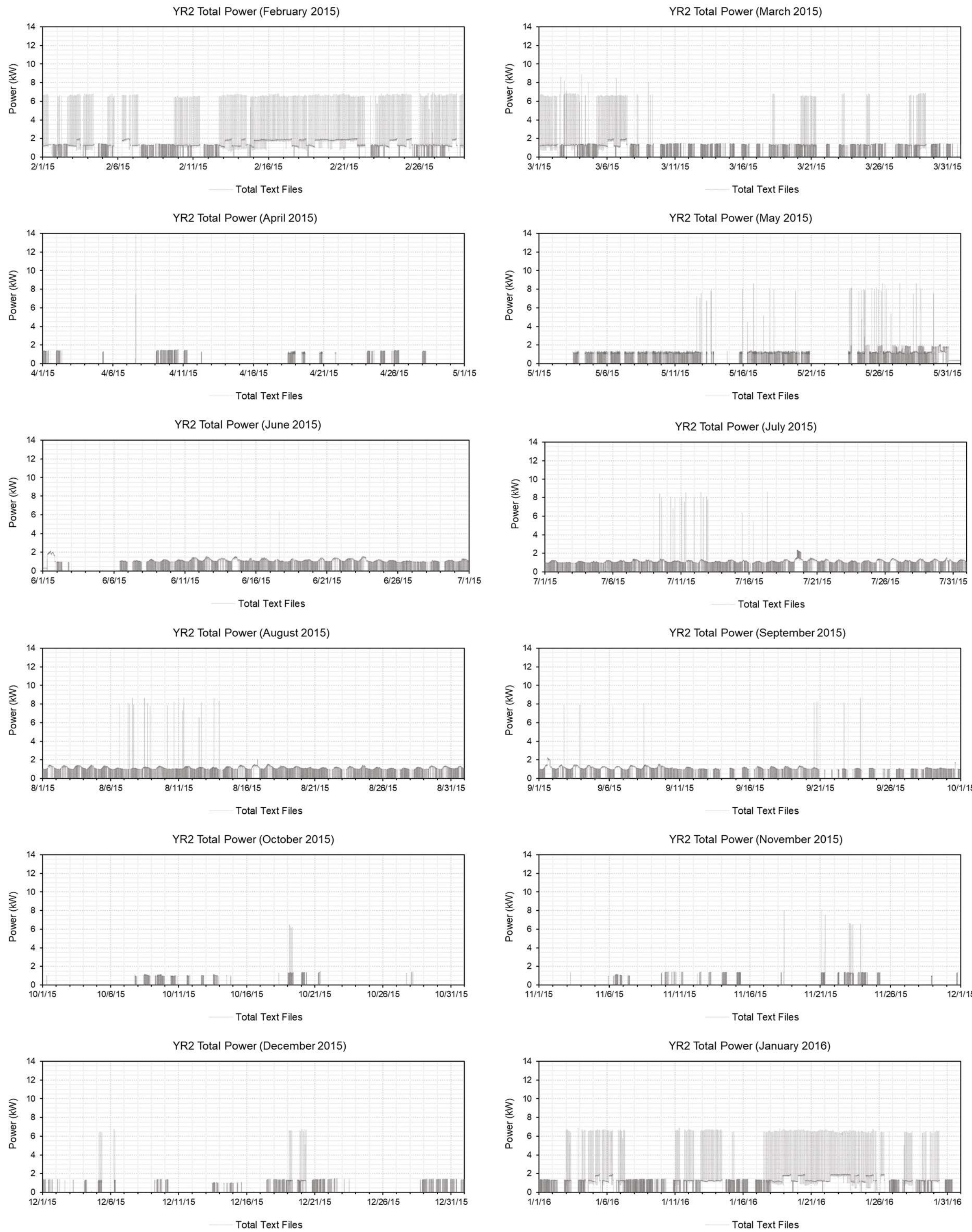

Figure C-82: Year 2 1-Min Heat Pump Total Power.

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APPENDIX D: GLOBE-TO-AIR TEMPERATURE DIFFERENCE

Appendix D graphically present the globe-to-air temperature difference (i.e., ΔT (°C) = Tg – Ta) calculated using the 5-min average temperature data collected from the five primary rooms (i.e., LR, KIT, MBR, BR2, and BR3). Data were color-coded by system types (i.e., yellow for YR1 HTTD, dark orange for YR1 LTTD, and green for YR2). This includes:

- Cooling season (Figure D-1);
- Heating Season (Figure D-2); and
- Transitional Season (Figure D-3).

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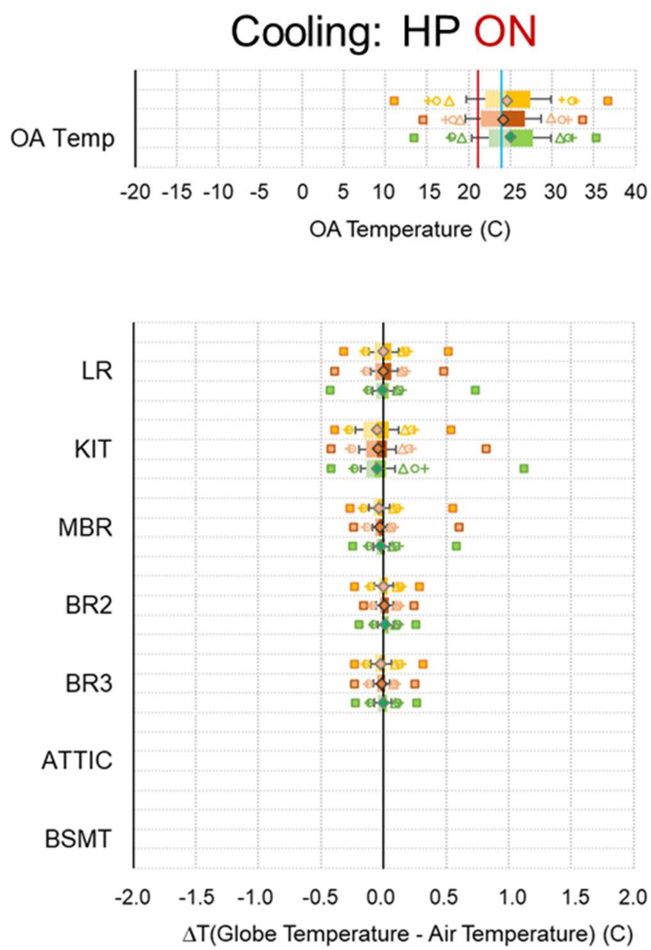

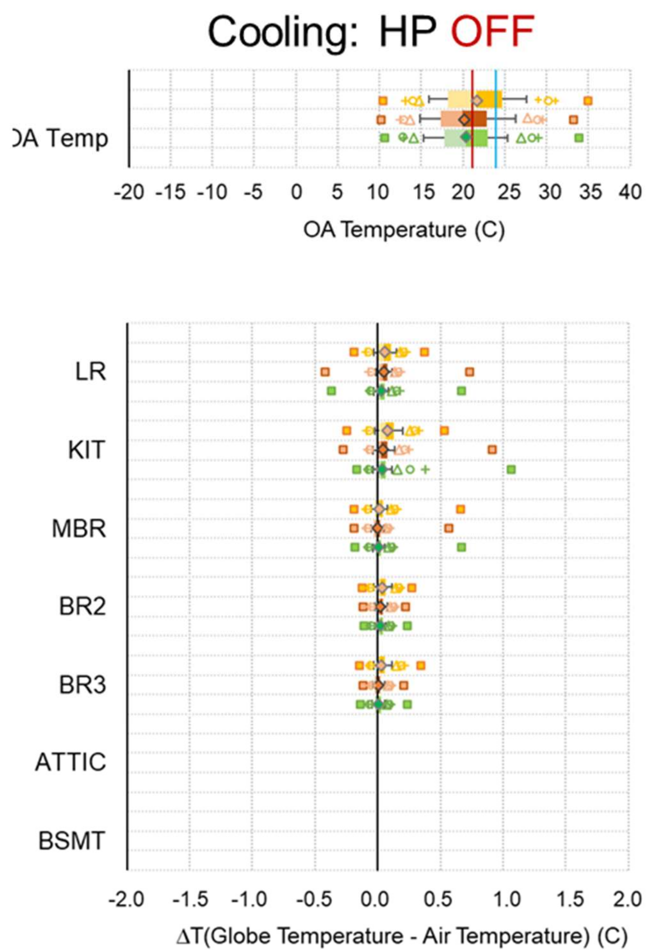

Figure D-1: Graphical Summaries of the 5-Min Average Globe-To-Air Temperature Differences When the Heat Pump System Was On Cycle (Left Figure) and Off Cycle (Right Figure) for the Cooling Season.

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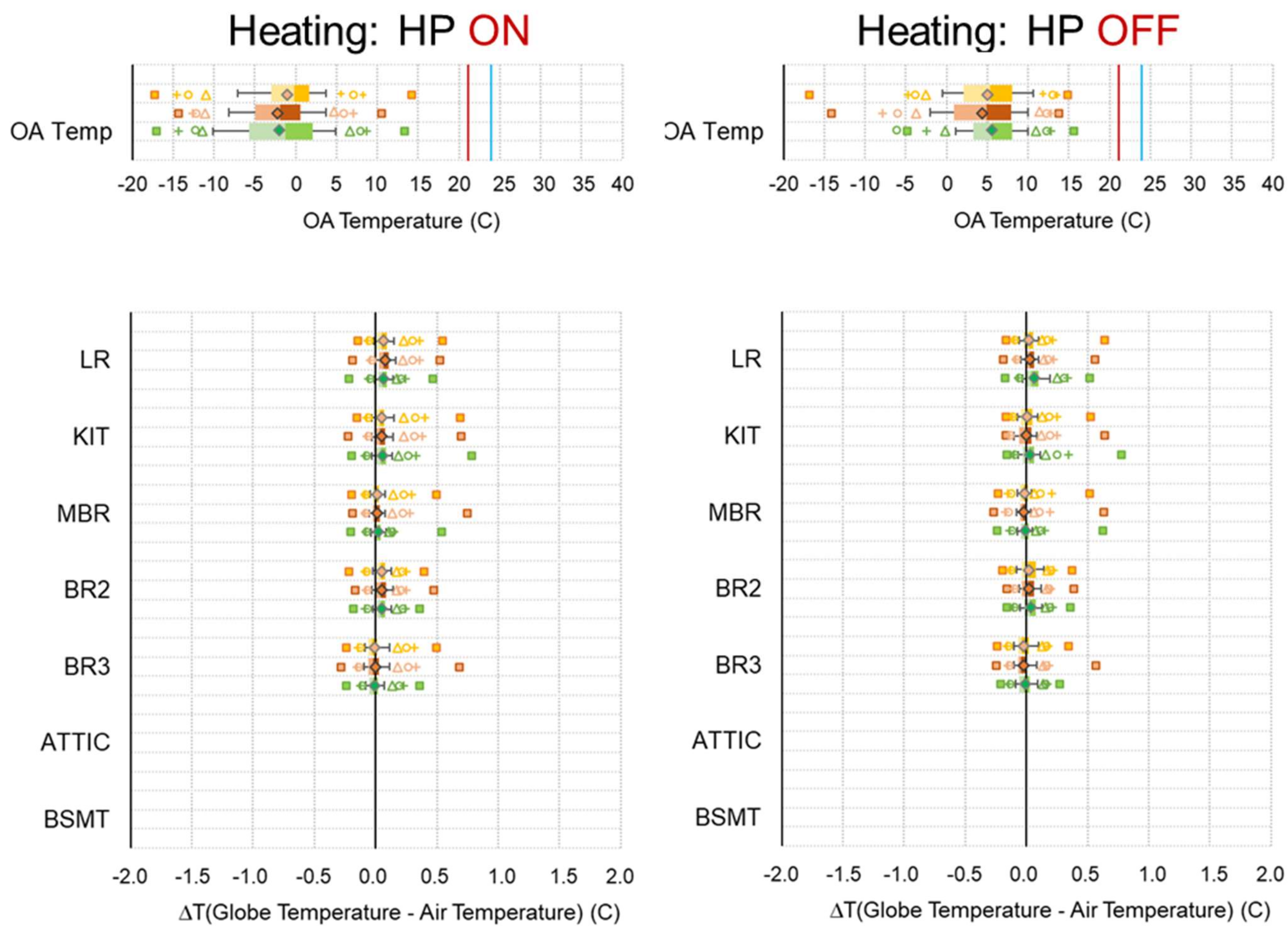

Figure D-2: Graphical Summaries of the 5-Min Average Globe-To-Air Temperature Differences When the Heat Pump System Was On Cycle (Left Figure) and Off Cycle (Right Figure) for the Heating Season.

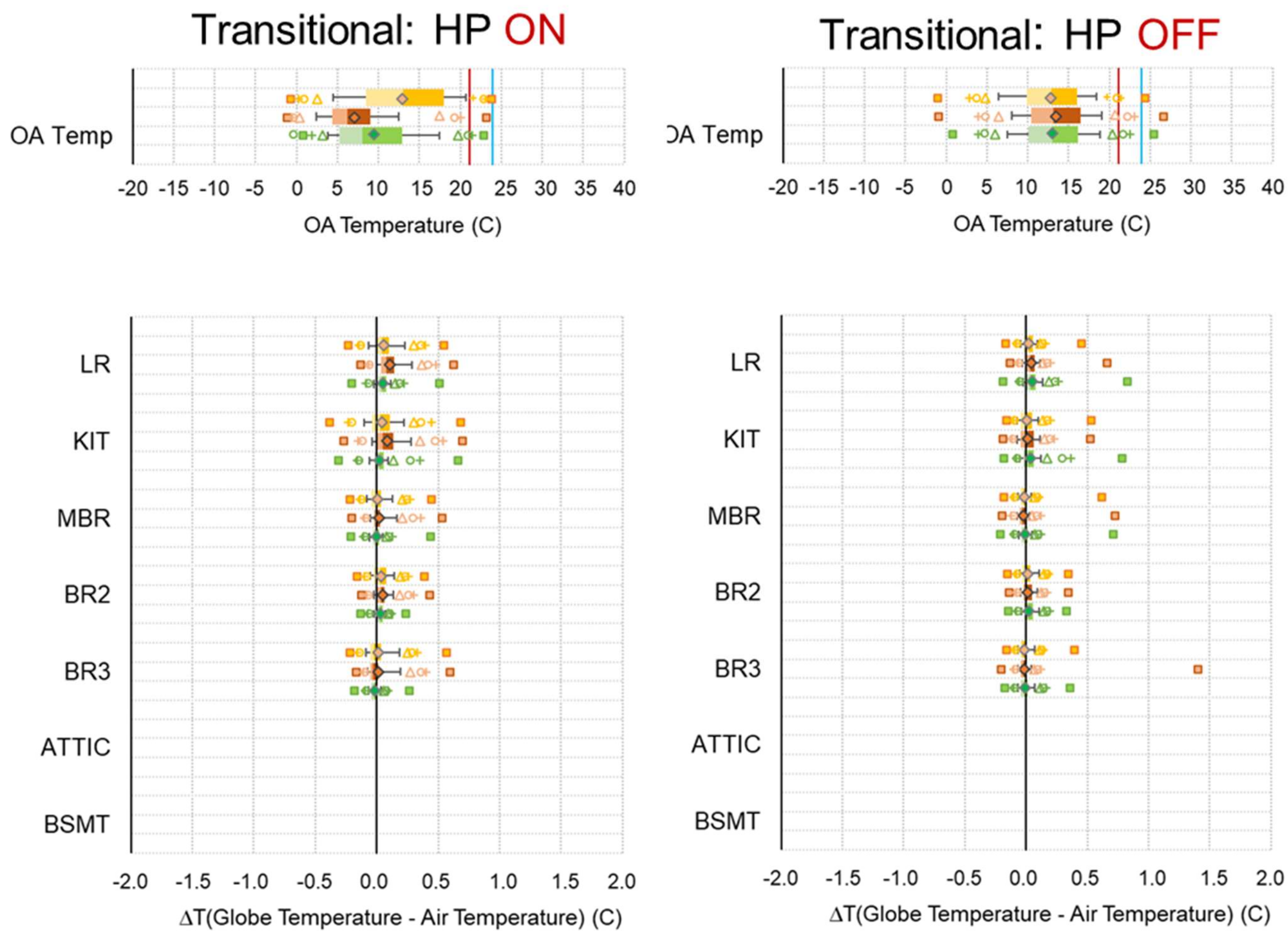

Figure D-3: Graphical Summaries of the 5-Min Average Globe-To-Air Temperature Differences When the Heat Pump System Was On Cycle (Left Figure) and Off Cycle (Right Figure) for the Transitional Season.

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APPENDIX E: Binned Room Air Temperatures and Humidity Ratios Against Outdoor Temperatures (Other Rooms)

Appendix E presents the binned room air temperatures and humidity ratios against outdoor temperatures for the following rooms as supplementary materials to Section 3.4:

- Room air temperature for MBR (Figure E-1);
- Room air temperatures for BR3 (Figure E-2);
- Room air temperature for ATTIC (Figure E-3);
- Room air temperatures for BSMT (Figure E-4);
- Room humidity ratios for MBR (Figure E-5);
- Room humidity ratios for BR3 (Figure E-6);
- Room humidity ratios for MBA (Figure E-7); and
- Room humidity ratios for BSMT (Figure E-8).

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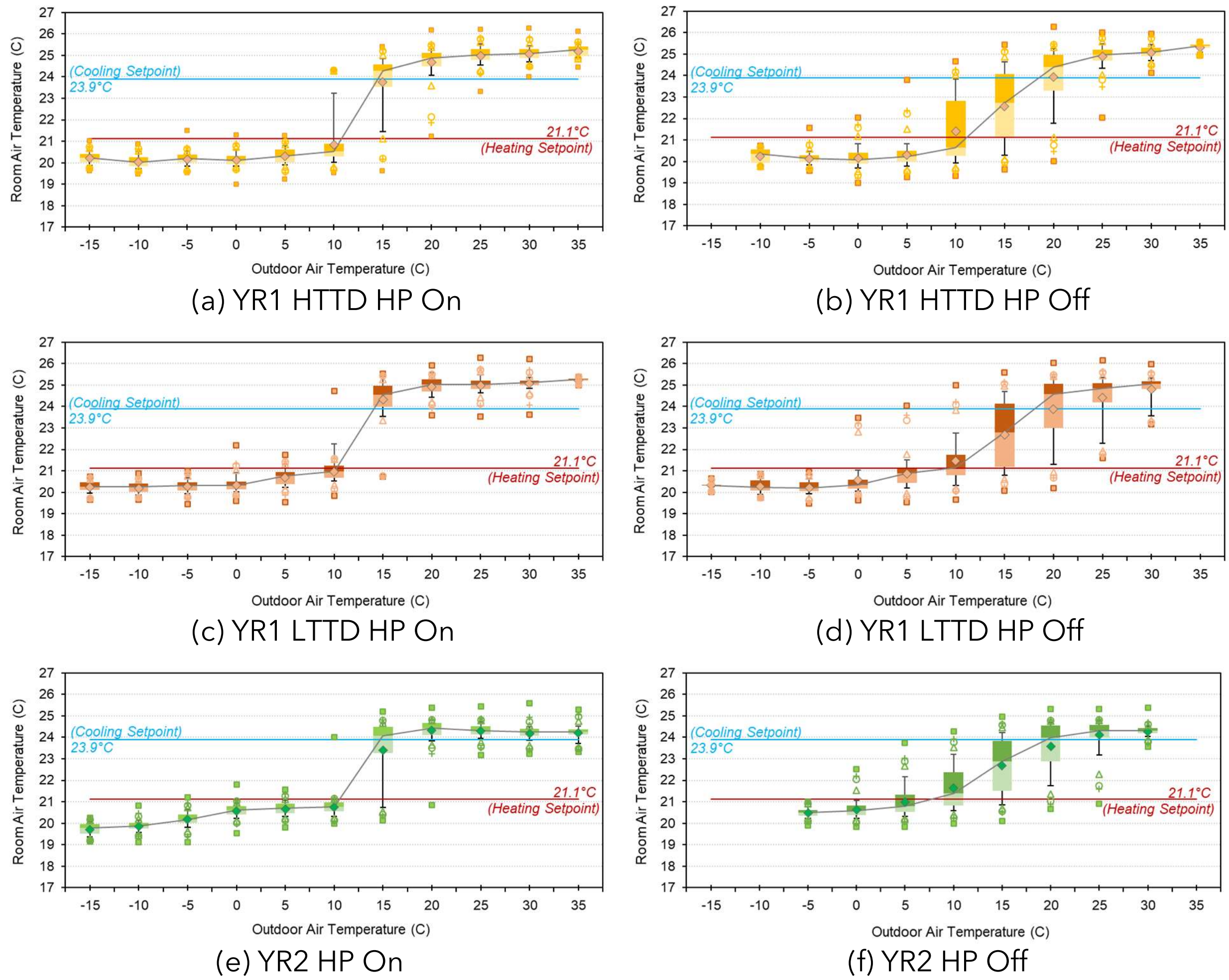
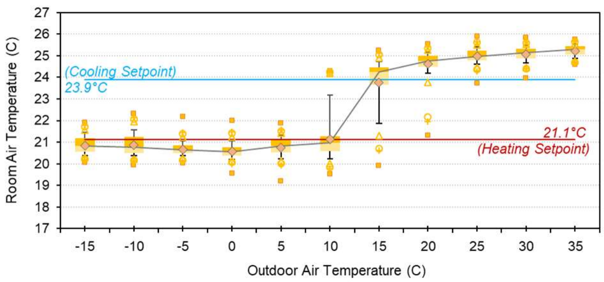
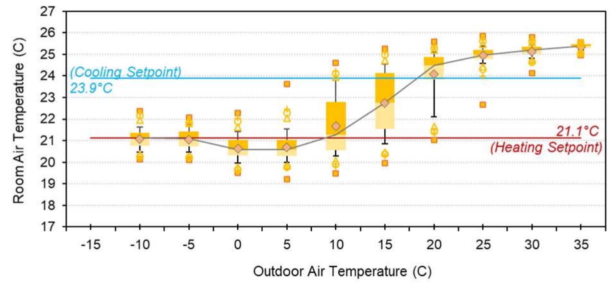


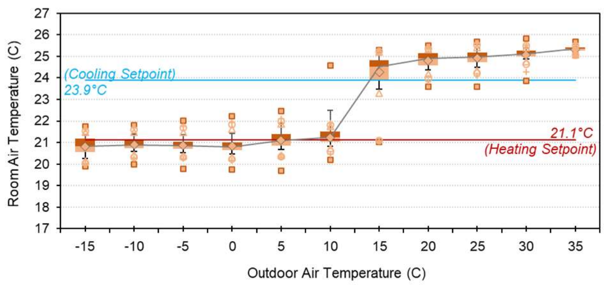
Figure E-1: Binned MBR Room Air Temperatures Against Outdoor Temperatures.



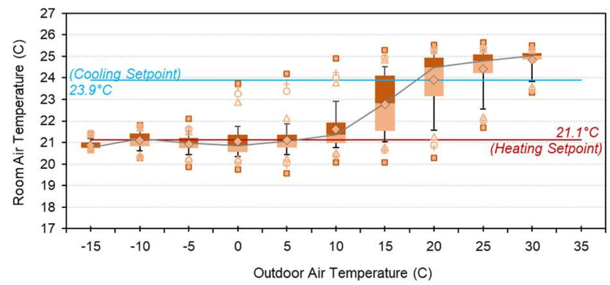
(a) YR1 HTTD HP On



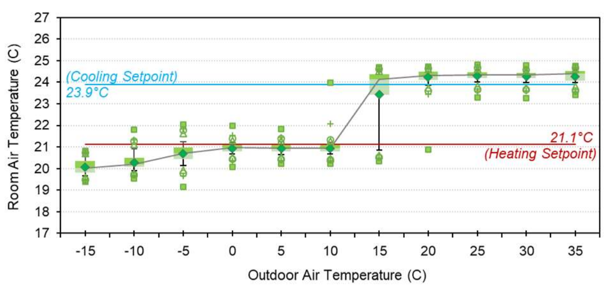
(b) YR1 HTTD HP Off



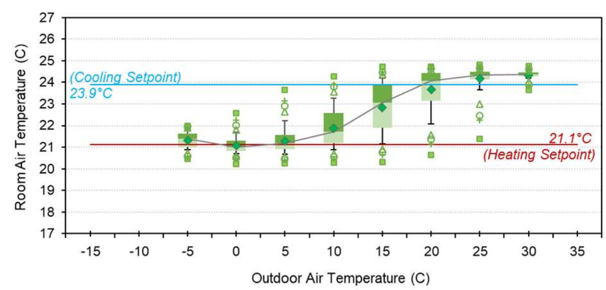
(c) YR1 LTTD HP On



(d) YR1 LTTD HP Off



(e) YR2 HP On



(f) YR2 HP Off

Figure E-2: Binned BR3 Room Air Temperatures Against Outdoor Temperatures.

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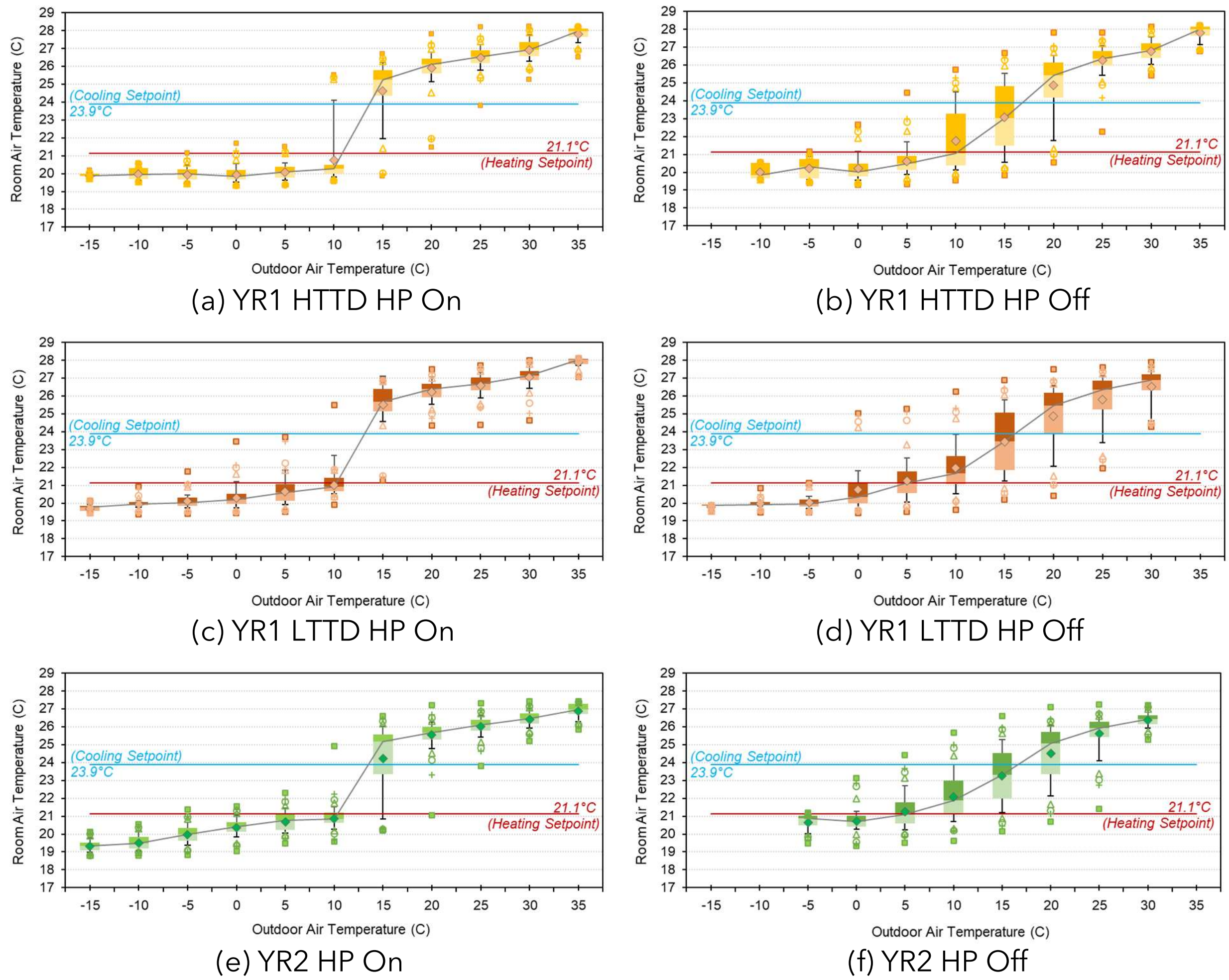

(a) YR1 HTTD HP On
(b) YR1 HTTD HP Off
(c) YR1 LTTD HP On
(d) YR1 LTTD HP Off
(e) YR2 HP On
(f) YR2 HP Off

Figure E-3: Binned ATTIC Room Air Temperatures Against Outdoor Temperatures.

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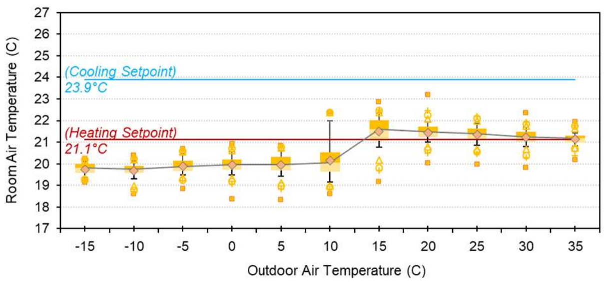
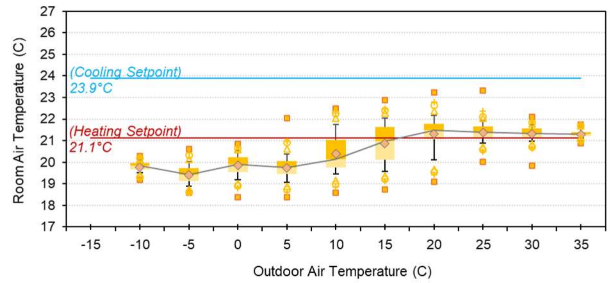
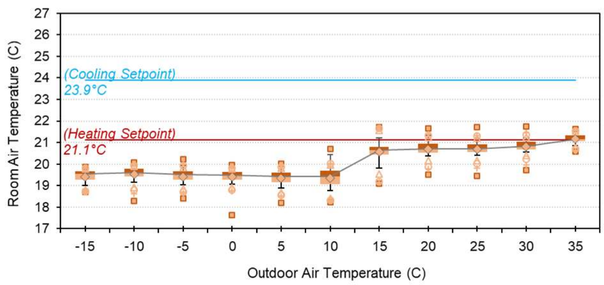


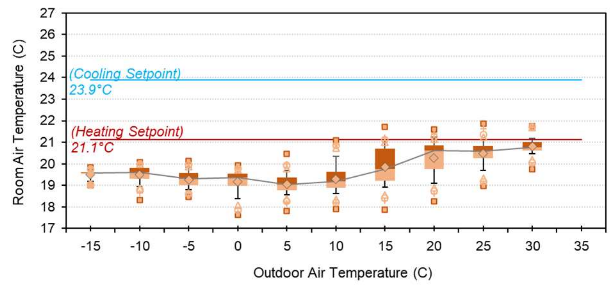
(a) YR1 HTTD HP On



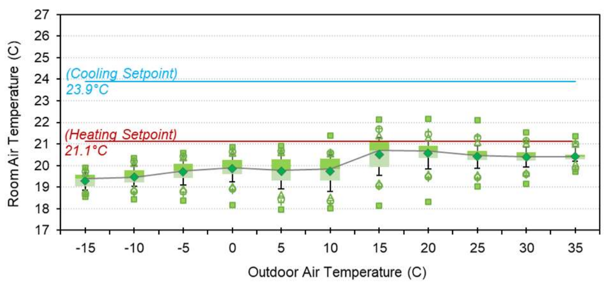
(b) YR1 HTTD HP Off



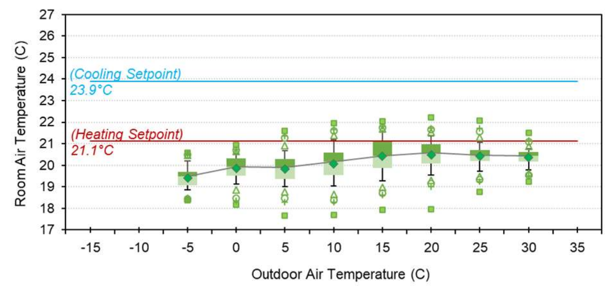
(c) YR1 LTTD HP On



(d) YR1 LTTD HP Off



(e) YR2 HP On



(f) YR2 HP Off

Figure E-4: Binned BSMT Room Air Temperatures Against Outdoor Temperatures.

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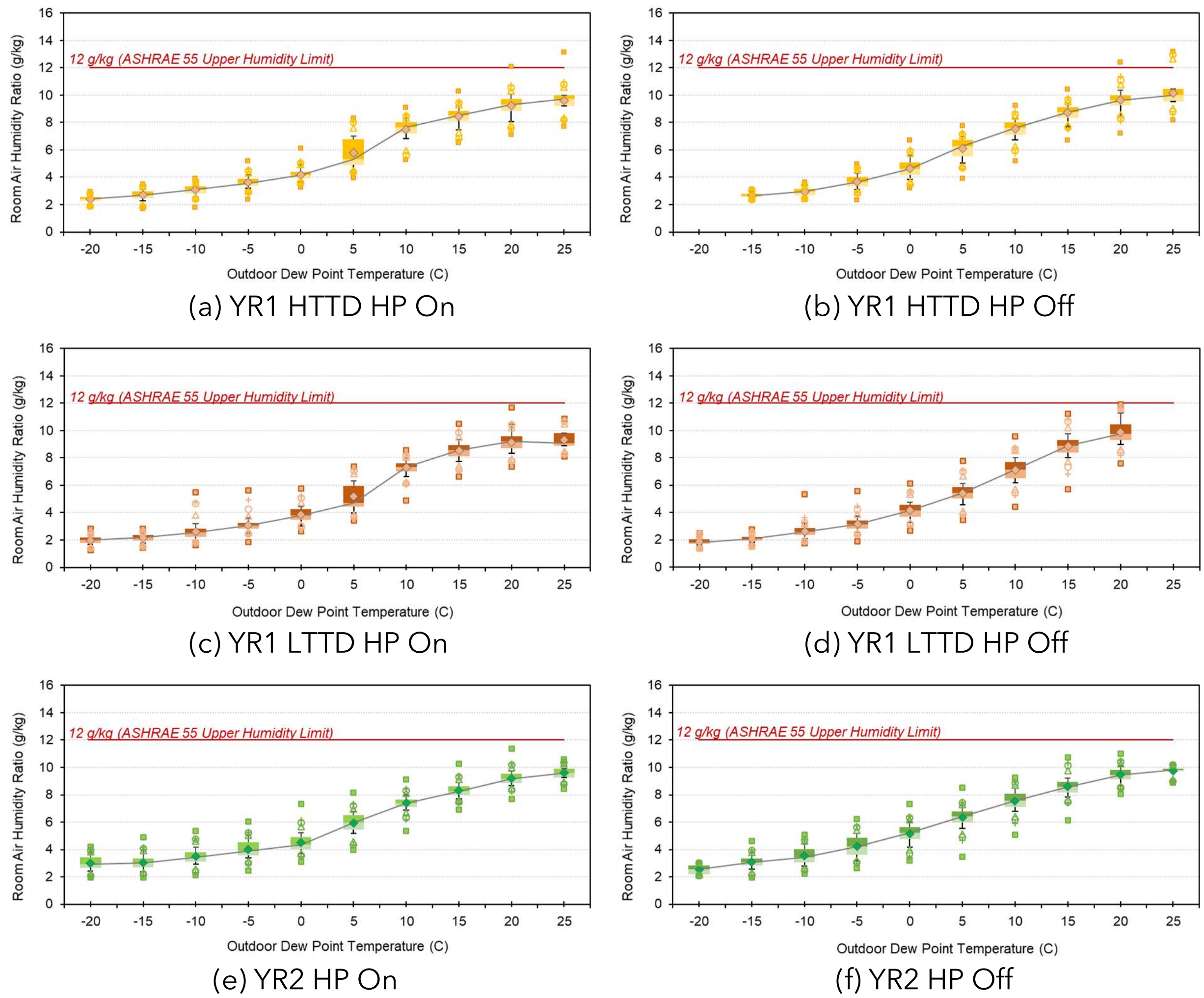

(a) YR1 HTTD HP On

(b) YR1 HTTD HP Off

(c) YR1 LTTD HP On

(d) YR1 LTTD HP Off

(e) YR2 HP On

(f) YR2 HP Off

Figure E-5: Binned MBR Room Humidity Ratio Against Outdoor Temperatures.

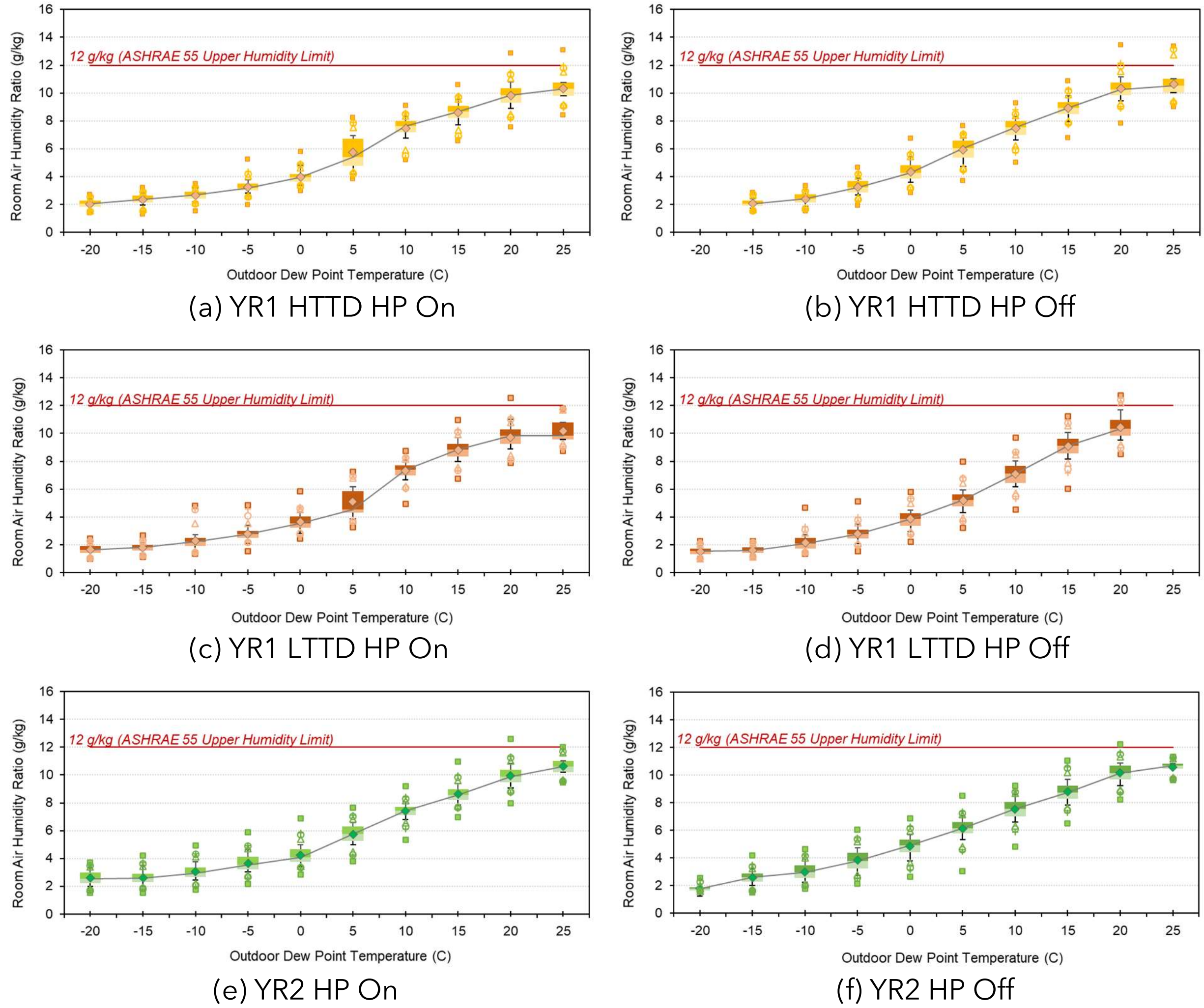

Figure E-6: Binned BR3 Room Humidity Ratio Against Outdoor Temperatures.

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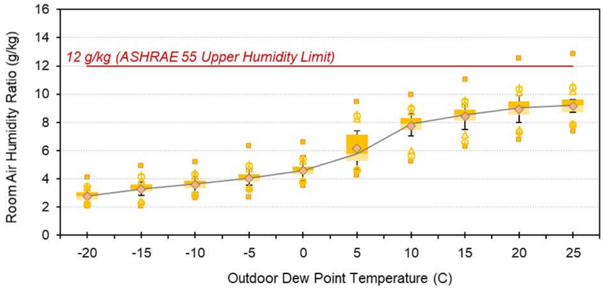
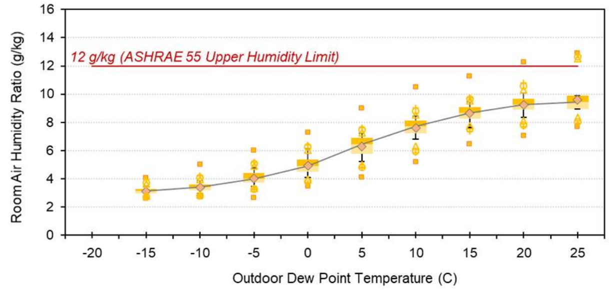
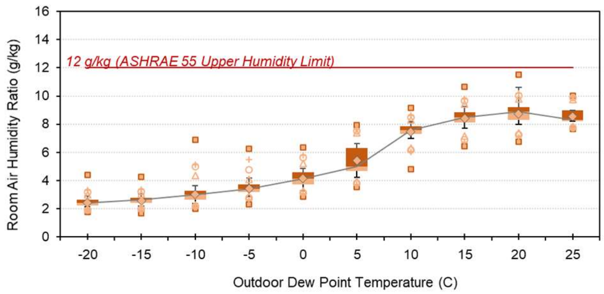


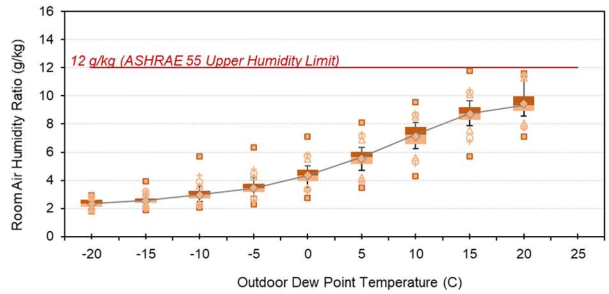
(a) YR1 HTTD HP On



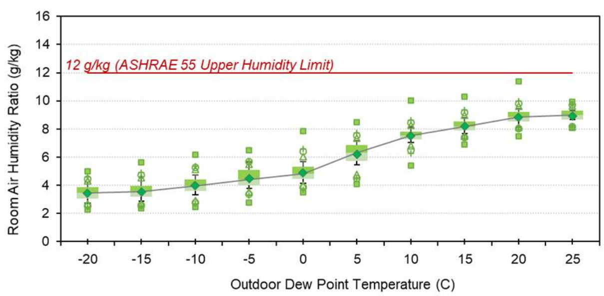
(b) YR1 HTTD HP Off



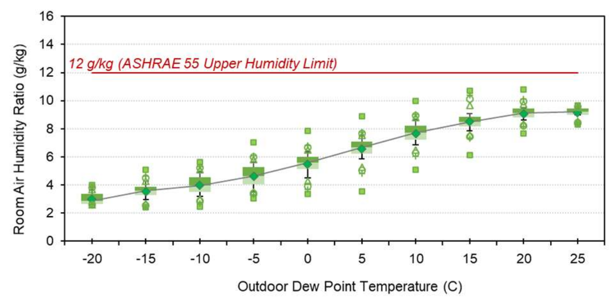
(c) YR1 LTTD HP On



(d) YR1 LTTD HP Off



(e) YR2 HP On



(f) YR2 HP Off

Figure E-7: Binned MBA Room Humidity Ratio Against Outdoor Temperatures.

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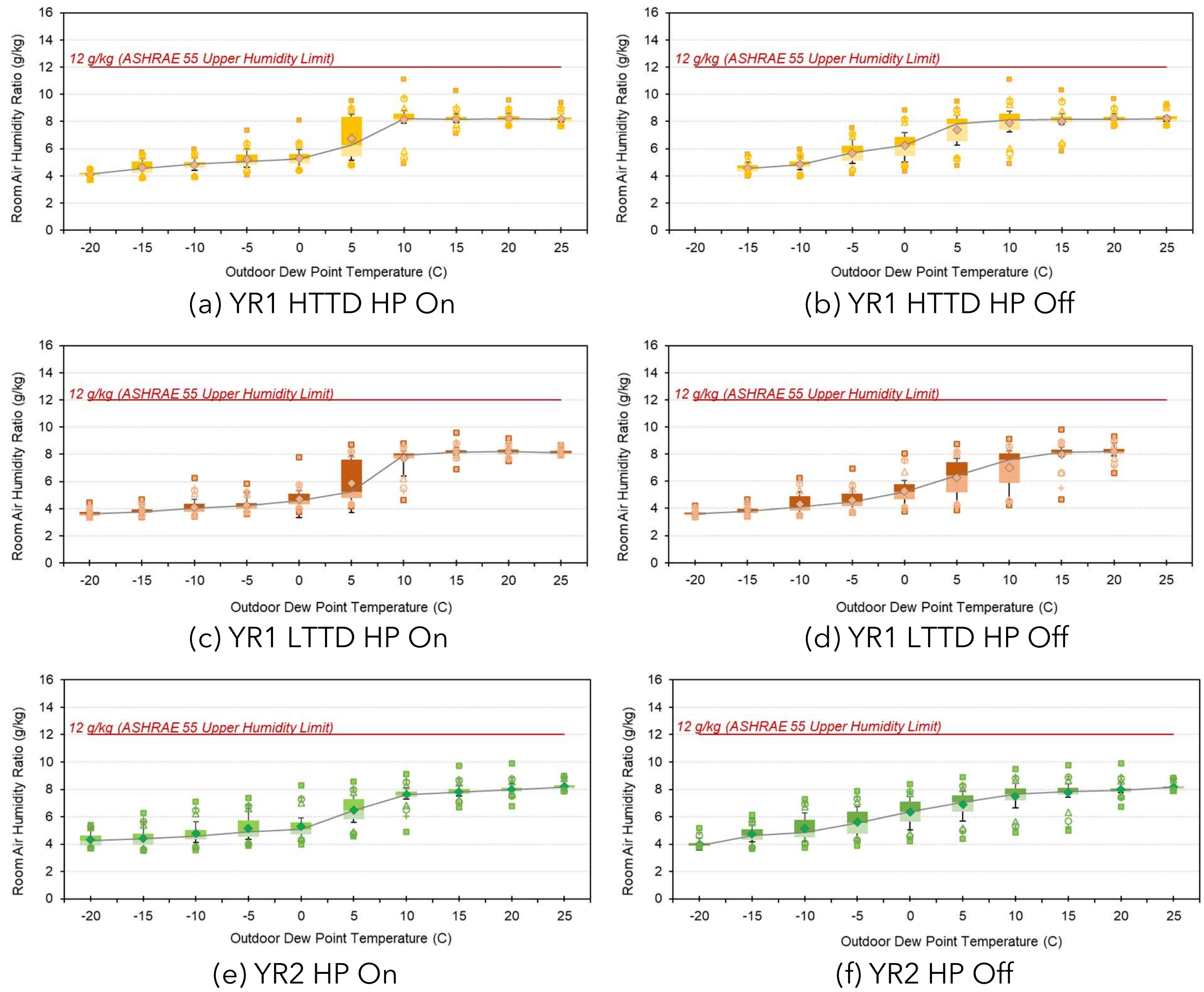

(a) YR1 HTTD HP On

(b) YR1 HTTD HP Off

(c) YR1 LTTD HP On

(d) YR1 LTTD HP Off

(e) YR2 HP On

(f) YR2 HP Off

Figure E-8: Binned BSMT Room Humidity Ratio Against Outdoor Temperatures.

APPENDIX F: Time-of-Day Colored Maps (Other Rooms)

Appendix F presents time-of-day colored maps applied to the hourly average room temperatures over the measurement periods for the following rooms as supplementary materials to Section 3.5:

- MBR (Figure F-1);
- BR3 (Figure F-2);
- BR4 (Figure F-3); and
- DR (Figure F-4).

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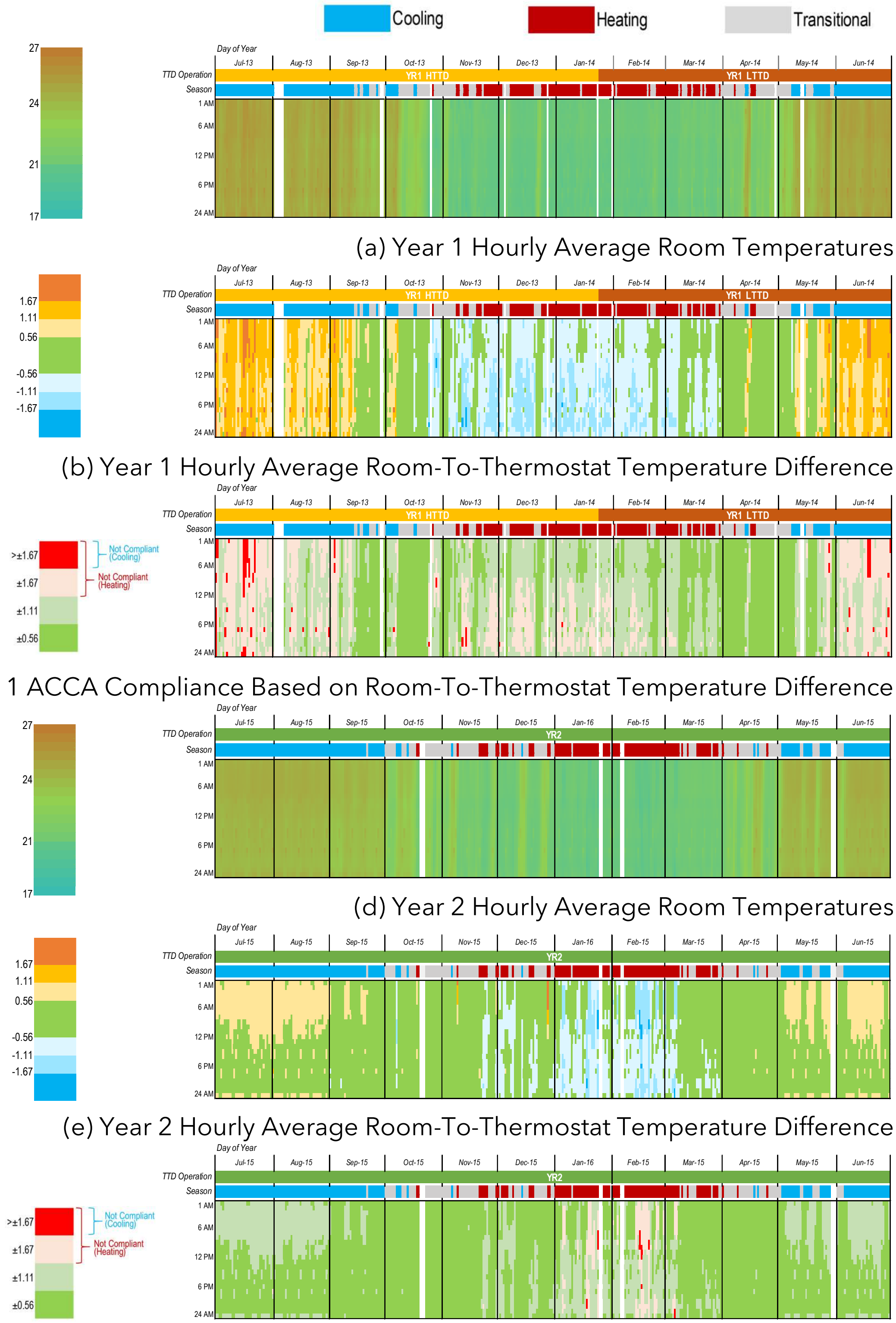

(a) Year 1 Hourly Average Room Temperatures

(b) Year 1 Hourly Average Room-To-Thermostat Temperature Difference

(c) Year 1 ACCA Compliance Based on Room-To-Thermostat Temperature Difference

(d) Year 2 Hourly Average Room Temperatures

(e) Year 2 Hourly Average Room-To-Thermostat Temperature Difference

(f) Year 2 ACCA Compliance Based on Room-To-Thermostat Temperature Difference

Figure F-1: Time-of-Day Colored Map of MBR Temperature.

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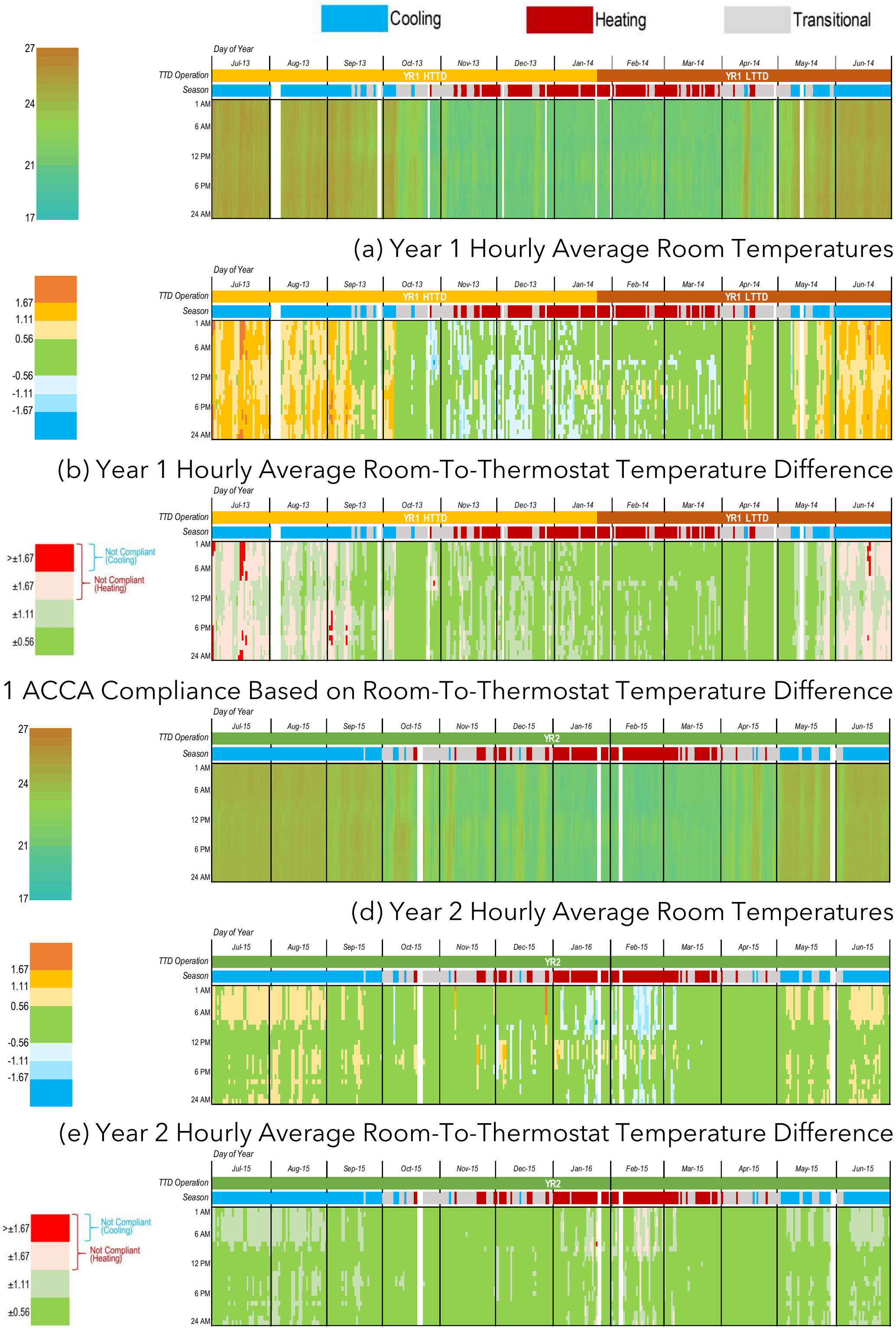

(a) Year 1 Hourly Average Room Temperatures

(b) Year 1 Hourly Average Room-To-Thermostat Temperature Difference

(c) Year 1 ACCA Compliance Based on Room-To-Thermostat Temperature Difference

(d) Year 2 Hourly Average Room Temperatures

(e) Year 2 Hourly Average Room-To-Thermostat Temperature Difference

(f) Year 2 ACCA Compliance Based on Room-To-Thermostat Temperature Difference

Figure F-2: Time-of-Day Colored Map of BR3 Temperature.

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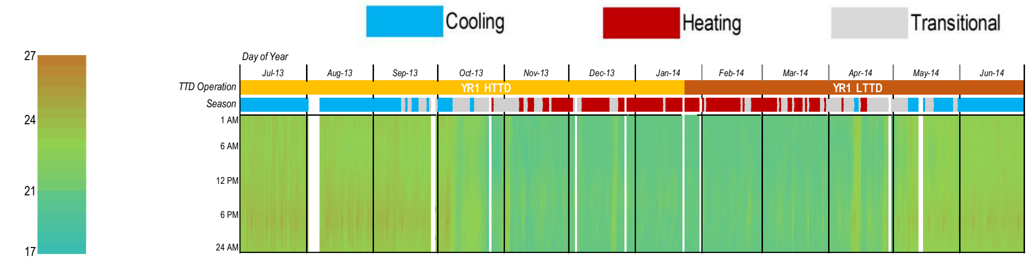
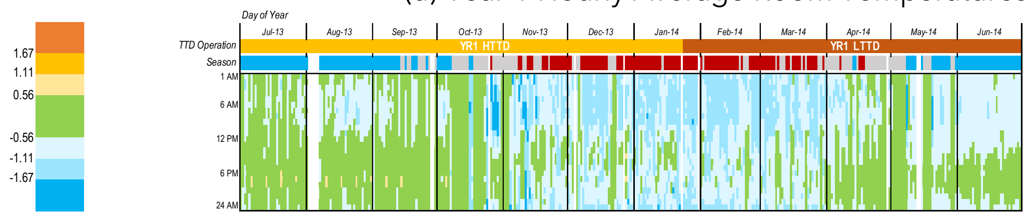
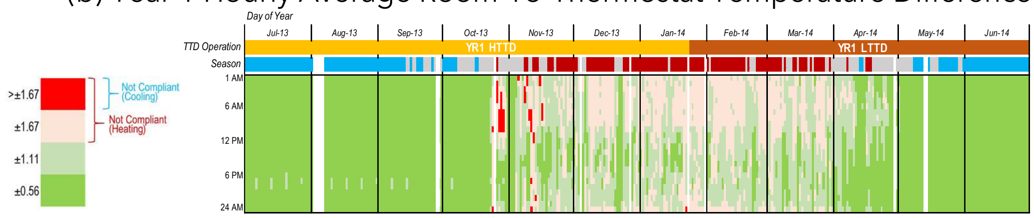


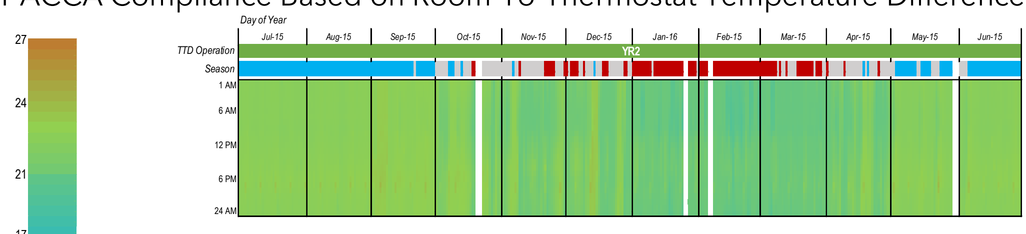
(a) Year 1 Hourly Average Room Temperatures



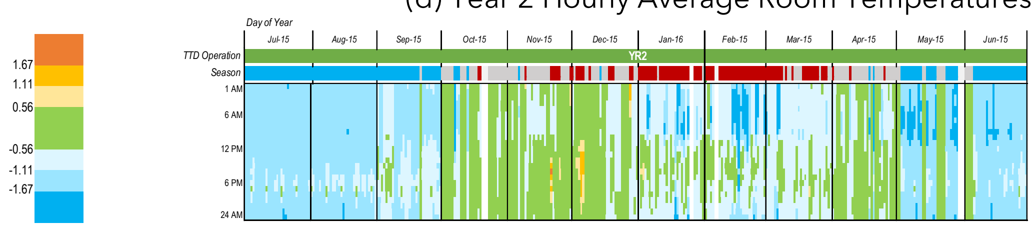
(b) Year 1 Hourly Average Room-To-Thermostat Temperature Difference



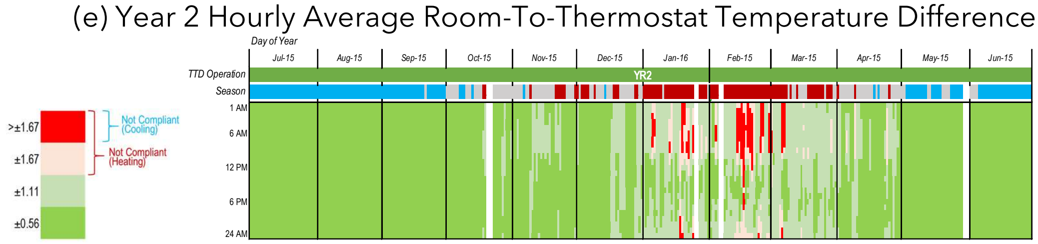
(c) Year 1 ACCA Compliance Based on Room-To-Thermostat Temperature Difference



(d) Year 2 Hourly Average Room Temperatures



(e) Year 2 Hourly Average Room-To-Thermostat Temperature Difference



(f) Year 2 ACCA Compliance Based on Room-To-Thermostat Temperature Difference

Figure F-3: Time-of-Day Colored Map of BR4 Temperature.

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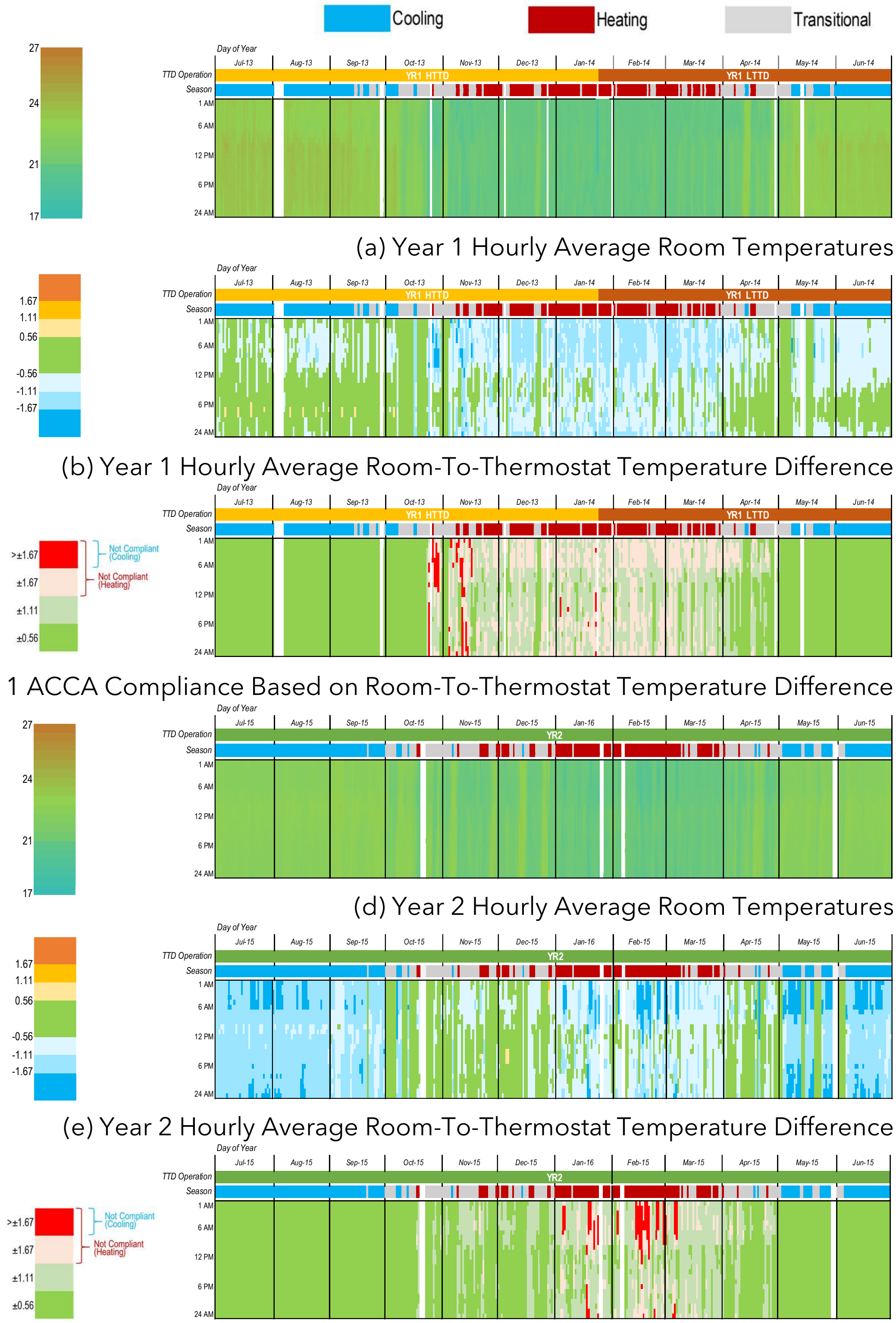

(a) Year 1 Hourly Average Room Temperatures

(b) Year 1 Hourly Average Room-To-Thermostat Temperature Difference

(c) Year 1 ACCA Compliance Based on Room-To-Thermostat Temperature Difference

(d) Year 2 Hourly Average Room Temperatures

(e) Year 2 Hourly Average Room-To-Thermostat Temperature Difference

(f) Year 2 ACCA Compliance Based on Room-To-Thermostat Temperature Difference

Figure F-4: Time-of-Day Colored Map of DR Temperature.