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Office of Strategic Planning and Development Effectiveness

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TECHNICAL NOTE Nº IDB-TN-01827

December 2019

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Inter-American Development Bank

Cataloging-in-Publication data provided by the
Inter-American Development Bank
Felipe Herrera Library
Davis, Lucas W.
Deploying temperature and humidity loggers in the field / Lucas W. Davis, Sebastián Martínez.
p. cm. — (IDB Technical Note ; 1827)
Includes bibliographic references.
1. Dwellings-Heating and ventilation-Mexico. 2. Temperature measuring instruments-Mexico. 3. Hygrometry-Mexico. 4. Data loggers-Mexico. I. Martínez, Sebastián. II. Inter-American Development Bank. Office of Strategic Planning and Development Effectiveness. III. Title. IV. Series.
IDB-TN-1827

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Lucas W. Davis[1] and Sebastian Martinez[2]

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Abstract: In this paper, we discuss new advances in temperature and humidity logging technology. We then report results from a deployment of loggers to measure interior thermal comfort in 450+ homes in a housing development in Mexico. We discuss best practices for deployment and data analysis and demonstrate how data from loggers can be used to examine thermal comfort across months of the year, hours of the day, and for different climatological conditions. We see great potential for increased application of data loggers in evaluating energy-efficiency investments and related building technologies.

Keywords: Thermal Comfort, Temperature Loggers, Humidity Loggers.

JEL Codes: C81, D12, O18, Q54.

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I. Introduction

One billion new homes will be needed worldwide by 2025, at an estimated total cost of $9-$11 trillion USD (United Nations, 2016). Housing serves many purposes but one of the principal purposes is to protect occupants from extreme temperatures. Increased deployment of temperature and humidity loggers can help better design homes to ensure that occupants stay cool in the summer and warm in the winter.

In this paper, we discuss new advances in temperature and humidity data logging. These sensors like the LogTag HAXO 8, are designed to measure and record thermal comfort information over long time periods. We describe our experience with a recent large-scale field trial in Mexico in which we deployed loggers in 450+ homes over a 16+ month period (Davis et al, 2020).

Before beginning the field trial, we conducted an initial 6-month operational pilot testing seven different models of data loggers in a sub-sample of 45 homes. We describe what we learned from the operational pilot about the advantages and disadvantages of each model, and how we eventually decided on the LogTag HAXO 8 as our preferred logger for the full-scale deployment.

We then describe the field trial in detail. We explain how we worked with households to deploy and collect information from the loggers, as well as our approach for cleaning and assembling the 16+ months of raw data. Finally, we present a series of figures showing the rich data collected on temperature and humidity. We present the information in a variety of different ways including by month of year, by hour of day, and across climatological conditions.

This is the first study that we are aware of to deploy such large numbers of high-frequency data loggers to measure interior temperature and humidity. This kind of accurate and affordable measurement of indoor temperature and humidity will become increasingly relevant, particularly with regard to heat, under climate change. With three billion people living in the tropics, understanding how to build homes to improve thermal comfort is an important societal priority.

We view these data as a valuable complement to engineering analyses of building shell performance. See, e.g., Givoni (1992), Baker and Standeven (1996), Nicol and Humphrey (2002), and Nikolopoulou and Steemers (2003). The granularity of these data make possible highly detailed comparisons of *ex ante* model predictions with *ex post* building performance in practice, consistent with a growing literature in economics that performs such analyses (Dubin et al., 1986, Aydin et al.. 2017, Fowlie et al., 2018.

We see broad potential for deploying data logger technology like this to inform engineering models, for program evaluation, and other contexts. Quickly learning what works and does not work is key to technological advancing. New home construction is a major focus of governments and development agencies, and there is a large gap between projected demand and supply of affordable housing in low- and middle-income countries (United Nations, 2016), so this knowledge is of significant policy interest.

Improved sensors are also valuable for understanding energy consumption from buildings. According to the U.S. Energy Information Administration, energy consumption from buildings is forecast to increase 65% worldwide between 2018 and 2050, from 91 quadrillion to 139 quadrillion Btu (EIA, 2019). Policymakers are turning to energy-efficiency as a way of potentially stemming these increases, and improved measurement of thermal comfort is valuable for testing energy-efficient technologies.

II. Background

Introduction to Temperature and Humidity Loggers

Temperature and humidity loggers are stand-alone devices that measure ambient temperature and humidity using sensors and store a history of measurements on an internal memory device. Most loggers are battery powered and can thus operate independently of an electrical power outlet. Data stored on loggers are either downloaded directly from the device using a cable, USB port or interface connected to a computer, or, increasingly, loggers with wireless data transmission features allow for real-time data access. There are numerous logger products available on the market with a wide range of features, including memory size, battery life, precision of the temperature and humidity measurements, and data transmission technology. Consequently, price ranges also vary widely, from under $20USD for basic temperature loggers with limited memory, to hundreds of dollars for devices with more advanced features.

Pilot Testing Seven Alternative Logger Technologies[3]

To inform the selection of loggers that would be deployed to measure temperature and humidity in over 450 homes included in our field trial, we conducted an initial operational pilot on a sub-sample of 45 homes over a 6-month period. The pilot compared seven logger models from five manufacturers, ranging in price from under $40 to over $300 per unit. Loggers were installed in dwellings by trained technicians and multiple follow-up visits were conducted to verify the continued functionality of the devices and download data.

Table 1 presents a summary of the specifications, advantages and disadvantages of each of the seven loggers tested during the pilot. Given that our objective was to inform the selection of a logger that would best suit the needs of our field trial, the pilot evaluated each logger’s physical dimensions, weight, interface, memory,

[3] Implementation of the pilot was conducted by *Three Consultoría Medioambiental* between March and September 2015. This section draws on reports issued by the consultant during the pilot (Three Consultoria Medioambiental, 2015(a) and 2015(b)).

measurement error and ease of downloading data. Of particular interest to our study was the data storage capacity and battery life, which would determine the number of times that homes would need to be visited by technicians to download data over the 16-month field trial and would be a significant determinant of the overall data collection cost. The logger models varied considerably, ranging from just over 2000 data points and requiring downloading data every 43 days, and up to 84,000 data points and over 4 years of battery life when logging measurements every 30 minutes.

In addition to comparing the price and technical specifications, the pilot focused on field testing the logger's installation and data downloading procedures, developing instructions for residents and identifying variance in temperature readings within homes to determine the number of location of sensors to be installed. To inform the consistency of measurements across the household and inform the number of loggers to be installed in each dwelling, we installed three loggers in each home, one on an interior wall in the living/dining area and one on an exterior facing wall in each of the home's two bedrooms. Variation in temperature readings between sensors was within 1 degree centigrade and were not statistically significant, leading to the decision to monitor only one room per household during the field trial.

Table 1: Loggers

<table>
<tr><th>Brand</th><th>Model</th><th>Dimensions (cm)</th><th>Weight (gr)</th><th>Screen</th><th>Price Range</th><th>Data Capacity (number of data points)</th><th>Operational Days (measurment every 30 minutes)</th><th>Can be tampered with by residents</th><th>Hardware for data download</th><th>Humidity error range</th><th>Minimum precision (°C)</th><th>Ease of downloading /accessing data</th></tr>
<tr><td>Rotronic</td><td>HL1D</td><td>9 x 6 x 2.3</td><td>85</td><td>yes</td><td>mid</td><td>16,000</td><td>333</td><td>yes</td><td>cable</td><td>3%</td><td>+/- 0.3</td><td>mid</td></tr>
<tr><td>LogTag</td><td>HAXO-8</td><td>8.6 X 5.4 X 0.8</td><td>35</td><td>no</td><td>mid</td><td>8,000</td><td>167</td><td>no</td><td>interface</td><td>3-5%</td><td>+/- 0.1 °C</td><td>easy</td></tr>
<tr><td rowspan="2">HOBO</td><td>MX100-003</td><td>3.66 X 8.48 X 2.29</td><td>56</td><td>yes</td><td>mid</td><td>84,650</td><td>1,764</td><td>yes</td><td>cable</td><td>3.5%</td><td>+/- 0.024 °C</td><td>mid</td></tr>
<tr><td>MX100-011</td><td>3.66 X 8.48 X 2.29</td><td>30</td><td>yes</td><td>high</td><td>84,650</td><td>1,764</td><td>yes</td><td>bluetooth</td><td>2.5%</td><td>+/- 0.024 °C</td><td>mid</td></tr>
<tr><td rowspan="2">NEWSTEO LOG</td><td>COL11-002</td><td rowspan="2">9.8 X 6.4 X 3.4</td><td rowspan="2">42</td><td rowspan="2">no</td><td>high</td><td rowspan="2">32,250</td><td rowspan="2">672</td><td rowspan="2">no</td><td rowspan="2">wireless</td><td rowspan="2">1.8%</td><td rowspan="2">+/- 0.02 °C</td><td>easy</td></tr>
<tr><td>LOG 20-001</td><td>high</td><td>easy</td></tr>
<tr><td>iButton</td><td>DS1921G-F5</td><td>1.7 X 0.5 (diamter x width)</td><td>3.3</td><td>no</td><td>low</td><td>2,048</td><td>43</td><td>no</td><td>interface</td><td>N/A</td><td>+/- 1 °C</td><td>mid</td></tr>
</table>

Source: Logger pilot test report (Three Consulting , 2015)

The pilot revealed that sensors could be damaged or lost, requiring adequate training for residents to avoid manipulating, moving or otherwise tampering with the sensor. The principal challenges with the sensors included loss or misplacement of the sensor, loss of sensor data, and the absence of residents in the dwelling to access the sensor for data extraction. Visible features of some loggers also created suspicions amongst residents that the sensors might have built in microphones or other recording devices embedded.

Given the scale and duration of our field trial, the full cost of measuring temperature and humidity would include the purchase price of the data loggers, installation costs and the cost of visiting homes during the trial to replenish the energy supply, download data and clear memory when it reached capacity. The logger's dimensions, interface, hardware for downloading data and (to a lesser extent) weight were relevant for ease of installation and potential for tampering or manipulation by residents. Four of the seven loggers we tested required physical contact with the device to extract data which would require an adult resident to be in the household when a visit was conducted. Three loggers allowed for wireless access without entering the dwelling.

Our Selection Process

After considering the advantages and drawbacks of each model, we decided that the LogTag HAXO-8 was best suited for the context of our field trial. The LogTag HAXO-8 logger can measure and record up to 8,000 readings, with up to 167 days of dry bulb air temperature and relative humidity if measured every 30 minutes. The meter is highly accurate, plus or minus up to 1°C and up to 3% relative humidity. The LogTag logger works over a large range, -40° to 85° for temperature and 0% to 100% for relative humidity. Downloading logged data is performed using LogTag software included with the product and a small base which connects to the logger.

Another feature of the HAXO-8 is that it does not have a screen. This was an advantage in our context because the logger does not provide any information to the households. We did not want residents changing their behavior in response to information received from the loggers. In addition, we did not want residents to manipulate the devise to stop the measurements or change settings. Our experience in the pilot showed us that sensors were potentially at risk of being damaged or lost, so the relatively non-descript appearance of the HAXO-8 is valuable because residents are more likely to leave it alone.

While we ultimately decided on the LogTag HAXO-8 logger, other loggers tested during the pilot had positive features that are worth noting. Despite being at the top of the price range considered in the pilot, the NEWSTEO LOG models presented the advantage of transmitting data wirelessly using radio frequency, which would have allowed us to compile and analyze data in real time and avoid entering households during the trial. The added requirement for this feature, however, was the installation of receivers throughout the trial area which necessitated independent power stations and would have required multiple receivers to cover the area. We expect that as wireless logger technology continues to advance, and prices become more accessible, this option will become an attractive alternative.

Another logger model that we seriously considered was the iButton DS1921G-F5. The iButton has a very low purchase price and accurate temperature readings. However, the downsides for our context included the absence of a humidity sensor and relatively small memory storage capacity which would have required bi-monthly visits to replace the devices. Additionally, the small size of the loggers made them prone to loss or misplacement. Nevertheless, had we detected significant variance in temperatures throughout the dwelling, the iButton would have been a viable option for measuring temperature in multiple rooms concurrently, at least over a more limited time horizon. We should also note that in addition to the iButton DS1921G-F5, there are now several additional iButton models including versions with humidity measurement and extended memory capacity.

The Rotronic and Hobo models had the advantages of large memories and extended battery life that would have required fewer visits compared to LogTag HAXO-8. Despite its higher price tag, the Hobo MX100-011 bluetooth feature, allowing for data to be downloaded without entering the dwelling, was also a plus. However, for our application, the user interface screens and external appearance made them more noticeable than the LogTag HAXO-8, and residents could (intentionally or not) manipulate settings by touching the external buttons or panels. Furthermore, the Rotronic model was the hardest to install because of its weight.

The Field Trial

Both the initial operational pilot as well as the full-scale field trial took place in a large housing development in Northeast Mexico in the state of Nuevo Leon. The development is located west of Monterrey in the municipality of Garcia. Buyers in this housing development tend to have relatively low incomes by Mexican standards. For more on the demographics in this housing development see Davis, et al, (2020).

This area is hot during the summer, so this is a compelling setting for studying thermal comfort in a residential housing context. Air conditioner adoption is increasing rapidly in Mexico (Davis and Gertler, 2015), but in this particular housing development only 12% of households have air conditioning, mostly room air conditioners and mini splits. Whereas relatively few households have air conditioning, 90% of households have electric fans.

We began contacting households between June and August 2016. Households were offered a modest financial compensation in exchange for allowing us to measure their temperature and humidity. A total of 467 households agreed to have loggers installed in their homes.

The data loggers were installed by trained technicians. Loggers were installed 1.8 meters above the floor on an inner wall of the home facing the primary living quarters (living and dining room area). We selected the living and dining room area because we wanted to have an area of the house where people tend to spend time during the day, but not a spot that would be directly impacted by any cooking activities.

Instructions were given to household members to not tamper with the data loggers. Information from the loggers was then downloaded every three to four months over a 16+ month period. Households were given an additional modest financial compensation each time data was downloaded, as well as an additional modest compensation at the end of the project upon return of the data loggers.

III. Illustration of the Potential of These Data

In this section, we turn to the data from the 450+ homes in our field trial. We begin by examining the pattern of daily temperature and humidity. Then we examine the hourly pattern over the course of the day, and the correlation between indoor and outdoor temperature.

Seasonal Pattern for Temperature and Humidity

Figure 1 plots mean daily outcomes for interior temperature (in Celsius) and relative humidity. Each observation in these figures is a day, and we have 16+ months of data, so there are about 500 data points in each graph. The time period includes two summer seasons, but only one winter season.

Across all days and hours, mean temperature in these homes is 27°C. Temperature varies widely during the year, along with climatological conditions. During the summer, the average daily temperature frequently exceeds 30°C which is widely considered at the upper end of comfortable interior temperatures. These are averages across all 24 hours of the day, suggesting that peak temperatures are even higher.

During the winter, the average daily temperature fell below 20°C frequently during December and January. This is widely considered to be near the lower end of comfortable interior temperatures, though again, these are 24-hour averages, suggesting that low overnight temperatures are likely considerably lower.

Across all days and hours, mean humidity was 56%. Humidity varies widely during the year ranging from 20% to 80%, with less of a seasonal pattern than temperature. These large swings in temperature and humidity illustrate the high degree to which these households are subject to climatological conditions, and the relatively high fraction of days with poor thermal comfort.

Hourly Summer Pattern for Temperature and Humidity

Figure 2 plots mean temperature and humidity by hour-of-day during summer months. Along the x-axis hours run from 1AM to midnight, so the figure shows mean outcomes starting in the morning, then afternoon, and finally evening hours.

Temperature reaches its nadir in the morning, and then increases steadily throughout the day, peaking around 6PM. Humidity peaks much earlier, around 10AM, then reaches its nadir at 7PM. As with the seasonal pattern, this within-day pattern illustrates the high degree to which these households are subject to climatological conditions.

These figures include 95% confidence intervals, calculated using standard errors that are clustered by household to account for serial correlation. With many months of data from 450+ homes we have a high level of statistical precision, with relatively narrow confidence intervals. This statistical precision reflects the large sample size as well as the relative homogeneity of the housing units in this housing development, with long rows of nearly identical homes all constructed and sold at the same time.

Figure 3 provides the same information during winter months. As expected, temperatures tend to be much lower; notice that the y-axis differs between Figure 2 and Figure 3. The diurnal pattern is quite similar to the summer, however, with the nadir in the morning and peak around 6pm. Humidity tends to vary a bit less during the winter, and reach its nadir a bit earlier in the day.

Indoor vs Outdoor Temperature

Figure 4 plots mean indoor temperature as a function of mean outdoor temperature. The x-axis is outdoor temperature, measured using a small weather station installed on the roof of one of the buildings in the housing development. The y-axis is average indoor temperature measured at all homes and all hours during which a particular level of outdoor temperature was observed. For example, the first observation shows that during all hours for which outdoor temperature was 8°C, the average indoor temperature was about 16°C.

There is a strong positive relationship between indoor and outdoor temperature. The thermal mass of the homes protects households from the most extreme temperatures, so indoor temperature varies somewhat less overall than outdoor temperature. However, indoor temperatures still get very warm, for example, above 32°C on average during hours in which the outdoor temperature exceeds 36°C. Overall, extreme heat is a bigger problem in this setting than extreme cold.

The figure includes 95% confidence intervals for the sample means, calculated using standard errors that are clustered by household to account for serial correlation. The confidence intervals are extremely narrow. As with the confidence intervals in the previous figures, this statistical precision reflects the large sample size, even at the more extreme temperature levels.

As with the seasonal and hourly patterns observed in the previous figures, Figure 4

demonstrates the high degree to which these households are subjected to climatological conditions. Most households do not have air conditioning and even those that do own air conditioning do not tend to use it intensively enough to keep the home within a comfortable thermal range. When it is hot outside, it is hot inside.

Discussion

One of the striking findings in our field trial is the large fraction of high temperature hours. During summer months, interior temperature in these homes regularly exceeds 30°C and even 32°C. According to NOAA, nine of the ten hottest years in recorded history have occurred since 2005 (NOAA, 2018), so these uncomfortably warm thermal conditions are likely to continue to get worse with climate change.

Data from loggers could be used to test new building materials, a new construction technique, or a new energy-efficient technology. In the ideal experiment, a random subset of the homes would be selected to receive some new technology. Temperature and humidity could then be compared between treatment and comparison homes to facilitate cost-benefit analysis.

The highly-granular nature of the logger data make it possible to do unusually rich analyses. For example, better building insulation leads to cooler temperature during the day, but also warmer temperatures at night as it becomes harder to cool the building down. With hourly or even higher-frequency information from data loggers this entire diurnal profile can be tested.

Another related application for data loggers is building codes. In most countries, new homes are subject to specific requirements for windows, insulation, and other features. Data loggers could be used to measure the impact of building code revisions on thermal comfort. Several studies have used energy data in this context. See, e.g., Aroonruengsawat, et al. (2012), Jacobsen and Kotchen (2013), Levinson (2016), and Kotchen (2017). Evidence on thermal comfort impacts would be a valuable complement to these existing analyses.

IV. Conclusion

Temperature and humidity logging technology is getting better and cheaper. In this paper, we have argued that these loggers have great potential for improving building design. Our experience with a large-scale field trial in Mexico has made us even more excited about this technology. First, the technology works. We had very few problems overall with deploying and then recording data from these loggers. Second, we were surprised by the overall richness of the data. While we expected the loggers to work for measuring average temperature and humidity, we failed to appreciate the highly-granular nature of the data, and the ability to perform within-day and other highly-detailed analyses. We urge researchers to incorporate this technology into studies of building codes, energy-efficiency, air conditioning, and related topics.

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Figure 1: Mean Daily Temperature and Humidity

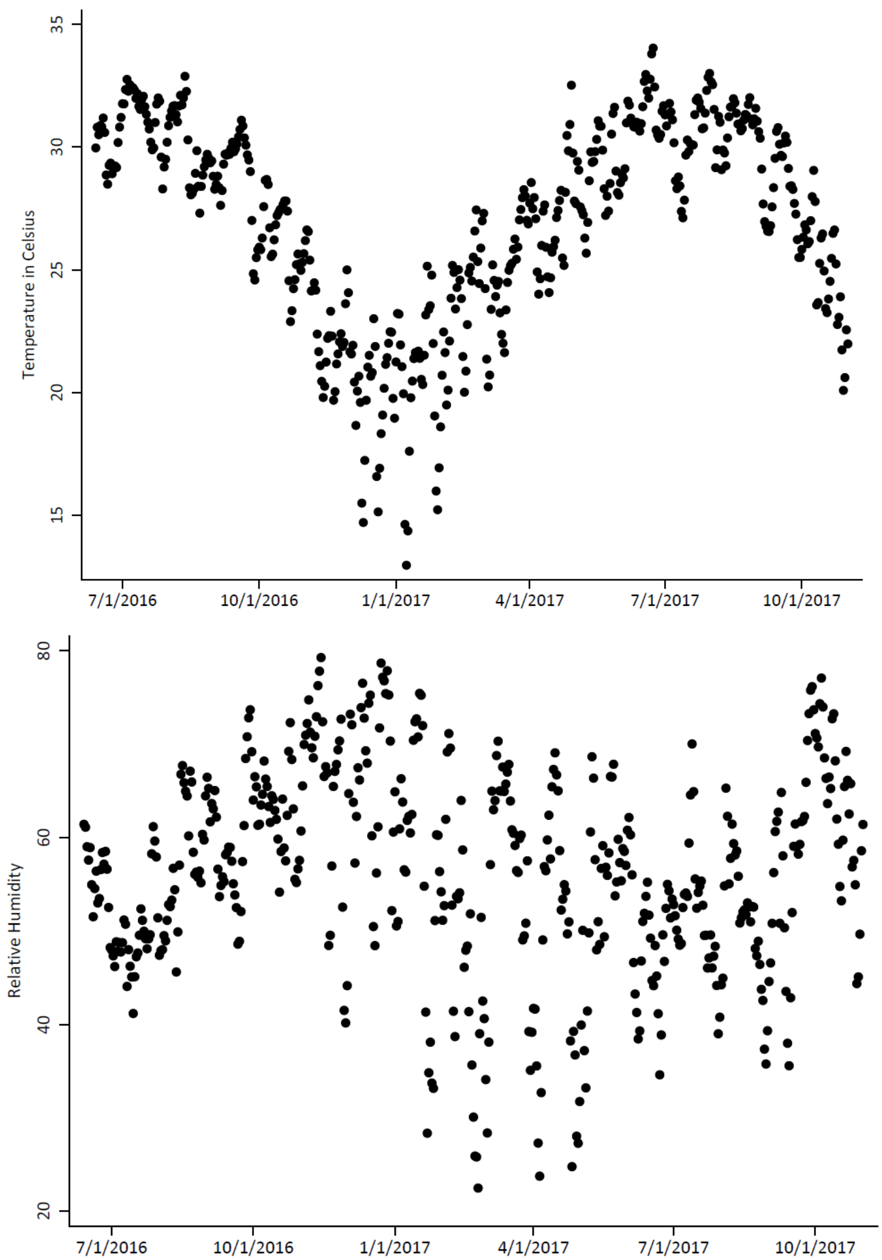
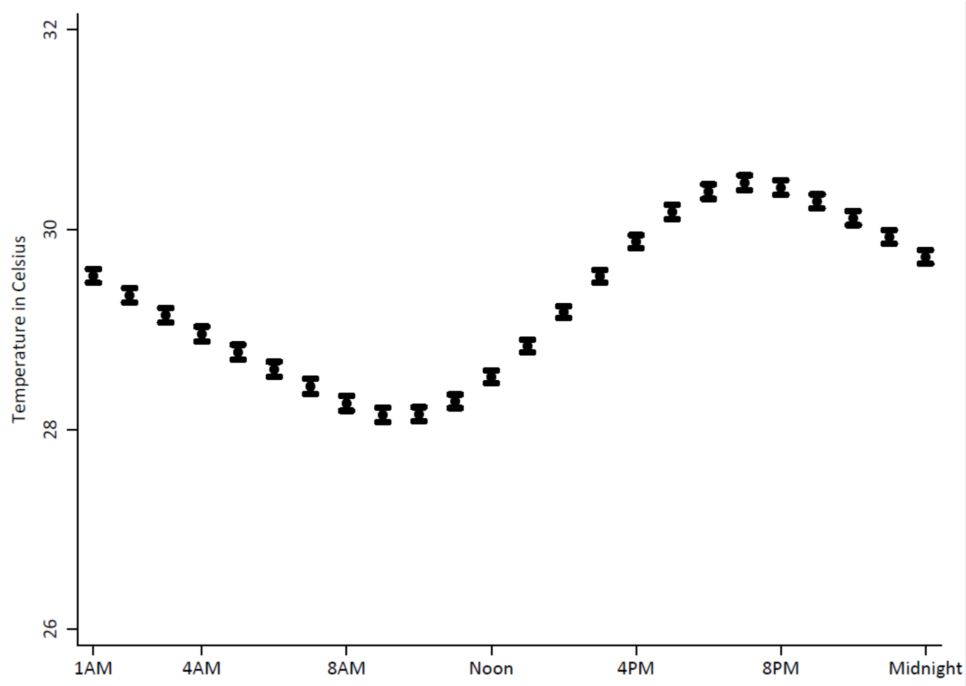


Figure 2: Mean Hourly Temperature and Humidity, May to October



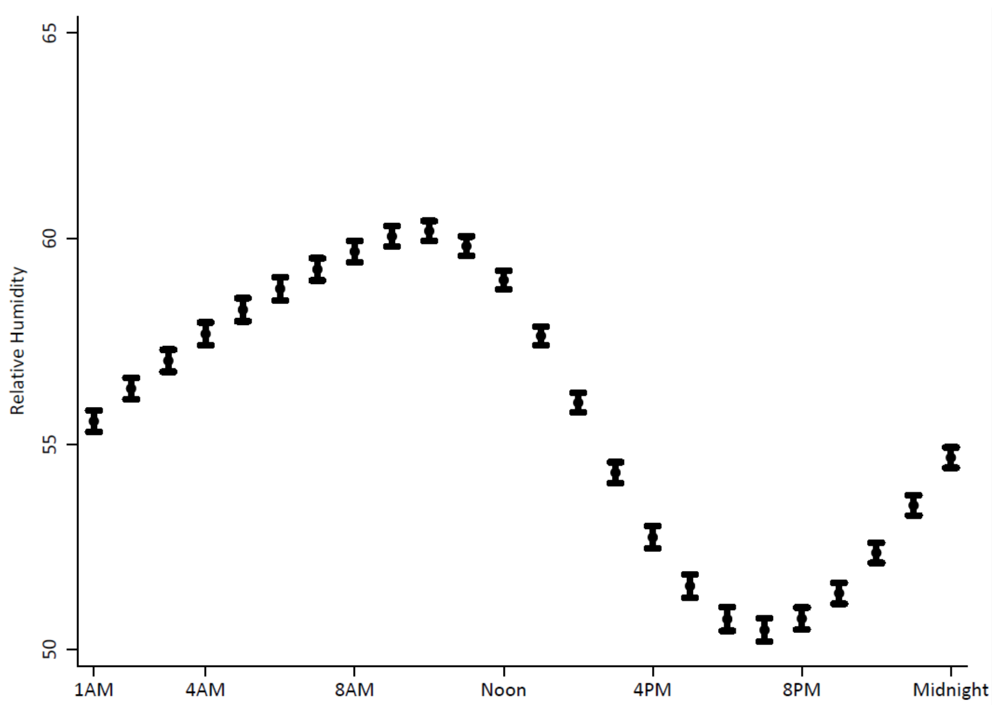
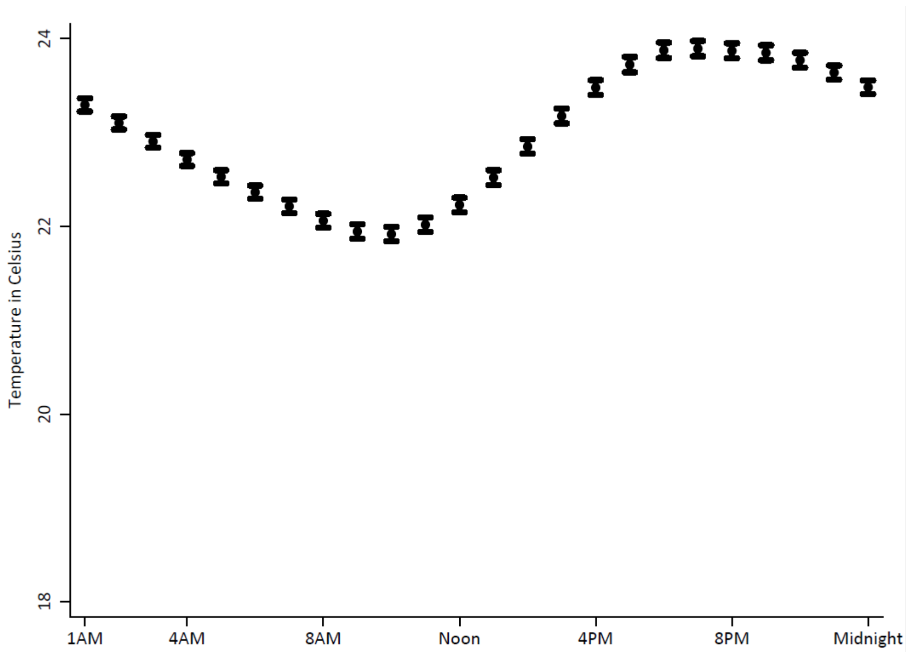


Figure 3: Mean Hourly Temperature and Humidity, November to April



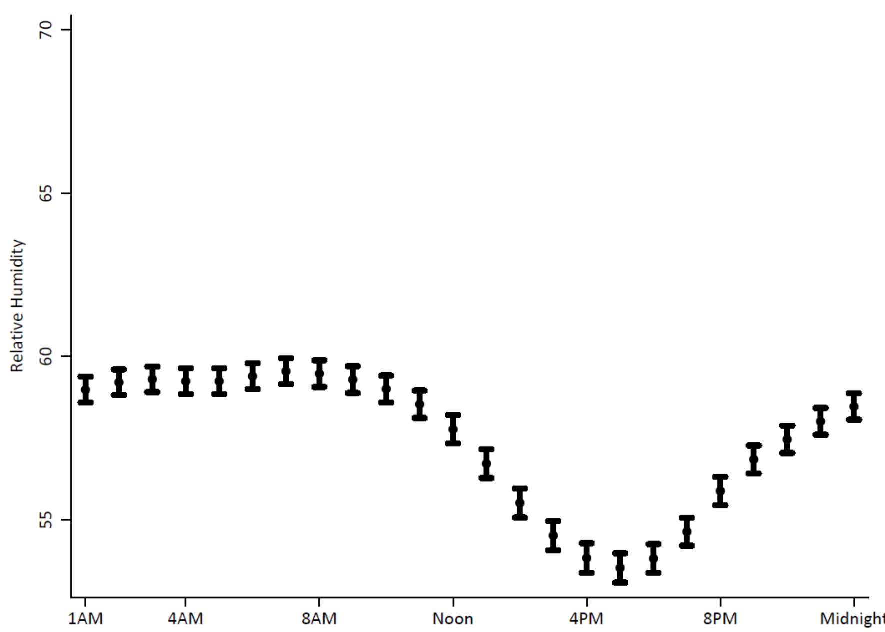


Figure 4: Indoor vs Outdoor Temperature