
# A Report on Moisture Control in Homes

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## FOREWORD

At Build Equinox, we have always included moisture management as a primary aspect of CERV2 smart ventilation design. Our free-to-use ZEROs (Zero Energy Residential Optimization software) model is one of the few residential programs that can predict dehumidification and humidification in residences. Health, comfort and energy impacts of humidity are important!

Moisture is complex and has many facets, however it is an old, old problem that experienced HVACR engineers know how to address. This report discusses sources of moisture in homes, and how to manage moisture. We look around North America to learn how climate zones impact moisture management in homes. More and more regions around the world are experiencing increased temperature and humidity and the need for active comfort conditioning is expanding.

Build Equinox conducts residential research encompassing health, well-being, comfort, sustainable living, and energy efficiency topics. We hope sharing our knowledge will be a benefit to our growing CERV community. It is time to move beyond energy, designing homes with exceptional indoor environments that improve our health, comfort and well-being!

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Introduction – Climate Moisture Variations

We examine average weather characteristics in Part 2 by "traveling" around the lower 48 United States to see how temperature and moisture vary around the country and throughout the year. Detailed, hourly plots of real weather data are included to provide better perspective of variations of "real" weather in contrast to that of "averaged" weather commonly used for home design modeling.

Figure 1 is a psychrometric plot with psychrometric quadrants drawn around assumed indoor comfort conditions of 70F and 60% relative humidity (humidity ratio of ~0.010). The quadrants represent hot/wet, hot/dry, cold/dry, and cold/wet conditions. The fraction of time in a year, and the average weather conditions of each quadrant allow estimation of moisture management needs using the moisture relations introduced in Part 1.

Build Equinox is very fortunate to be in Urbana Illinois with the worse weather in North America! Figure 2 is a plot of hourly weather conditions for 2010 for Urbana-Champaign Illinois. An envelope drawn around Urbana hourly data provides a reference as we investigate weather characteristics in other locations. Urbana-Champaign has one of the largest weather variations in North America. Central Illinois is uniquely placed with cold arctic blasts from Minnesota in the winter, and hot, humid Gulf of Mexico weather from New Orleans in the summer. Although winter and summer durations of extreme weather are less than those experienced in Minnesota and Louisiana, comfort conditioning systems in central Illinois must have the capability to move about a very broad range of psychrometric conditions.

Monthly Average Weather Characteristics

Appendix A shows monthly average psychrometric conditions for several locations around the lower 48 US states. Several interesting trends are observed. Among them, most locations except for the arid southwest and intermountain regions have average relative humidity between 60 and 80% throughout the year. The humidity ratio (ratio of water mass to air mass) varies significantly with temperature, but in general, atmospheric moisture in most of the lower 48 states retains 60 to 80 percent of the water that can be vaporized at ambient temperatures. Another characteristic of the lower 48 states outside of the arid regions is very little hysteresis in the psychrometric path throughout the year. That is, the temperature and moisture profile in the spring and fall time periods are quite similar. Fall tends to be a bit lower in ambient moisture content, but not significantly so.

Appendix A shows an increasing hysteresis in psychrometric conditions from west Texas (El Paso), across Arizona and into the arid portions of California. The southwest US has increased moisture in the fall, resulting in a counterclockwise seasonal path movement on a psychrometric chart. In general, spring/summer/fall regions have relative humidity falling between 30% and 60%, unlike the rest of the lower 48 with 60 to 80% relative humidity. More northerly intermountain regions (Reno, Salt Lake City, and Denver) are arid, however the spring to fall psychrometric path hysteresis is reduced with much smaller differences in spring and fall humidity.

Pacific coast regions from San Diego to Seattle have psychrometric paths with 60 to 80% relative humidity and very little seasonal hysteresis in psychrometric conditions. Summer to winter ambient temperatures decrease in an orderly manner as one moves north from San Diego. Relative humidity in Arcata California is one of the highest in the lower 48 US, slightly exceeding 80%rh for much of the year on average. Arcata is a relatively cool climate with summer average temperature of 55F. Heating Arcata's 55F, 80% relative humidity air to a comfortable 70F (without changing moisture levels) results in a very nice 50% relative humidity. Further movement north from Arcata to Portland Oregon and Seattle Washington show decreasing winter temperatures and increasing summer temperatures (with summer humidity decreasing to the 60 to 80%rh range). Eastward movement from the upper northwest to Spokane WA and Billings MT results in a progression to the arid intermountain conditions observed for Salt Lake City, Boise, and Denver, except with colder temperatures.

Appendix A plots continue a geographic climatic progression across the Midwest region of the lower 48, to the northeast, and then a southward progression along the Atlantic coast to the southeast where we started our journey. As before, average relative humidity for the Midwest and east coast regions stay in the 60 to 80% range with little hysteresis in psychrometric paths. Progression from more northerly regions (Minneapolis MN, Chicago IL, Burlington VT) to more southerly locations (Kansas City MO, Nashville TN, Washington DC) has a general increase in both winter and summer temperatures.

The plots in Appendix A cover a broad range of conditions that show a systematic change of weather across a broad geographic region. Simple, yet powerful moisture conditioning analyses can be performed with these weather maps. Using the maximum (summer) and minimum (winter) conditions from one of the Appendix A psychrometric maps coupled with the simple relations developed in Part 1, we can get an idea of whether one needs to dehumidify or humidify a home. Or, alternatively, one can determine a home's average indoor relative humidity if there is no dehumidification or humidification.

## Expanded Moisture Example

Let's explore use of the Appendix A psychrometric maps by continuing our example from Part 1. We had three conditions; Contractor Loose's house with 230cfm of air flow (140cfm of infiltration plus 90cfm of ASHRAE 62.2-2016 ventilation), Contractor Tight's house with 104cfm of air flow (14cfm of infiltration plus 90cfm of ASHRAE 62.2-2016 ventilation), and Contractor Smart's home with smart ventilation with 27cfm of air flow (14cfm of infiltration and 13cfm of ventilation). We also assumed 2.4kg per day of occupant generated moisture for all homes.

We assume that during summer conditions, we maintain an indoor temperature of 72F with a relative humidity no greater than 60%rh (for a humidity ratio of 0.010….see Figure 1 psychrometric chart). During winter, many home occupants reduce indoor temperature (see comfort temperature plots from our Vermod report) to 68F. We speculate that occupants lower thermostats as a personal preference most likely due to heavy winter clothing making occupants more comfortable at lower temperatures.

Our Part 1 example assumed average Urbana Illinois summer (hot/wet) conditions with an outdoor humidity ratio of 0.013 relative to an indoor humidity ratio of 0.010. Figure 2 shows several times when outdoor humidity ratio exceeds 0.02, or somewhat greater than 3 times the difference in humidity ratio as the average summer outdoor humidity ratio relative to an indoor humidity ratio of 0.01. Therefore, daily dehumidification capacity can be much, much greater than average dehumidification capacity.

For our new example, we use Miami FL and Phoenix AZ, as well as Urbana Illinois. Using the relations developed in Part 1, the tables below show moisture balances for summer and winter conditions (average weather condition data is taken from Appendix A psychrometric plots). During summer, we would like to limit indoor relative humidity to 60% with a temperature of 72F. We assume 68F winter indoor temperature with a minimum indoor relative humidity of 30%, equivalent to a humidity ratio of 0.005 for the example.

Contractor Loose's Homes:

| Location | Season | T(F) | %rh | wo | V+I(cfm) | W(kg/day) | Occ(kg/day) | NetW(Kg/day) |
|---|---|---|---|---|---|---|---|---|
| Miami | Summer | 82 | 75 | .018 | 230 | 92 | 2.4 | 94.2 |
| Miami | Winter | 65 | 70 | .011 | 230 | 11.5 | 2.4 | 13.9 |
| Phoenix | Summer | 89 | 38 | .012 | 230 | 23 | 2.4 | 25.4 |
| Phoenix | Winter | 53 | 50 | .005 | 230 | 0 | 2.4 | ~32%rh |
| Urbana | Summer | 77 | 70 | .013 | 230 | 34.5 | 2.4 | 36.9 |
| Urbana | Winter | 21 | 80 | .002 | 230 | -23 | 2.4 | -20.6 |

Contractor Tight's Homes:

| Location | Season | T(F) | %rh | wo | V+I(cfm) | W(kg/day) | Occ(kg/day) | NetW(Kg/day) |
|---|---|---|---|---|---|---|---|---|
| Miami | Summer | 82 | 75 | .018 | 104 | 41.6 | 2.4 | 44 |
| Miami | Winter | 65 | 70 | .011 | 104 | 5.2 | 2.4 | 7.6 |
| Phoenix | Summer | 89 | 38 | .012 | 104 | 10.4 | 2.4 | 12.8 |
| Phoenix | Winter | 53 | 50 | .005 | 104 | 0 | 2.4 | ~35%rh |
| Urbana | Summer | 77 | 70 | .013 | 104 | 15.6 | 2.4 | 18 |
| Urbana | Winter | 21 | 80 | .002 | 104 | -10.4 | 2.4 | -8 |

Contractor Smart's Homes:

| Location | Season | T(F) | %rh | wo | V+I(cfm) | W(kg/day) | Occ(kg/day) | NetW(Kg/day) |
|---|---|---|---|---|---|---|---|---|
| Miami | Summer | 82 | 75 | .018 | 27 | 10.8 | 2.4 | 13.2 |
| Miami | Winter | 65 | 70 | .011 | 27 | 1.4 | 2.4 | 3.8 |
| Phoenix | Summer | 89 | 38 | .012 | 27 | 2.7 | 2.4 | 5.1 |
| Phoenix | Winter | 53 | 50 | .005 | 27 | 0 | 2.4 | ~40%rh |
| Urbana | Summer | 77 | 70 | .013 | 27 | 4.1 | 2.4 | 6.5 |
| Urbana | Winter | 21 | 80 | .002 | 27 | -2.7 | 2.4 | -0.3 |

Dehumidification is decreased by house envelope sealing and smart ventilating. On a raw energy basis, 0.67kWh per kg must be removed from water vapor to condense it to liquid. Proper construction with smart ventilation decreased Miami's average summer dehumidification energy from 62kWh to 9kWh, an energy difference equivalent to almost 200 miles of EV travel per day!!

The negative winter moisture balance for Urbana winter conditions indicates the amount of water that should be added to keep a minimum indoor relative humidity at 30% and 68F. Contractor Loose's home in Urbana needs nearly 21kg of water added daily during the winter. If no humidification occurs, indoor relative humidity drops to 15%, a level at which most people find uncomfortable due to dry skin, itching, scratchy eyes, and nose bleeds. Note that lower humidity levels increase the amount of moisture generation above 2.4kg/day assumed for occupant activities due to higher evaporation rates from respiration, cooking, plants, etc. The sealed, smart home requires less than a liter of water per day, which in many homes may be supplied by additional sources (eg, Equinox House has 50 plants rather than 10 plants assumed for Part 1's Table 1 moisture generation).

Phoenix requires no humidification through the year. During winter conditions, indoor relative humidity ranges from 32%rh (Contractor Loose) to 40% (Contractor Smart) with occupant generated moisture. Phoenix and other southwestern states have a "monsoon" season in the late summer and early fall that increases humidity sufficiently to warrant dehumidification. Dehumidification is lower than Urbana's dehumidification needs, but still significant.

## Hourly Weather Trends

Appendix B shows additional details of Urbana-Champaign Illinois' hourly weather data on a season-by-season basis. Six "Vonnegut" seasons display seasonal variations in 2 month increments over the course of a year. Author Kurt Vonnegut felt 2 month seasons with the addition of a "locking" season (November and December), and an "unlocking" season (March and April) were better descriptors instead of including those months in fall and spring.

Also shown in Appendix B is a plot showing the progression in daily temperature and humidity during summer, winter and fall. On "average", hourly psychrometric movements during a 24 hour period are horizontal, indication no moisture variations in the atmosphere over the course of a day. Weather fronts cause significant moisture shifts, but within the course of a typical day, air heats up during the day and cools down during the night along a fairly constant moisture (humidity ratio) level.

Appendix C includes hourly data for 12 lower 48 US locations. These plots illustrate how hourly data varies relative to average data for each month. Each plot includes the "envelope" from the Urbana hourly weather plot to provide perspective of the location's seasonal variations. Each location's monthly average psychrometric loop and Urbana's psychrometric loop are added. A table below each plot lists the psychrometric quadrant averages that can be used for seasonal moisture balance calculations as presented in the Part 1 example.

Figure 3 displays pie charts of the psychrometric quadrant time fractions for each location. The charts in Figure 3 are laid out in a rough geographic orientation. The southeast has very high hot/wet fractions, while northern locations are dominated by cold/dry weather. Miami is in hot and humid conditions for nearly 75% of the year while Seattle spends only 2% of the time in conditions that are warmer and more humid than indoor comfort conditions. Interestingly, Los Angeles has the largest time fraction spent in cold and humid conditions, although the average of those conditions (63F and 0.011 humidity ratio) are quite close to comfort and are mostly converted to comfortable indoor conditions from occupant generated heat sources (human metabolism, cooking, lights, computers, televisions, etc).

Making It Real – Equinox House Data

Equinox House is a 2100 $ft^2$ home with 2 occupants located in Urbana Illinois.  The home is sealed to 0.5ACH at 50 Pa, and has a CERV smart ventilation system (installed in 2010).  Equinox House's CERV has had online data available for viewing since 2016 when Build Equinox developed CERV-ICE (CERV-Intelligently Controlled Environment), our online monitoring, control, and OTA (Over-the-Air) upgrading system.  Visit [Build Equinox website](), and scroll down the home page to "Take Control", and click on the screen to activate live control and monitoring of the CERV in Equinox House.  Data is live, and the controls are active, allowing you to change setpoints as desired, however, any actions taken are not enacted (hopefully).

Historic data is available (see History button on left side of Take Control screen) since the Equinox House CERV-ICE became active in 2016.  Figures 4 shows screen shots the last week of August 2019 for indoor air quality ($CO_2$ and VOCs), indoor and outside temperature, and indoor and outside humidity.  Figure 5 shows screen shots of the same data for Equinox House over the past year (September 1 2018 to September 1 2019).  No active humidification is used in Equinox House during winter.  The kitchen is regularly used and Equinox House has 50 plants, large and small, scattered throughout the home.  On average, the plants receive 6 liters of water per week, with winter watering averaging 7 liters per week and summer averaging 5 liters per week.  The 2 occupants are out of the house 8 to 10 hours per day during weekdays, and home most of the day during weekends unless traveling.

The late August week displayed in Figure 4 show an indoor humidity of 60 to 65% relative humidity, typical for our house in the summer.  As discussed in Part 1, with 9 years of CERV smart ventilation operation, there is absolutely no sign of any mold, mildew, odor, or discoloration in bathrooms, kitchen or laundry room.  Periodically during the summer when indoor humidity rises to 65%, the 1 ton minisplit heat pump will be operated in "dry mode" (dehumidification mode) for approximately 8 hours.  Indoor relative humidity is reduced below 60% by this operation.  This method of summer humidity management has been very efficient and effective at handling Illinois' humid summer weather.

Equinox House summer indoor temperature setting on the CERV and the ductless minisplit heat are set at 74F.  Figure 4 shows indoor temperatures remaining below the temperature setpoint.  The August outside temperatures are mild, with diurnal swings going above and below the indoor temperature setpoint.

Indoor air quality plots of carbon dioxide and total VOCs (Volatile Organic Compounds) are largely kept below the 850ppm concentration setpoint we use for CERV air quality control.  The vertical, green bands show fresh air ventilation periods.  Figure 4 shows three broad ventilation periods on August 30, 31, and September 1.  The August 30 and 31 ventilation periods were triggered by opportunities for "free" ventilation, a time when outdoor temperatures dropped below indoor temperature, and indoor temperatures were at the upper temperature limit (74F).  The free cooling periods ("free cooling" indicates no compressor or active cooling in which the CERV brings in fresh, filtered air while exhausting a similar amount of house air) lasted approximately 6 to 8 hours, starting around midnight each night.

On September 1, a broad ventilation period occurred due to a dinner party of 9 people.  Both VOCs and cooking increased above the 850ppm setpoint, triggering CERV fresh air ventilation.  CERV fresh air ventilation (approximately 150cfm for the first generation CERV, our new CERV2 can ventilate to 300cfm with proper duct design) kept indoor $CO_2$ and VOC concentration to a maximum of 1100 to 1200ppm.

The triggered ventilation period seamlessly triggered into free cooling mode as air quality was reduced below the 850ppm setpoint later in the night.

Figure 5 shows a year of CERV data for Equinox House. The annual set of data “smooths” short term trends such as those shown in Figure 4, however, a more refined examination of a shorter time period will increase resolution to the level shown in Figure 4. Figure 5 shows Equinox House indoor relative humidity to range from 40% relative humidity (winter) to 65% relative humidity (summer). Indoor temperatures range from 68F (winter) to 74F (summer), and are solely dictated by occupant comfort preferences (Equinox House is a Zero Positive house with a monthly service fee of $14). Indoor air quality is automatically maintained at an excellent level throughout the year. A few exceptions are observed where events (parties!) have high occupant pollutant loadings. In June, we had a graduation celebration with several guests, and in July we had a combined birthday party (5 family member birthdays!) that results in one big party.

In summary, Equinox House operates very similar to Contractor Smart’s home in our example. That is, these analyses work, and they work very well.

Now that we have the means to predict our moisture load throughout the course of the year for a broad range of climatic conditions, house construction characteristics, and occupant loadings, Part 3 introduces methods for actively managing moisture.

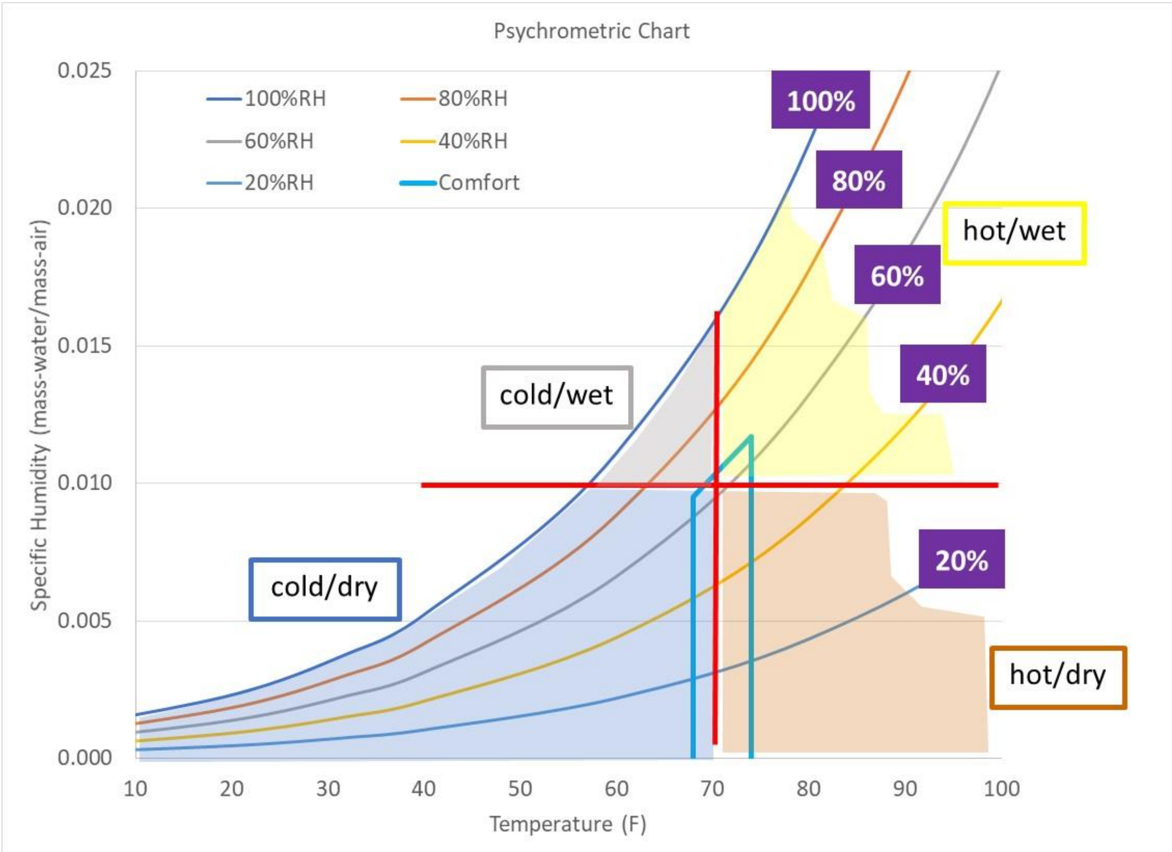
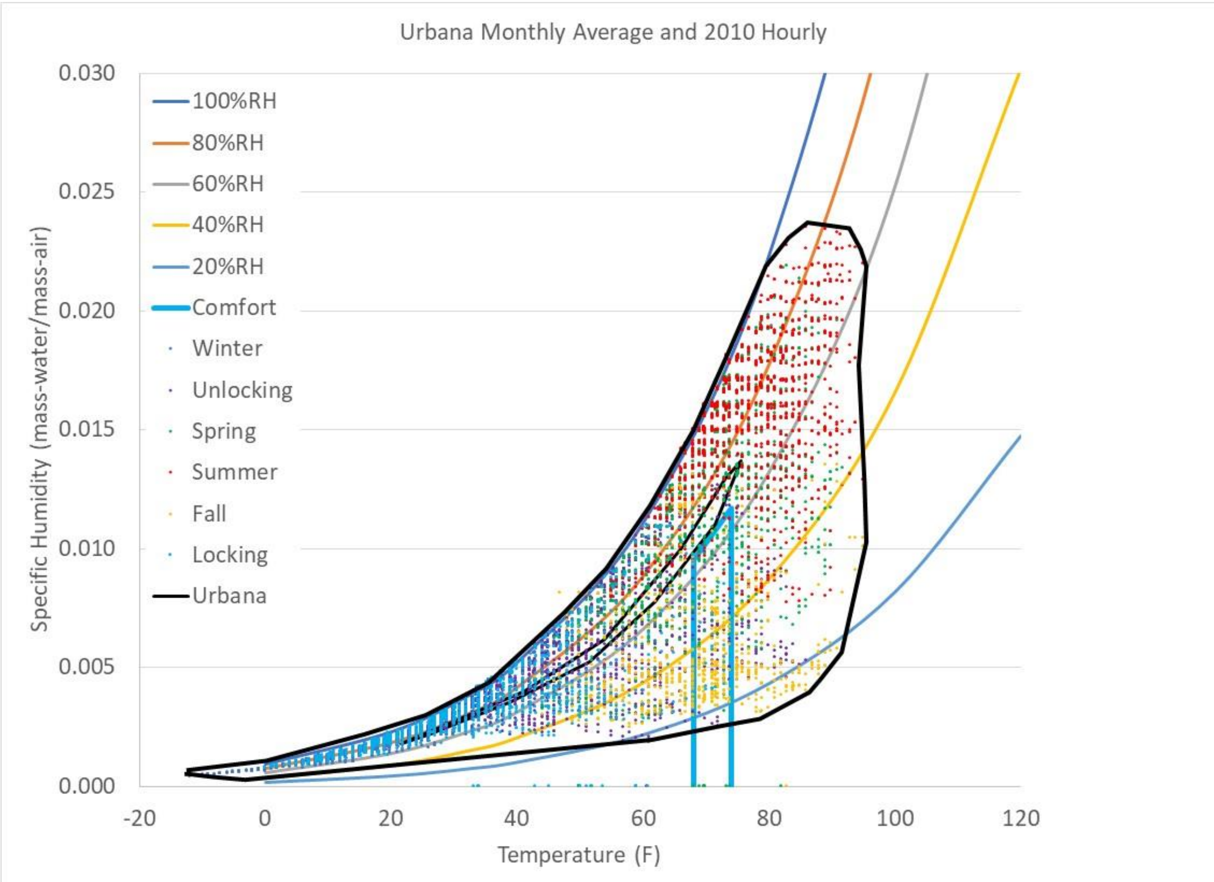



Figure 1  Psychrometric map divided into four quadrants (C/D, C/W, H/W, H/D) surrounding comfort conditions (68-76F).




Urbana-Champaign IL; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.596 | ave C/D Tave(F) | 40.3 | ave C/D W(kgw/kga) | 0.004 | ave C/D wind (mph) | 10.75 |
| fraction hot/dry | 0.032 | ave H/D Tave(F) | 74.9 | ave H/D W(kgw/kga) | 0.006 | ave H/D wind (mph) | 12.96 |
| fraction cold/wet | 0.145 | ave C/W Tave(F) | 65.8 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 9.60 |
| fraction hot/wet | 0.227 | ave H/W Tave(F) | 77.4 | ave H/W W(kgw/kga | 0.013 | ave H/W wind (mph) | 8.39 |

Figure 2 Hourly and average monthly psychrometric weather data for Urbana-Champaign Illinois with table listing time fractions in hot/wet (H/W), cold/wet (C/W), hot/dry (H/D), and cold/dry (C/D) quadrants, and average temperature, humidity ratio and wind speed for each quadrant.

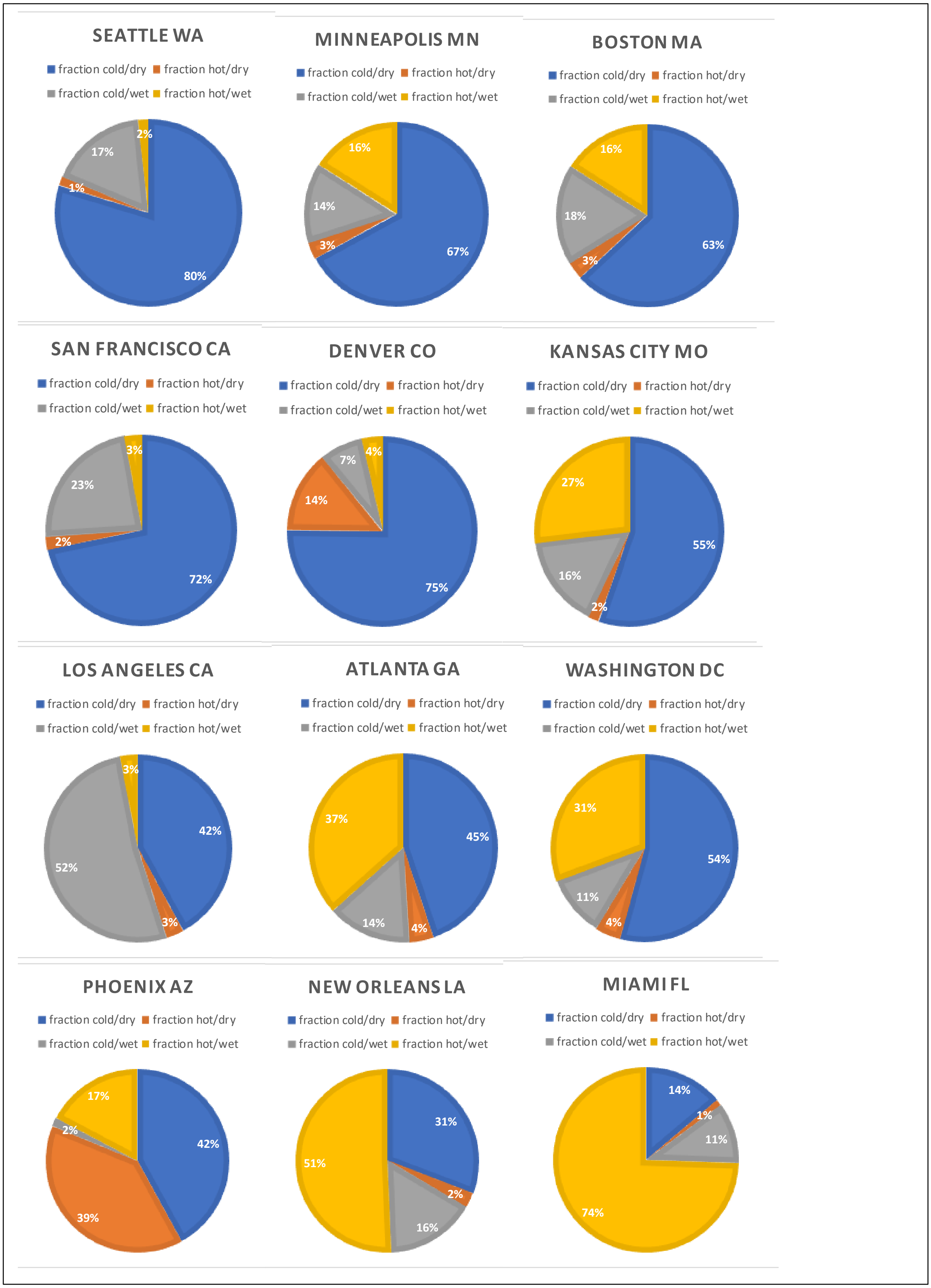



Figure 3 Lower 48 geographic variation of psychrometric quadrant time fractions.

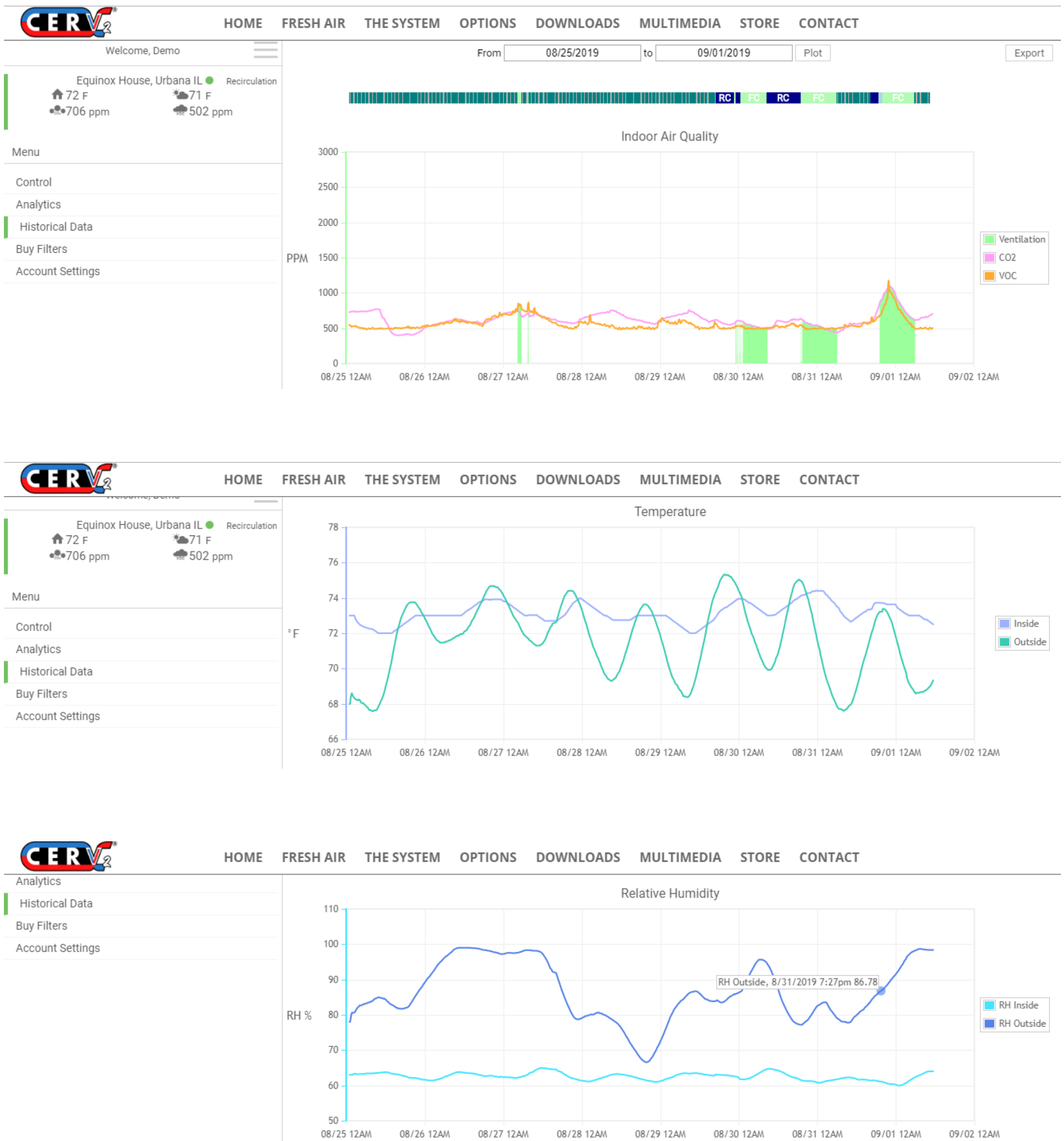



Figure 4 Screen shots from “Take Control” live data (CO2/VOC, Indoor/Outside Temperature, Indoor/Outside Relative Humidity) from Equinox House for humid August summer week.

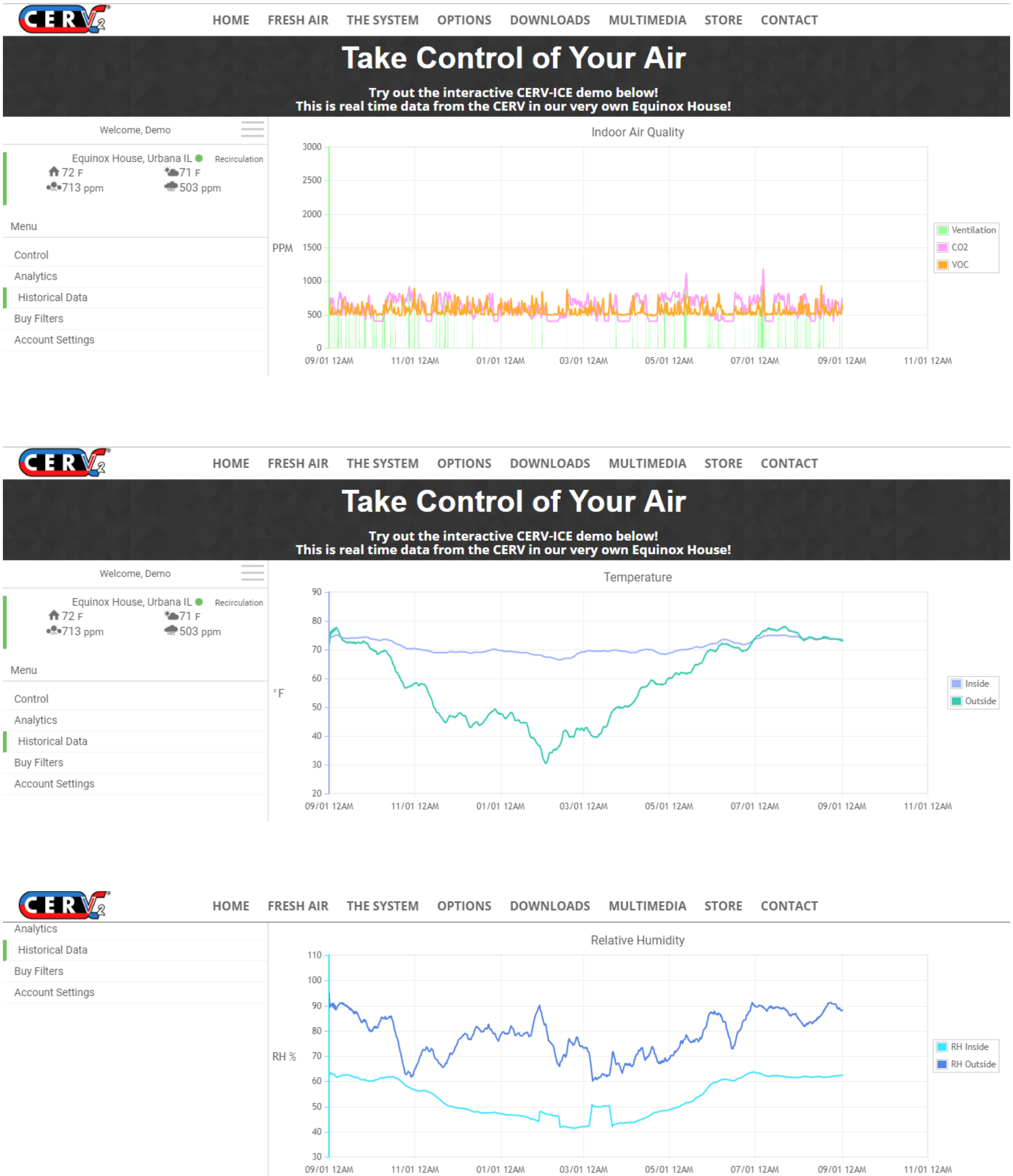



Figure 5 September 1 2018 to September 1 2019 Equinox House indoor air quality, temperature and humidity data.

Appendix A - Monthly Average Weather

How does the weather in Miami differ from Seattle? Seattle is the least air conditioned major city in the lower 48 states of the US, while Miami is perhaps the most air conditioned. Hot, humid 2018 and 2019 summers have convinced many people from Portland Oregon to Portland Maine that perhaps air conditioning is something to consider.

"Average weather" no longer exists. As a young engineer in the 1970's, I could look up the historical average weather for a location and assume that would continue to represent a region's climate. Now, when consulting ASHRAE Handbook of Fundamentals, I find charts and relations that project the change in weather over the next few decades. With this in mind, the "average" weather charts we present are moving toward higher temperatures.

Professor Don Wuebbles, a well-known University of Illinois climate scientist who was part of the 2007 Nobel Peace Prize winning Intergovernmental Panel on Climate Change (IPCC) team, has shown that Illinois is moving to Texas. As much as I enjoy visiting Texas, Illinois is my home and where I would like to stay. As Wuebbles shows in his projections, we will exceed 900ppm of carbon dioxide in the atmosphere in the next few decades without a carbon reduction. Keeping a home's indoor carbon dioxide concentration levels below 900ppm with today's 400ppm atmospheric $CO_2$ concentration is difficult enough. How in the world does one keep their indoor climate below 900ppm when the outdoor environment exceeds 900ppm?

Jay Leno once quipped that the primary impact of global warming is that people will more frequently ask "Is it me, or is it hot in here?" That may be one of the effects, but cost and suffering are two more that will grow. Public health officials euphemistically refer to heat wave deaths as "harvesting" as heat causes premature death among youth, the infirm, and elderly. Chicago's 1995 heat wave is reported to have caused nearly 739 deaths. The 2003 French heat wave is estimated to have resulted in nearly 15,000 deaths. Overall, summer heat waves across the United States are estimated to cause more deaths than the combined deaths from rain, floods, lightning, hurricanes, and tornadoes.

A discussion of monthly average weather characteristics of the lower 48 states provides a snapshot of what has been typical of average conditions. Our grouping of climatic regions provides insight to where we may be heading. In many cases, the need for dehumidification is increasing over the lifetime of homes being built and renovated today.

**Florida**

We begin our climatic journey (pun intended) in Florida, the US pinnacle of high humidity, starting with Key West, the peak of the peak of Florida moisture. Figure 1A shows the psychrometric loop Key West weather takes through the course of a year. Note that temperatures, on average, are comfortable or warmer than comfortable. Average humidity is always above preferred comfort levels. The open air nature of buildings in Key West minimizes the impact of indoor moisture generation to discomfort. For "modern" homes that control indoor comfort conditions, dehumidification is a must every month of the year in south Florida.

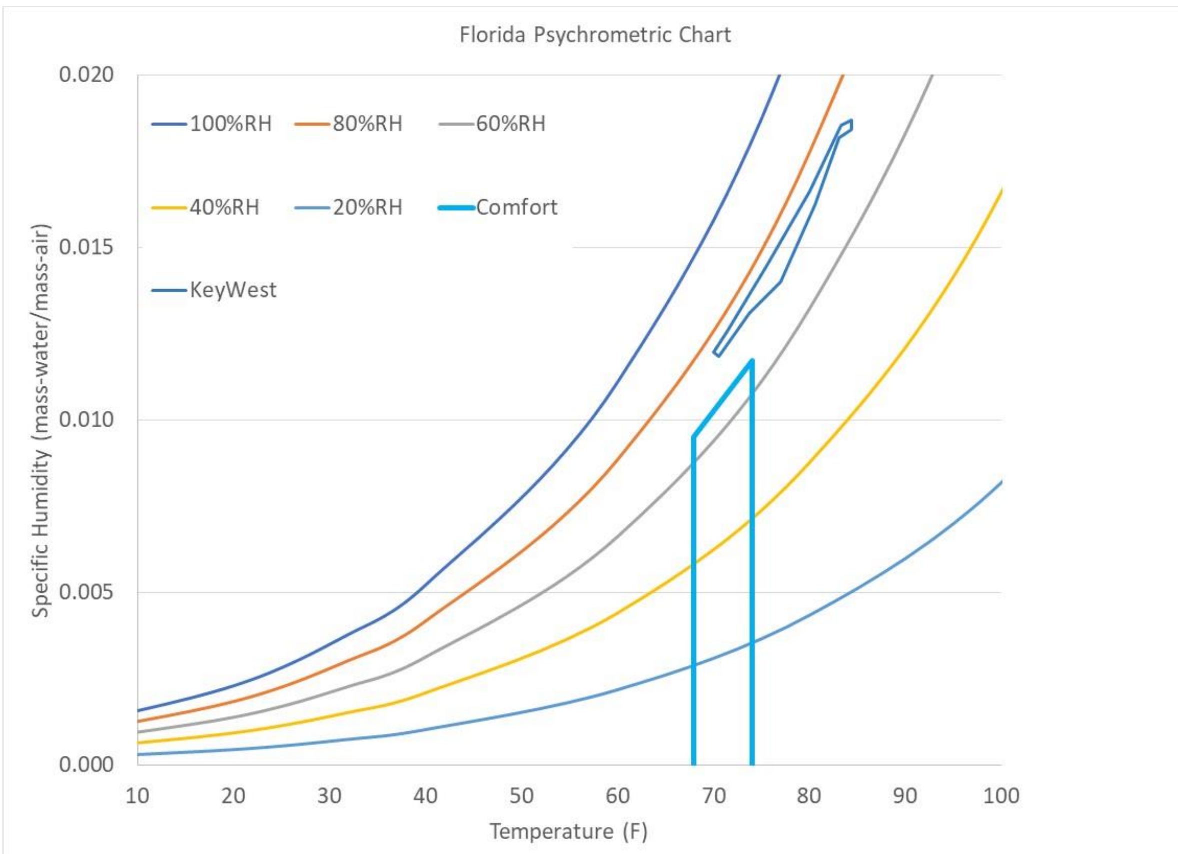



Figure 1A Key West Florida monthly average temperature and humidity. January is the lower left and July is the upper right of the psychrometric weather loop.

Moving north to Miami, Figure 2A shows slightly cooler and less humid conditions. Overall, the same comments apply to Miami. Any "controlled" indoor environment with a sealed, insulated home requires dehumidification throughout the year to avoid excessive indoor humidity levels and moisture problems. As in Key West, homes of yesteryear featured large open air porches and sun-shielded, open windows to keep indoor conditions as close to outdoor conditions as possible. The inside of a house without active comfort conditioning systems will always be hotter and more humid than outside conditions because humans and our activities add heat and moisture to indoor environments.

Continuing northward to Tampa, Jacksonville and Tallahassee, Figure 3A shows a continued progression toward somewhat cooler winters, but still very significant hot and humid summers. In fact, average mid-summer temperature and humidity are essentially the same as those in Key West and Miami. Tampa's winters may not need much heating because internal heat gain from occupants and solar heat gain may be sufficient to maintain comfort (and perhaps requires cooling during the winter conditions for those home designs that did not properly account for these factors). Jacksonville and Tallahassee homes most likely do require some home heating for winter comfort.

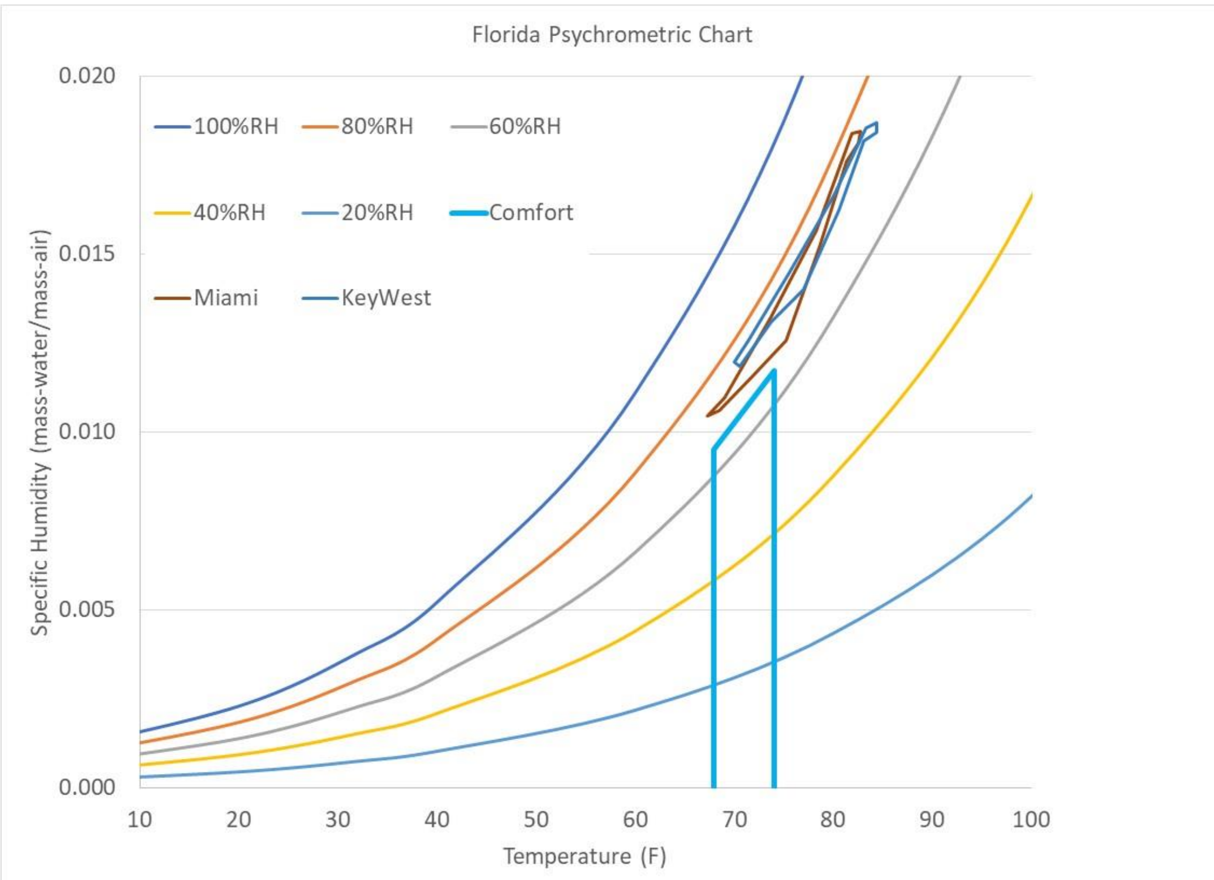



Figure 2A Miami's weather is very similar to Key West with only slight decrease in average temperature and humidity. Unfortunately, the population density of large cities such as Miami preclude "open-air" conditioning due to particulate-laden outside air, wind blockage, heat island effect, and security concerns.

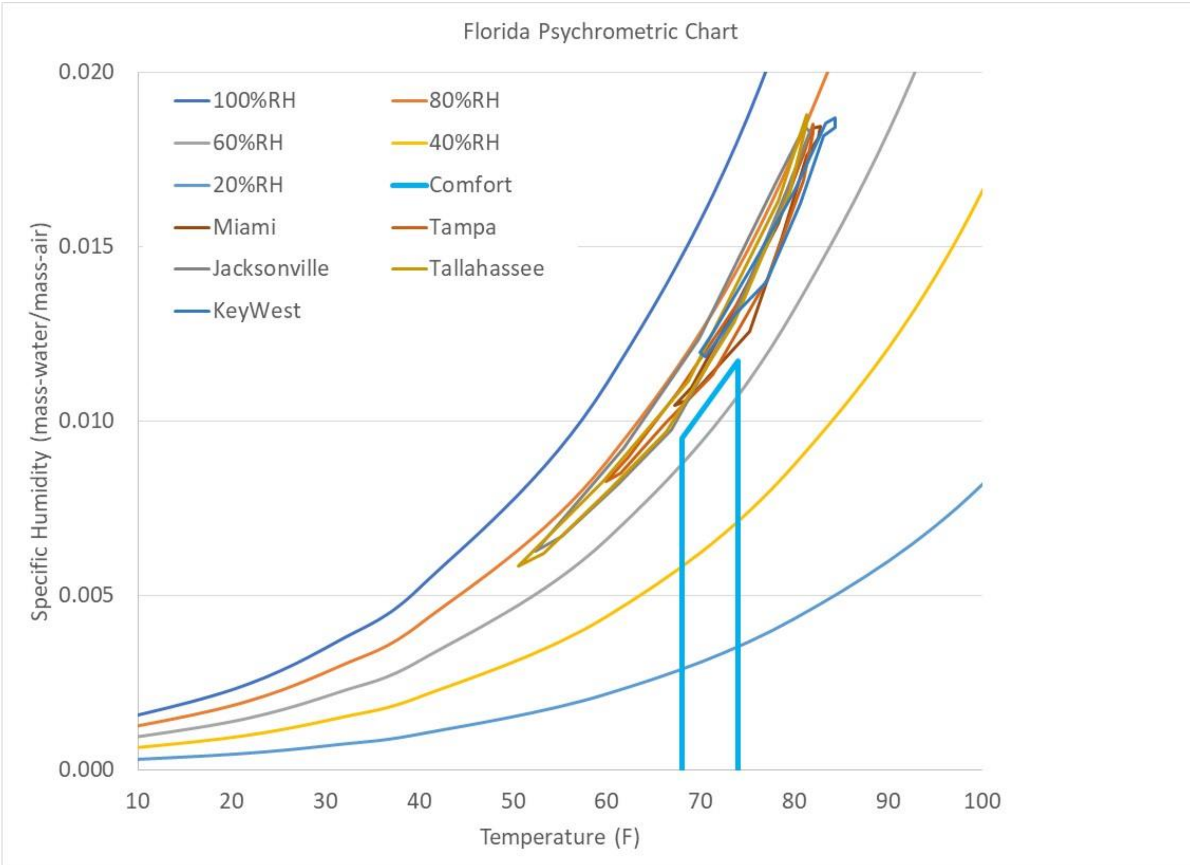



Figure 3A  A northward progression from Key West and Miami through Florida shows a continued decrease in average winter temperature and humidity while mid-summer heat and humidity levels remain similar to that experienced in Key West and Miami.

**Southeast (Alabama, Georgia, Kentucky, Louisiana, Mississippi, South Carolina, Tennessee)**

We move in a clockwise manner around the lower 48 states to observe the progression of average weather characteristics as we travel from humid-to-dry, and warm-to-cold regions.

Figure 4A shows average temperature and humidity for New Orleans and Atlanta. New Orleans is similar to Tallahassee and Jacksonville, indicating that similar average weather occurs along that region of the Gulf Coast.

Moving northward to Atlanta, an overall downward shift in average temperature and humidity ratio in both winter and summer is observed. Average summer temperatures have dropped from 80F to the upper 70's, while winter's average low temperatures have decreased from 50F to 40F. Moving northward from the Gulf Coast requires some level of heating in the winter to maintain comfort, the amount of which is very dependent on house design and occupants. In fact, as shown in our Vermod report describing energy characteristics of 13 identical high performance homes in Vermont, a home with 2.5 or more occupants uses more energy for occupant activities (cooking, hot water, laundry, TVs, etc) than it does for heating in a very cold climate! Atlanta's weather requires moisture management in order to keep humidity levels comfortable for much of the year.

Figure 5A adds additional cities to Figure 4A, with average temperature and humidity shown from Charleston SC to Louisville KY. The trend from south to north is systematic, with increasing colder winters, however, even as far north as Louisville, the average winter temperature remains above freezing. Some decline in average summer temperature and humidity is observed with northward movement to Louisville, however, all regions within this area have warm and humid summers. Perhaps some microclimate regions in more mountainous areas have reduced cooling and dehumidification (with increased winter heating) needs, but even in these regions, moisture must be removed if one would like to keep their indoor home environment comfortable.

A common characteristic of Florida and the southeast region is that average outdoor "relative" humidity stays between 60% and 80% throughout the year. Relative humidity is a measure of the percentage of moisture in air relative to the most moisture that can be absorbed in air <u>at the same temperature</u>. The amount of moisture that can be vaporized in air increases at a greater rate than the sensible (temperature) energy content of air. In fact, for every 10C (18F) temperature increase the maximum moisture limit nearly doubles. That is, 10C (50F) relative to 0C (32F, freezing) has nearly twice as much water vapor holding ability. 20C (68F) holds nearly twice as much water vapor as 10C (50F), and 30C (86F) can hold nearly twice as much water as 20C (68F). Temperature increases above 30C begin do not increase moisture so significantly, however, the increase in moisture content still outpaces sensible energy increases. Therefore, reducing moisture from air at elevated temperatures has significantly more energy transfer and energy conversion involved than managing moisture at cooler temperatures.

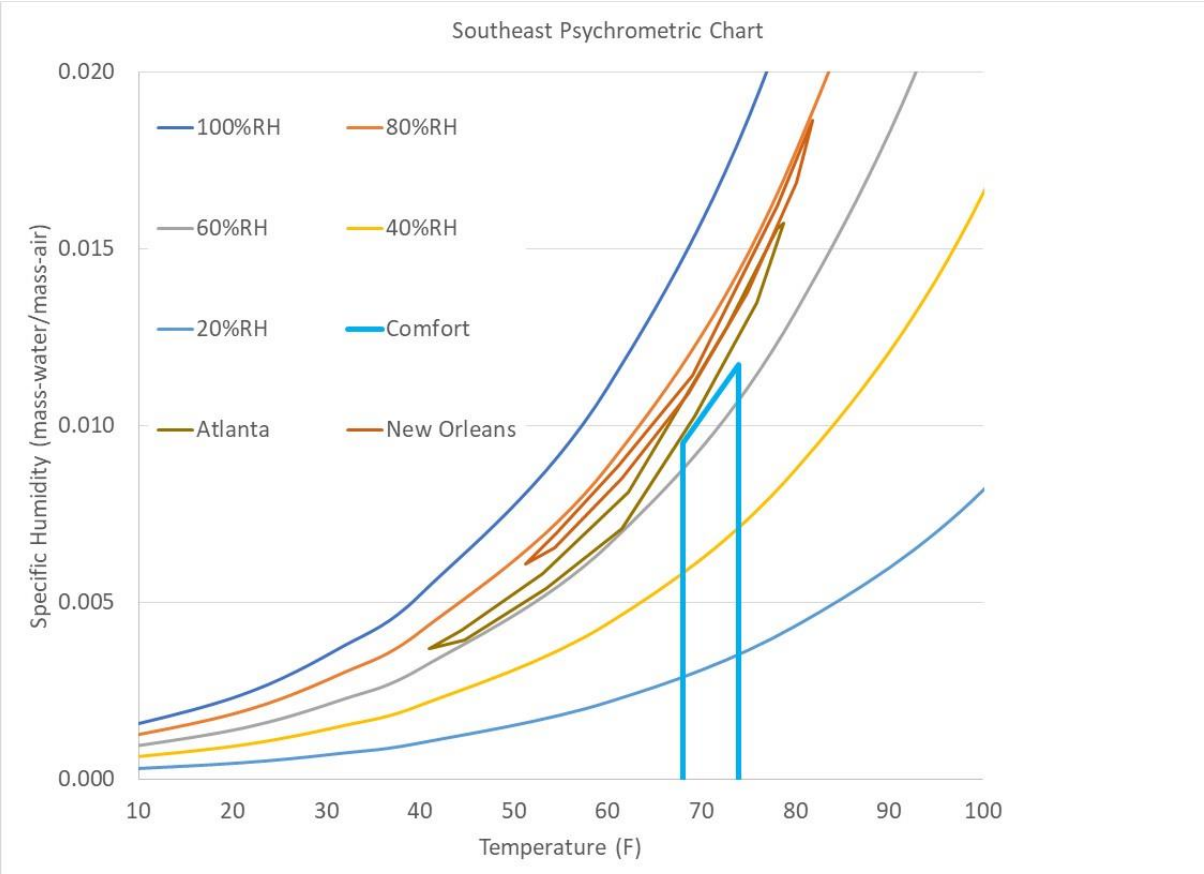



Figure 4A  Atlanta and New Orleans monthly average weather shows that gulf coast weather from Tallahassee to New Orleans are similar, while progressing north to Atlanta shows a decrease in both winter and summer temperature and humidity in comparison to Gulf Coast weather.

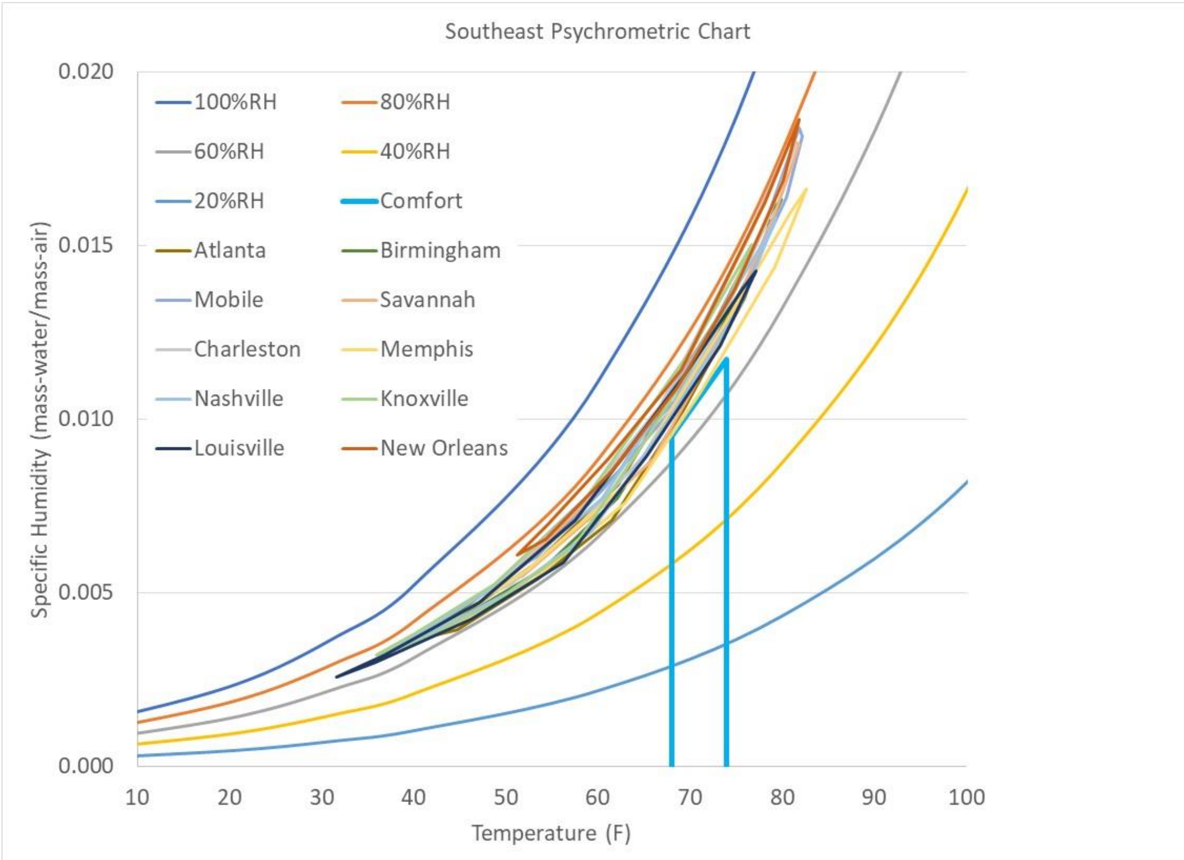



Figure 5A Average monthly weather for 10 cities in the southeast region of the US.

**Texas**

Texas is a big state with a broad climate spectrum. Texas climates form a bridge from the heat and humidity of the Gulf Coast to arid El Paso. As shown in Figure 6A, Bownsville is slightly warmer and more humid than Houston, but overall, they display similar characteristics as the rest of the Gulf Coast and Florida. Moving toward Amarillo in the panhandle region of Texas, we see an opening of the psychrometric loop and significant reductions of moisture level throughout the year. Further westward movement to El Paso continues this trend. The red arrow in Figure 6A shows the seasonal direction of temperature and humidity changes. Spring and summer are dry, followed by a more humid (but still dry) fall and winter.

Figure 7A adds the intermediate climates of Austin, Dallas-Fort Worth and San Antonio to the Figure 6A data. Interior Texas regions benefit from dehumidification during warmer months. Even El Paso homes may find some times when dehumidification is desirable, and perhaps with increasing frequency in the upcoming decades.

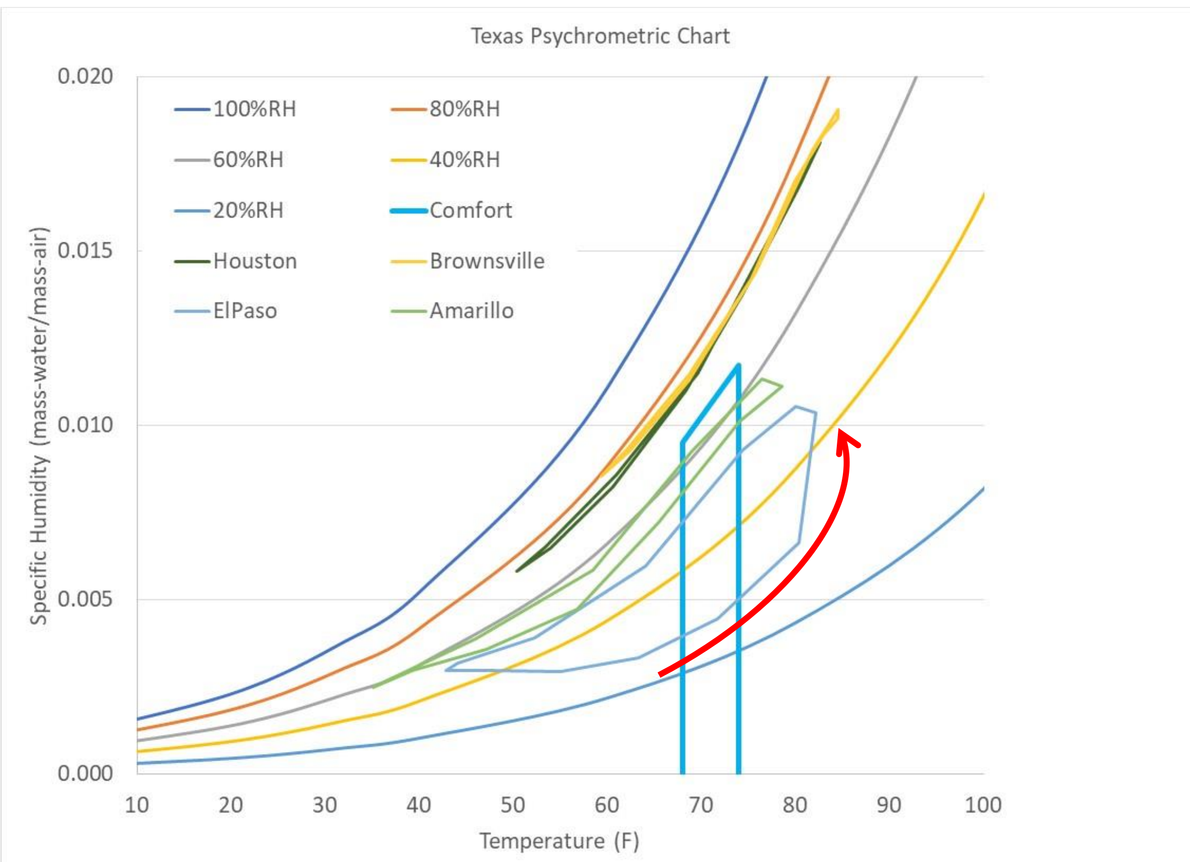



Figure 6A Houston and Brownsville show the progression of Gulf Coast heat and humidity to Amarillo and El Paso with more arid conditions.

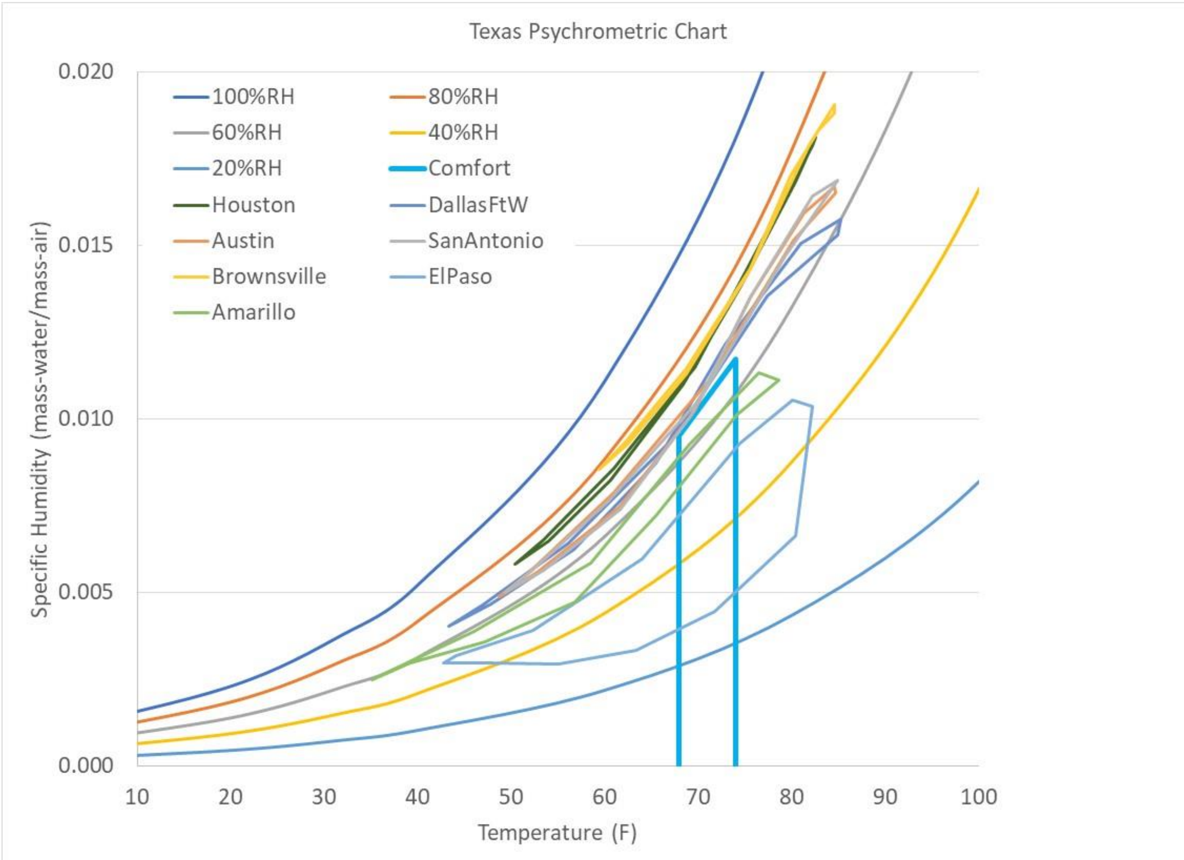



Figure 7A Texas locations show a progression from warm, humid Gulf Coast conditions to the arid conditions of El Paso, with Dallas-Fort Worth, Austin and San Antonio having weather intermediate weather.

### Intermountain Region

On our way to California, we stop in the intermountain region (Arizona, New Mexico, Nevada, Utah, Colorado, Idaho and Wyoming) to explore climate trends.  Figure 15 shows that the southern tier (Albuquerque, Tucson, Phoenix, Las Vegas) continues the characteristics observed for El Paso.

A common characteristic of the southern tier desert locations is a relatively moist late summer and fall in comparison to spring.  The psychrometric loop for the southern tier desert regions is open in comparison to other regions of the country in which fall and spring humidity variations are not so different.  The red arrow in Figure 8A indicates the seasonal movement around the psychrometric loop.

More northern intermountain locations (Denver, Salt Lake City, Boise, Cheyenne, and Reno) display similar characteristics to each other as shown in Figure 9A.  Summer temperatures are cooler than the southern locations with similar low humidity levels.  The more northern locations do not have the summer “monsoon” (July to September rains) of the southern region. Instead, the northern intermountain regions display similar spring and fall humidity levels. Dehumidification needs are very small, and because of the “low” high temperatures coupled with low humidity, one can consider evaporative cooling (ie, “swamp coolers”) for summer air conditioning.

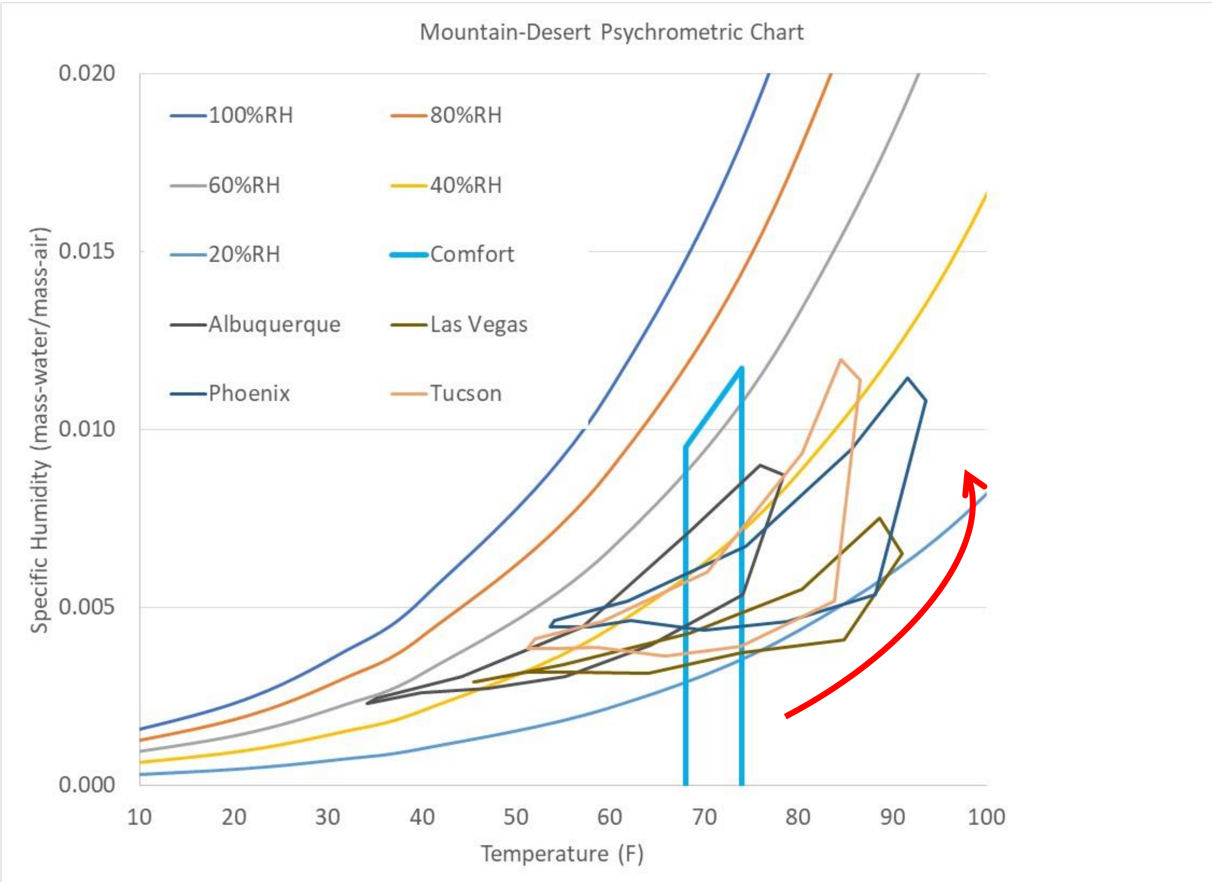



Figure 8A Southern tier locations in the intermountain region display higher humidity in the fall than spring, but in general, average humidity levels are not above comfort humidity.

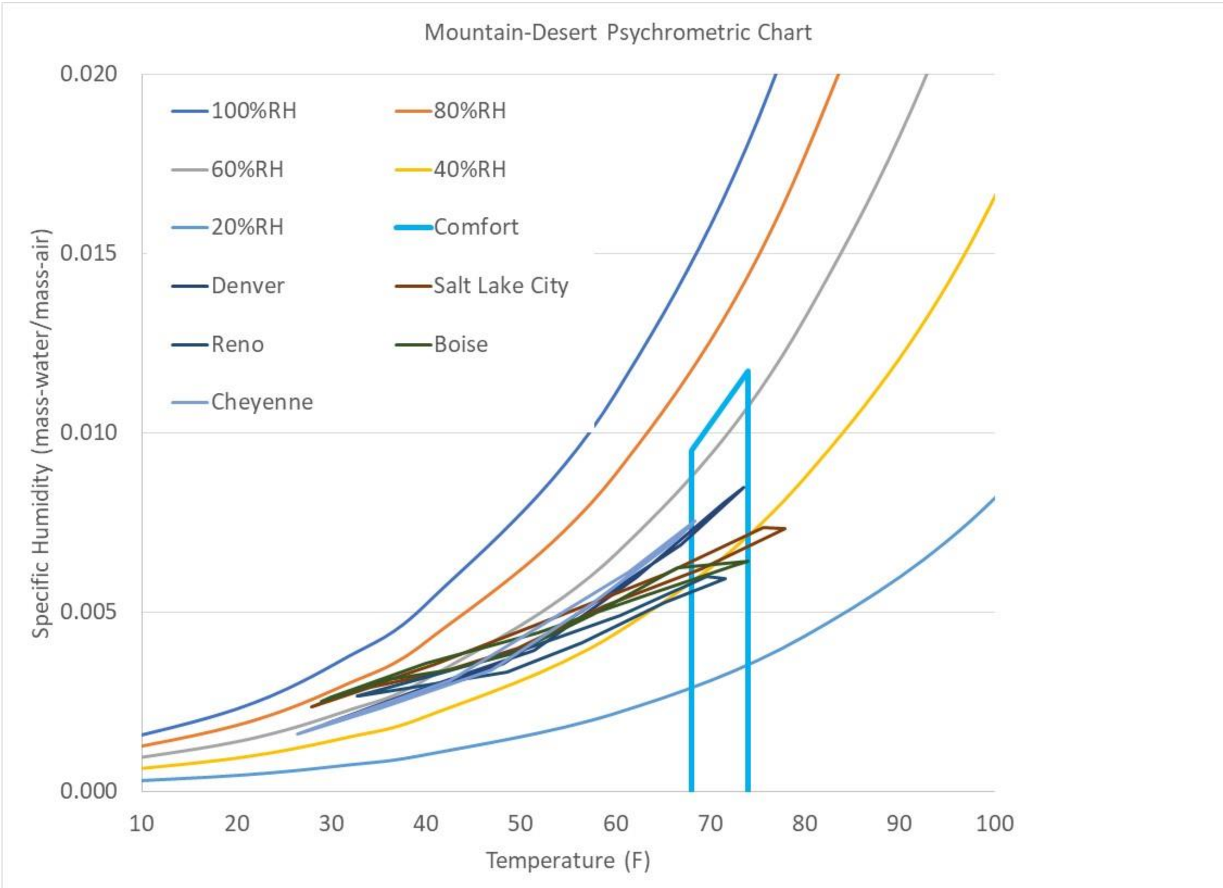



Figure 9A  More northerly intermountain locations have similar characteristics with summer humidity in the 40 to 60% relative humidity range and winter relative humidity in the 60 to 80% range.

## California

Moving across the intermountain region to California, Figure 10A shows a systematic trend from the low humidity, high temperatures of Arizona, New Mexico and Nevada to a climate mostly influenced by the Pacific Ocean. Daggett (between LA and Las Vegas) and Fresno are hot and dry. Sacramento displays characteristics similar to Reno. Los Angeles, by comparison, is primarily influenced by its proximity to the Pacific Ocean. Inland humidity conditions are typically lower than needed for comfort, resulting in limited need for dehumidification.

Figure 11A shows climate trends as one moves along the coast from San Diego in the south to Arcata in northern California. San Diego and Los Angeles are quite similar on average, while San Francisco is cooler and less humid (although San Francisco is higher in relative humidity). Arcata, along California's northern coast, continues the trend with cooler temperatures and lower humidity (although average relative humidity is generally greater than 80%).

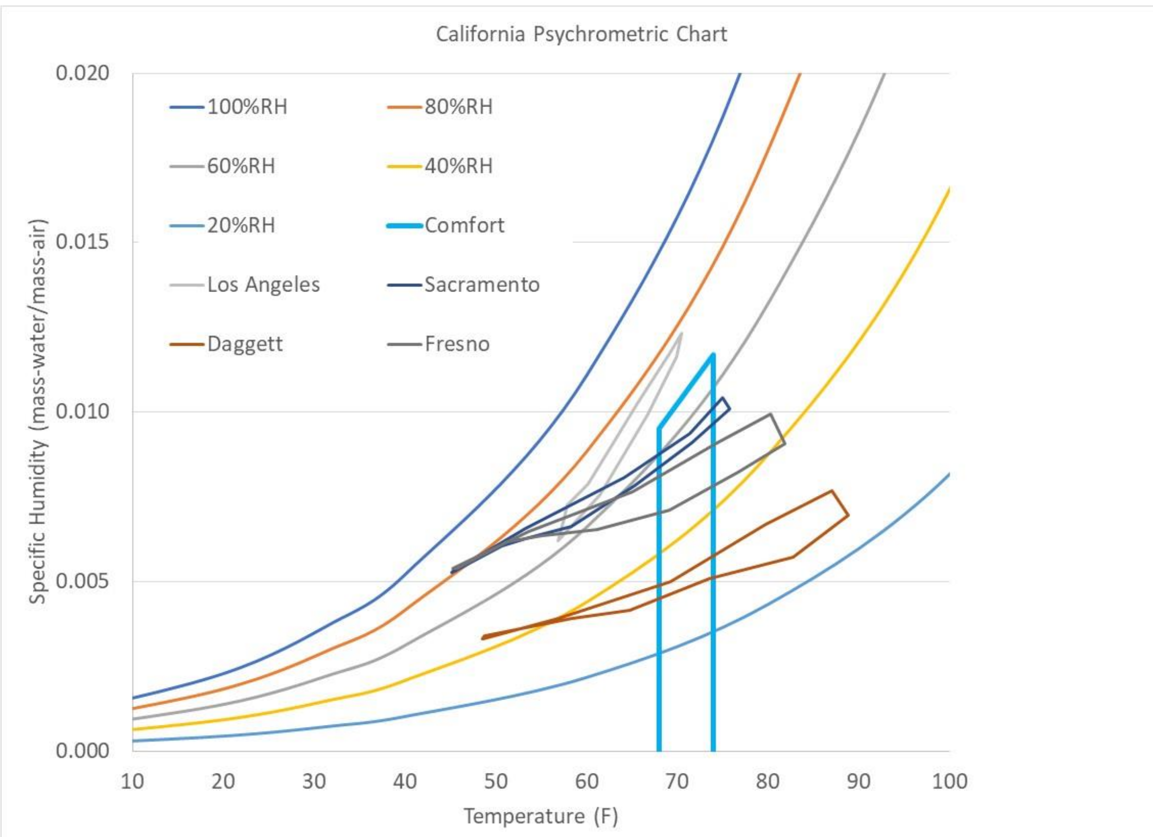



Figure 10A Moving from westward from California's desert region (Daggett) to Los Angeles, temperature and humidity systematically moves toward a climate dominated by coastal marine conditions.

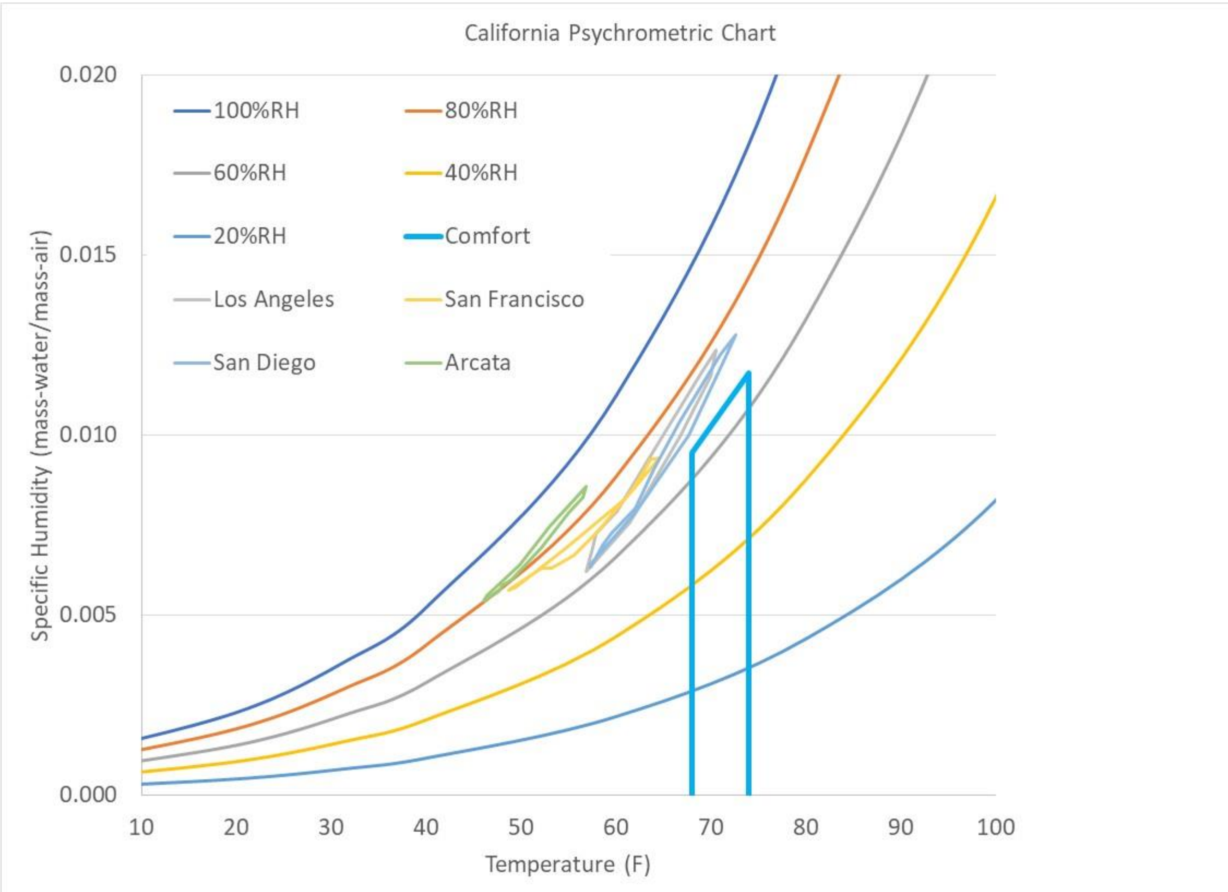



Figure 11A  Moving northward along California's coast, average temperatures decrease while relative humidity increases (but humidity ratio, the actual moisture content decreases as one moves south to north).

**Northwest**

Figure 12A shows northwestern climates along the Pacific coast to continue the marine influenced climate observed along California, however, Portland and Seattle have somewhat warmer summers and cooler winters than northern California coastal regions. Bend Oregon is similar to Arcata and San Francisco on an average monthly basis, displaying a microclimate that varies from that of Portland. Moving east from Seattle to Spokane and Billings MT, winters become colder and summers are drier. Note that even though Portland and Seattle are high in "relative" humidity, the humidity ratio is not very high in comparison to the humidity ratio levels observed in the southeast.

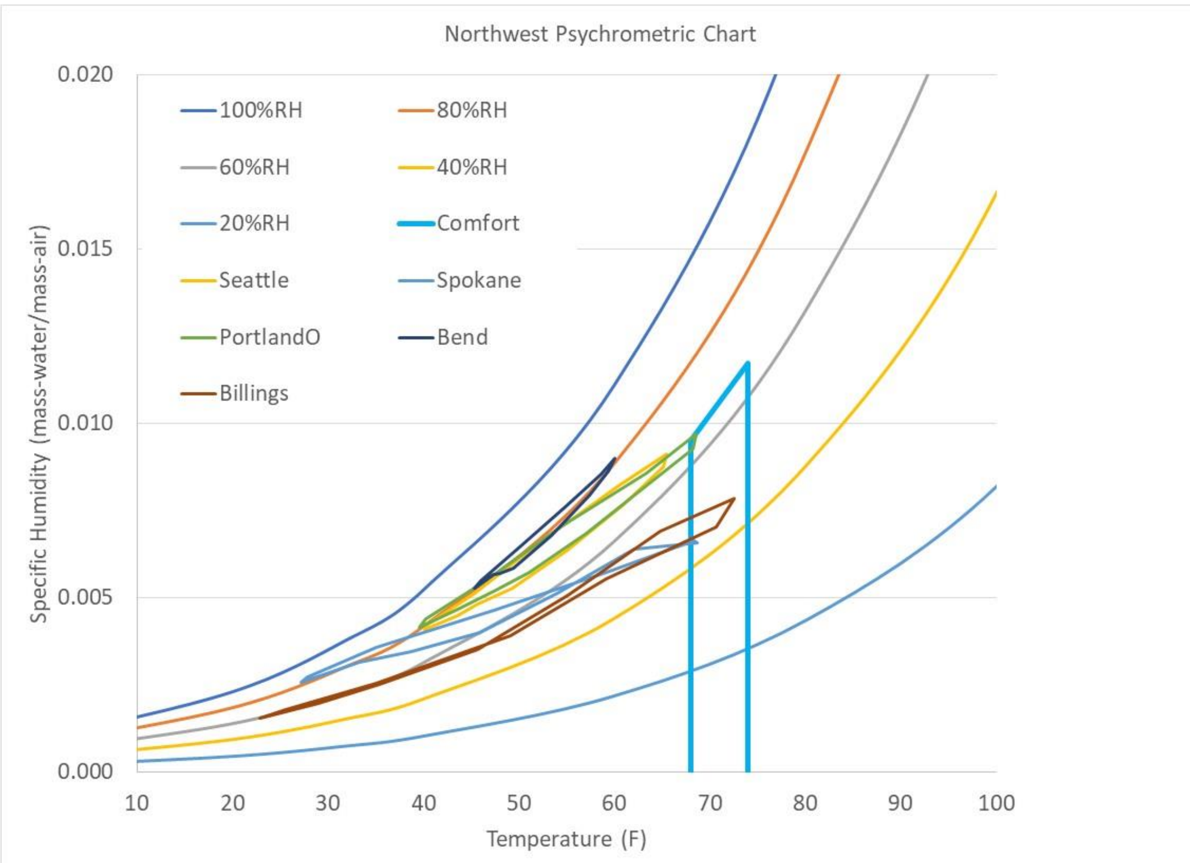



Figure 12A Northwestern climates display high relative humid with cool temperatures along the coast, while movement inland to Spokane and Billings MT decrease in moisture level.

**Midwest**

The Midwest is a large geographic region, stretching west-to-east from the Dakotas to Ohio, and south-to-north from Missouri to Minnesota. Figure 13A shows a dozen midwestern location average climate trends. Similar to the southeast region of the lower 48 states, the Midwest states display similar spring and fall humidity levels that are bounded between 60 and 80% relative humidity. Midwest states are colder throughout the year in comparison, as expected, in relation to the southeast. Western locations, such as Fargo and Pierre, are somewhat drier as well as cool, with low dehumidification needs. Dehumidification needs are significant for most of the region, with the highest capacities needed for the southern locations such as St Louis and Kansas City, and lower levels needed for northern locations such as Houghton MI and Minneapolis.

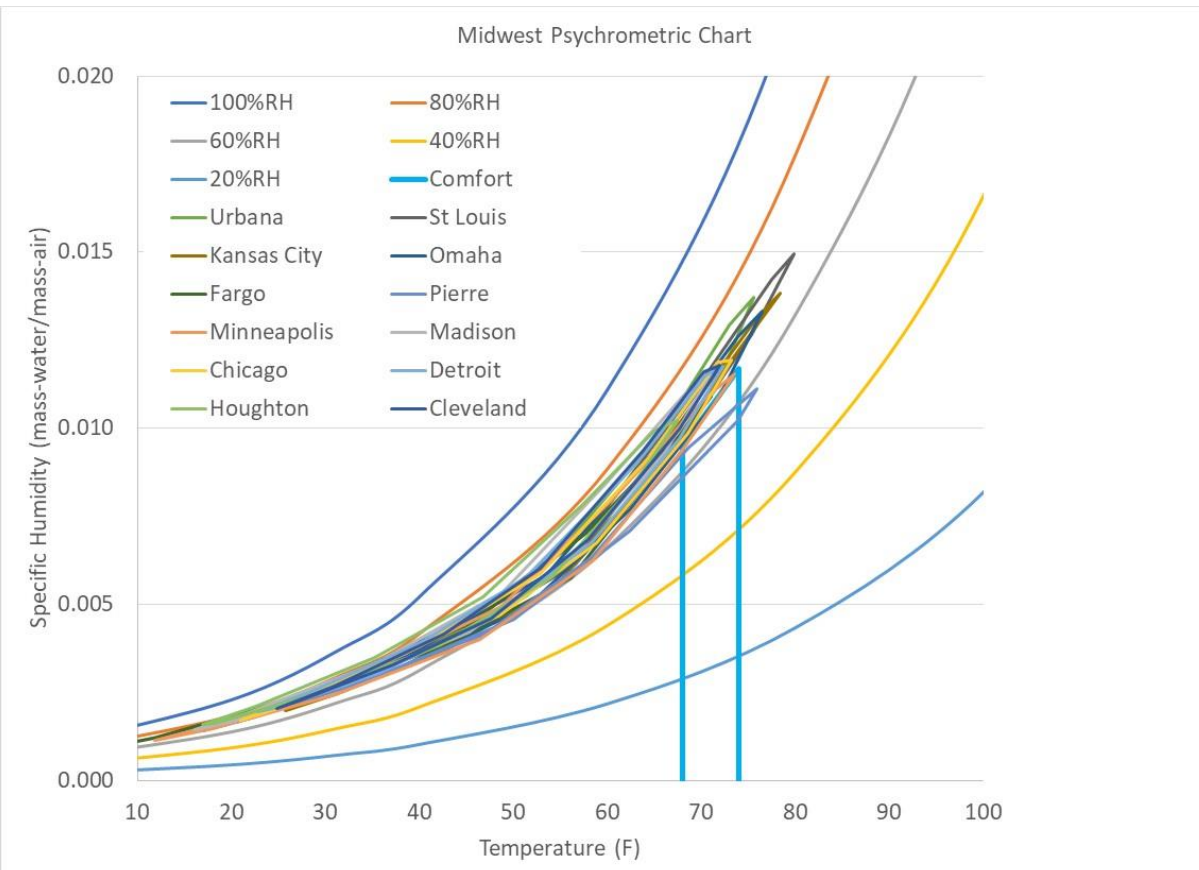



Figure 13A Midwestern climates range between 60% and 80% relative humidity throughout the year with temperatures decreasing as one moves from southern locations (eg, St Louis) to northern locations (eg, Minneapolis) of the midwest region.

## Northeast

The northeast has similar trends as those observed in the Midwest, which is expected with prevailing weather patterns moving from west to east. Figure 14A shows similar humidity and temperature changes, with the more northern locations (Burlington VT and Portland ME) cooler throughout the year in comparison to Boston and New York. Dehumidification will be needed for good comfort control for New York and Boston. Although Burlington and Portland haven't relied on air conditioning and dehumidification for comfort, recent summer heat and humidity may change house design practices.

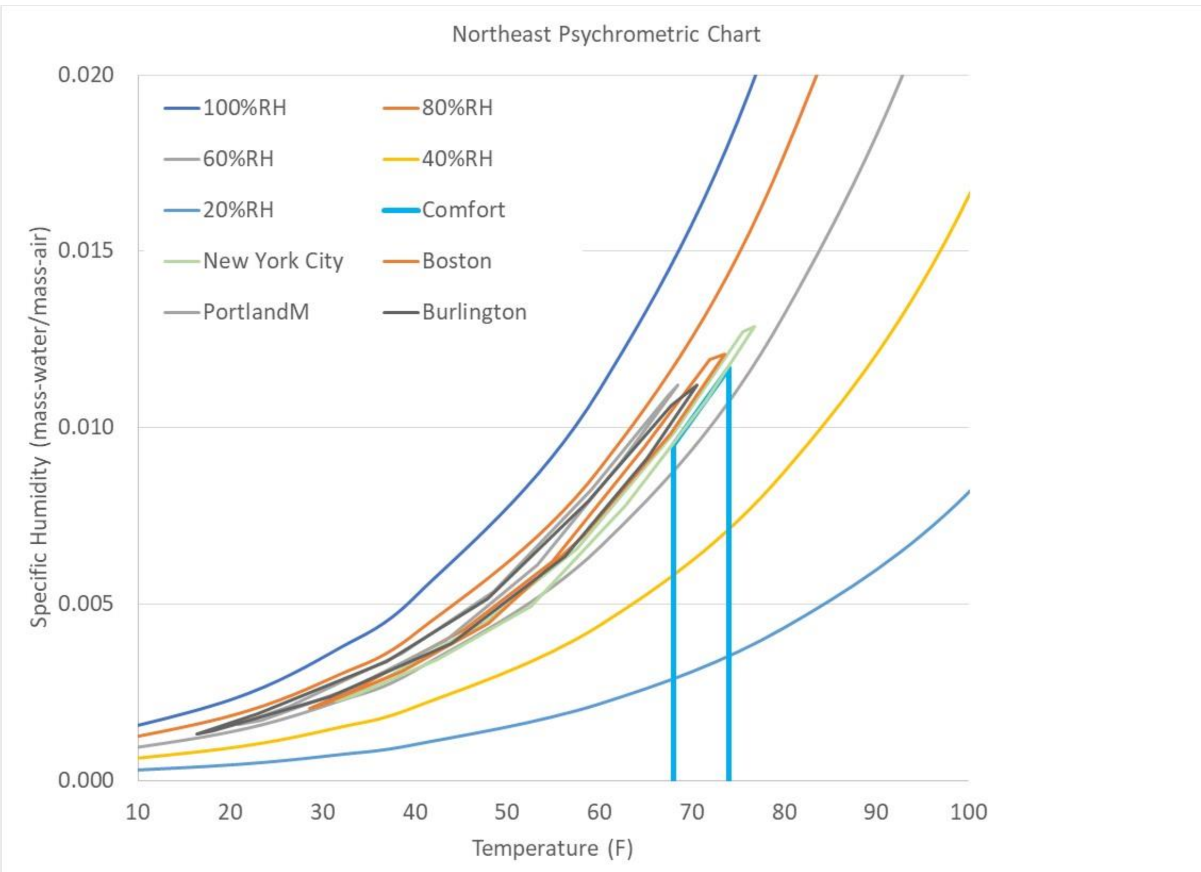



Figure 14A Northeast weather conditions for Burlington VT, Portland ME, Boston and NYC are similar to those observed in the Midwest.

## Mid-Atlantic States

The mid-Atlantic region returns us back to the southeast region of the lower 48 states, and completes our climatic tour. Figure 15A shows a continuing trend of increasing temperature moving south from Philadelphia to Wilmington NC. Weather in Wilmington NC is similar to weather previously discussed for southeastern states. Seasonal humidity cycles are reasonably similar for spring and fall seasons, with relative humidity generally staying in the 60 to 80% range.

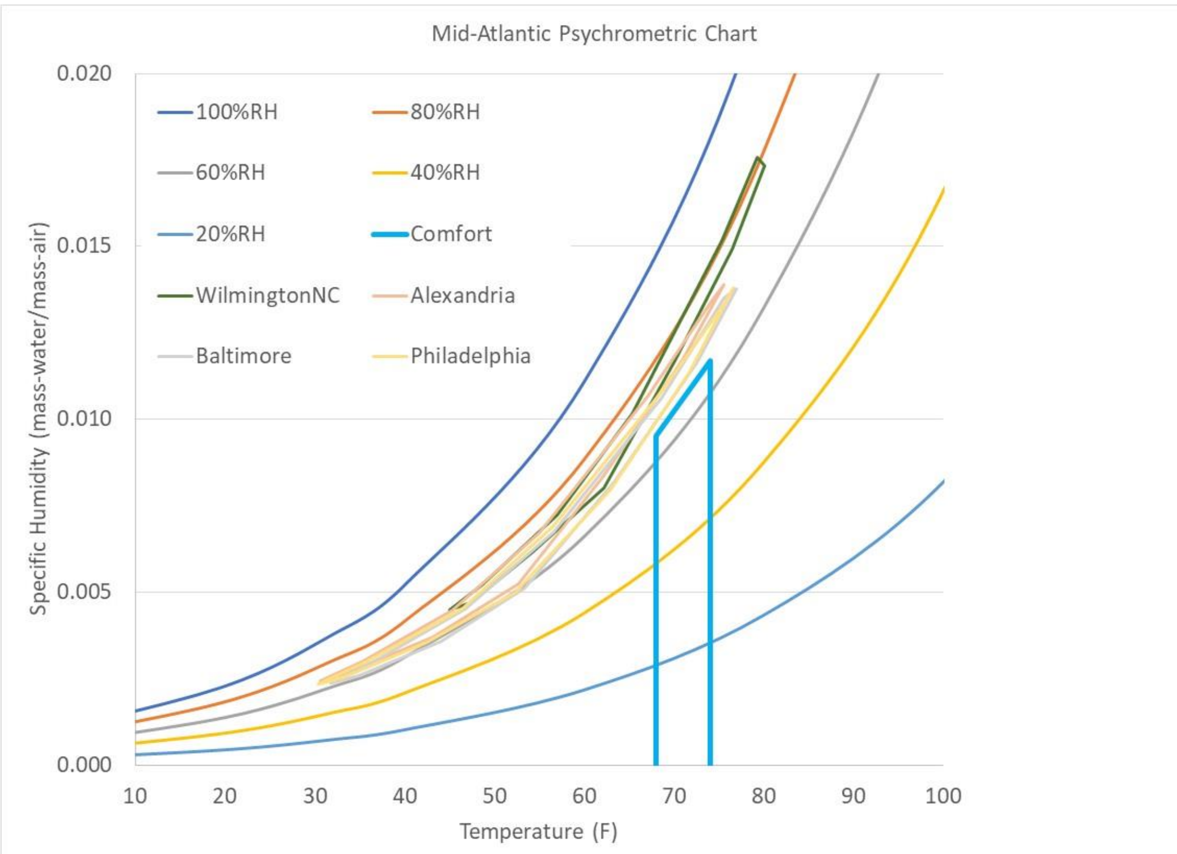



Figure 15A Moving south from Philadelphia to Wilmington NC, weather becomes warmer with relative humidity continuing to remain in the 60 to 80% range as observed in the southeast, Midwest and northeast.

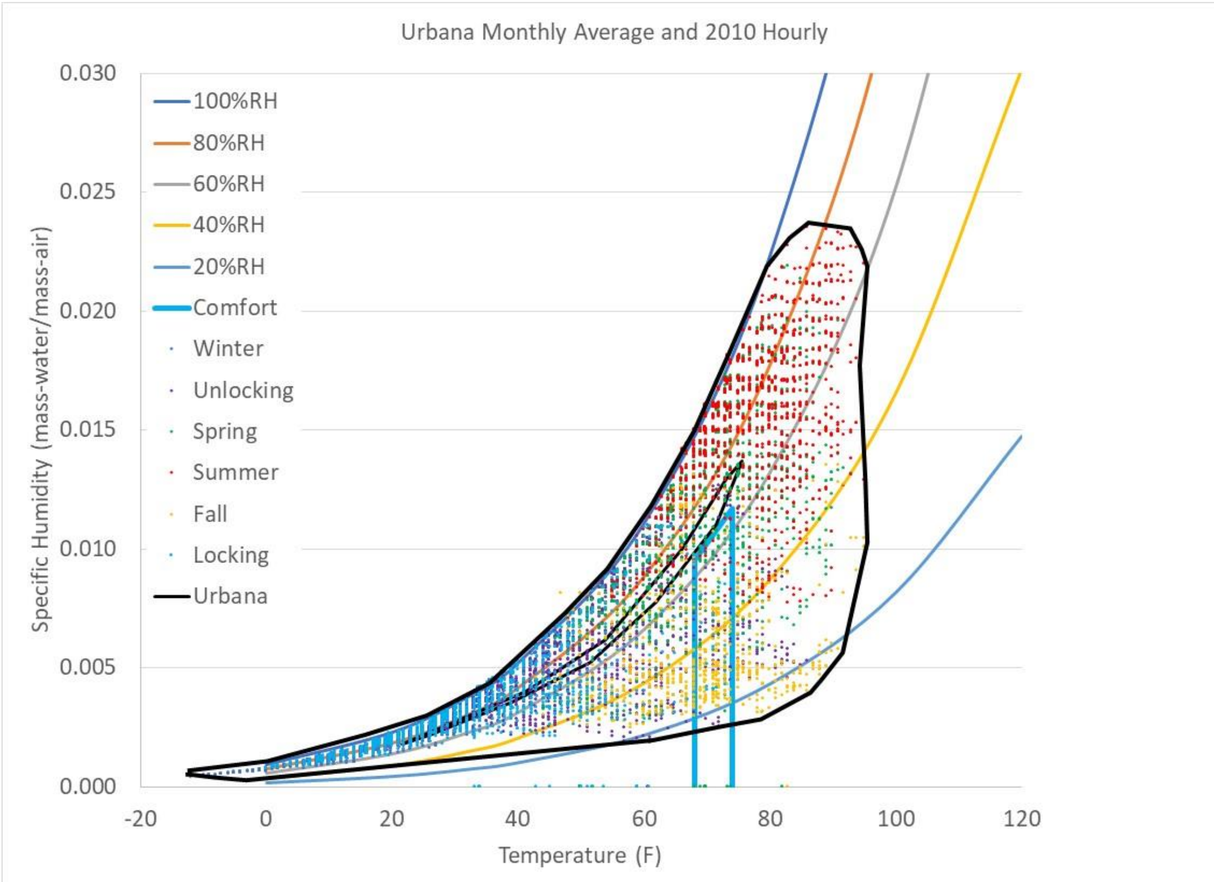
Appendix B - Hour-by-Hour Weather Variation Characteristics – Urbana Illinois

We have discussed the regional variation of average monthly temperature and humidity, which provides some ideas as far as the variability of weather around the lower 48 states. The actual hour-by-hour variation for a real weather year provides additional information for understanding our moisture handling needs. Urbana's average summer humidity is "only" 0.013kg-w/kg-a (76F and 72% relative humidity) in comparison to Gulf Coast states with a summer average humidity of 0.019kg-w/kg-a (85F and 72% relative humidity). Urbana and other regions around the country regularly exceed average Gulf Coast humidity conditions on a day-by-day and hour-by-hour basis with high dehumidification capacity needs.

Figure 1B shows hourly (2010) weather data for Urbana-Champaign Illinois. Also included with the plot is a table listed psychrometric quadrant data (fraction of year, temperature, humidity ratio and wind speed). The quadrant data can be used to estimate data and seasonal moisture balance (see Parts 1 and 2 house moisture examples for Contractors "Loose", "Tight" and "Smart").

Figures 2B through 7B break the Figure 1B data into 6 seasons, as defined by author Kurt Vonnegut. The 2 month seasons consist of winter (January/February), "unlocking" (March/April), spring (May/June), summer (July/August), fall (September/October), and "locking" (November/December). The two-month seasonal trend moves "clockwise" around the monthly average path.

Figure 8B shows typical daily psychrometric paths. Diurnal movements are primarily horizontal, indicating minor changes in moisture (humidity ratio) as temperature changes from day to night. When nighttime cooling reaches "dew point" (100% relative humidity), water condenses from ambient air as dew. Weather fronts cause shifts in temperature and moisture.




Urbana-Champaign IL; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.596 | ave C/D Tave(F) | 40.3 | ave C/D W(kgw/kga) | 0.004 | ave C/D wind (mph) | 10.75 |
| fraction hot/dry | 0.032 | ave H/D Tave(F) | 74.9 | ave H/D W(kgw/kga) | 0.006 | ave H/D wind (mph) | 12.96 |
| fraction cold/wet | 0.145 | ave C/W Tave(F) | 65.8 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 9.60 |
| fraction hot/wet | 0.227 | ave H/W Tave(F) | 77.4 | ave H/W W(kgw/kga | 0.013 | ave H/W wind (mph) | 8.39 |

Figure 1B Hourly weather data for Urbana Champaign Illinois (2010 weather year) relative to monthly average weather data. The table lists psychrometric quadrant averages for the hourly data.

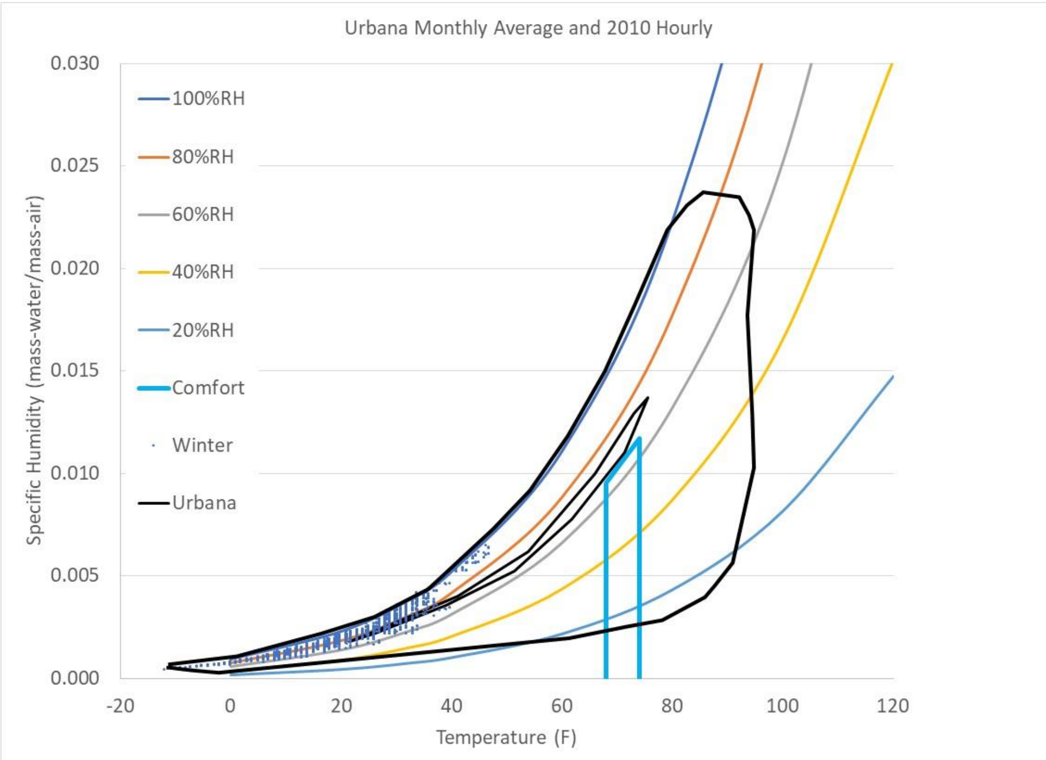



Figure 2B Hourly 2010 winter data for Urbana Champaign IL (January & February)

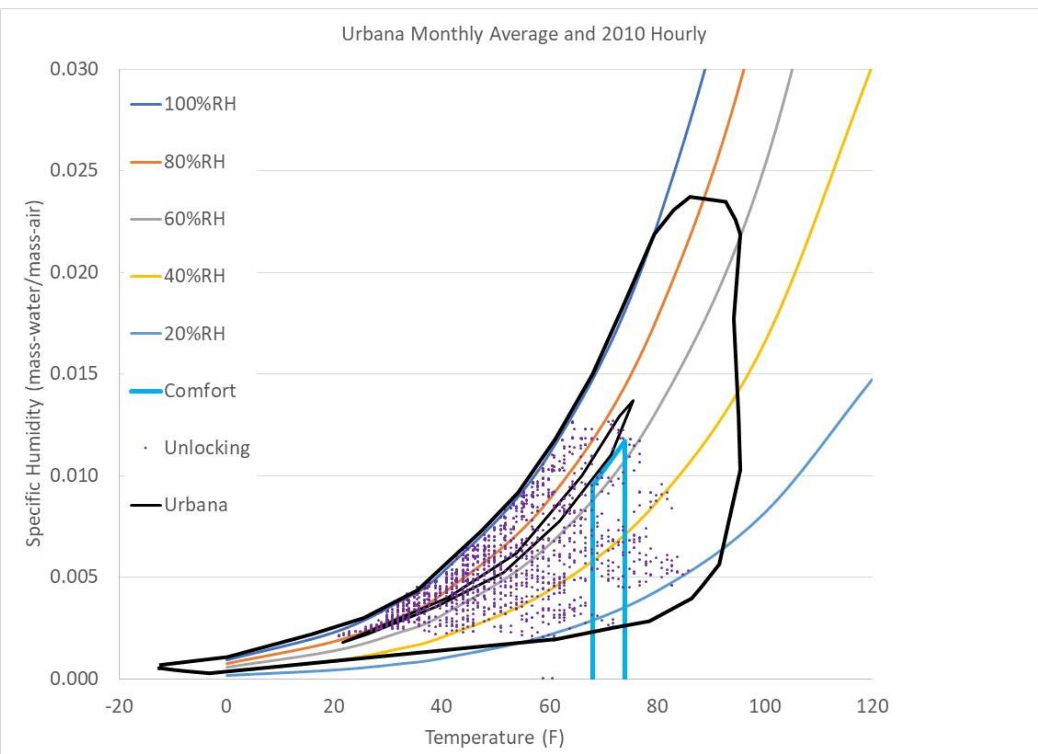



Figure 3B  Hourly 2010 “unlocking” data for Urbana Champaign IL (March & April)

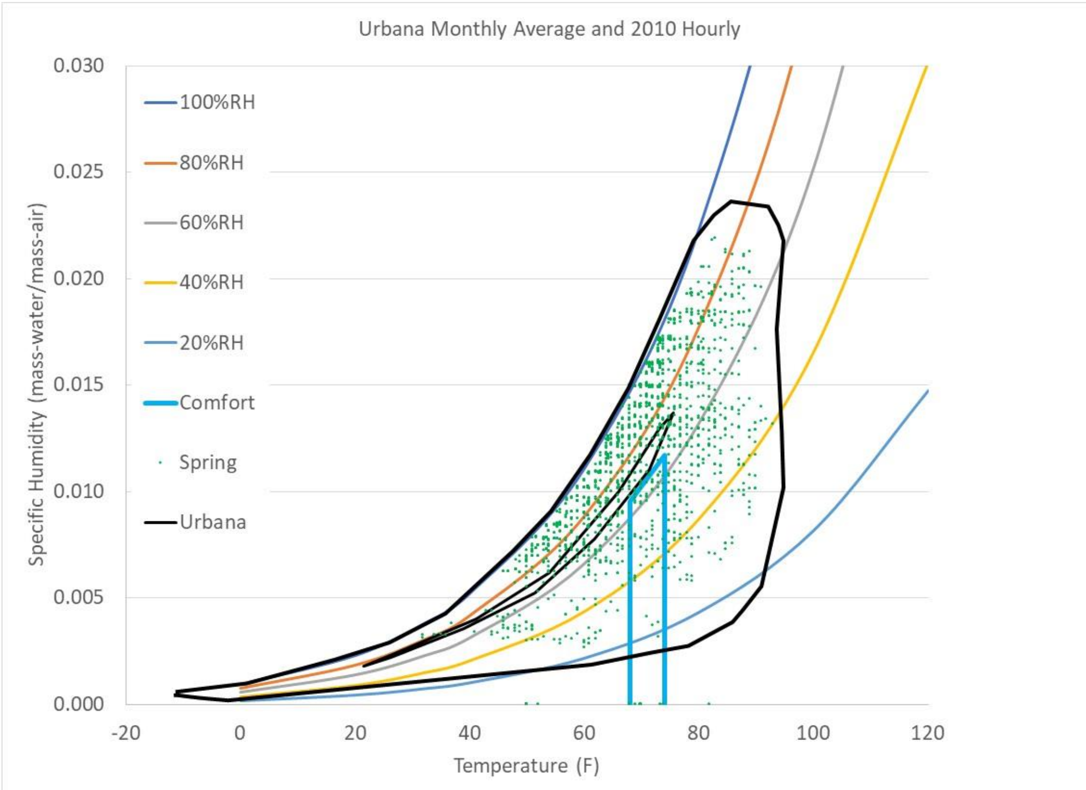



Figure 4B Hourly 2010 spring data for Urbana Champaign IL (March & June)

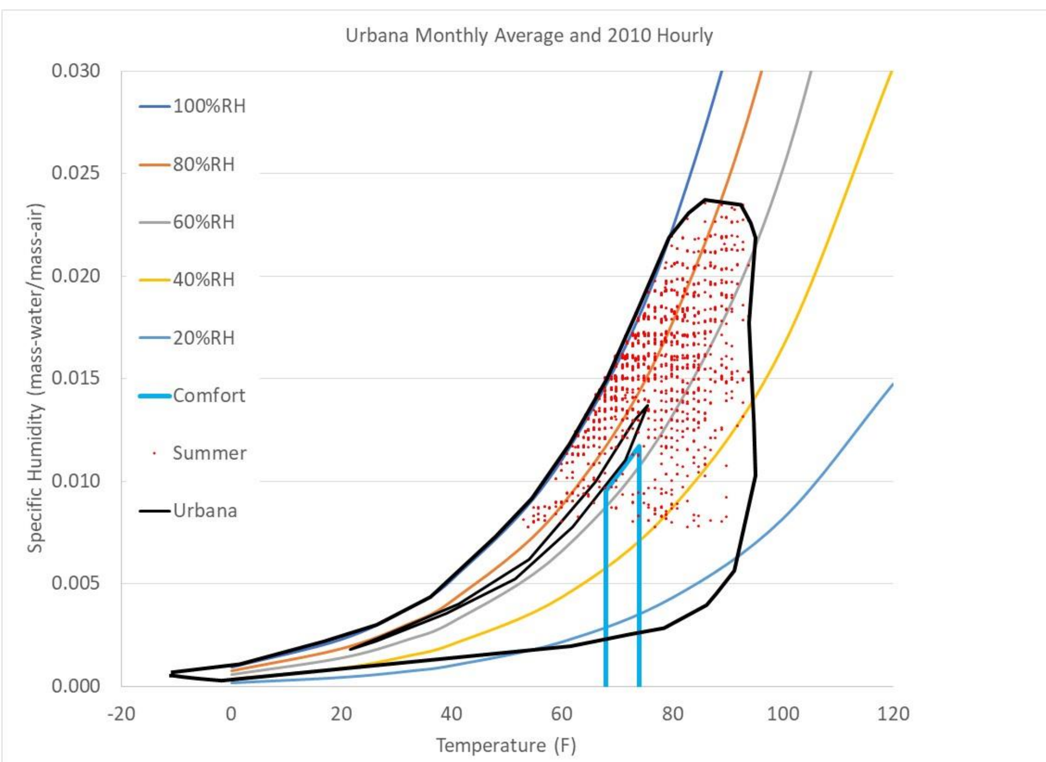



Figure 5B Hourly 2010 summer data for Urbana Champaign IL (July & August)

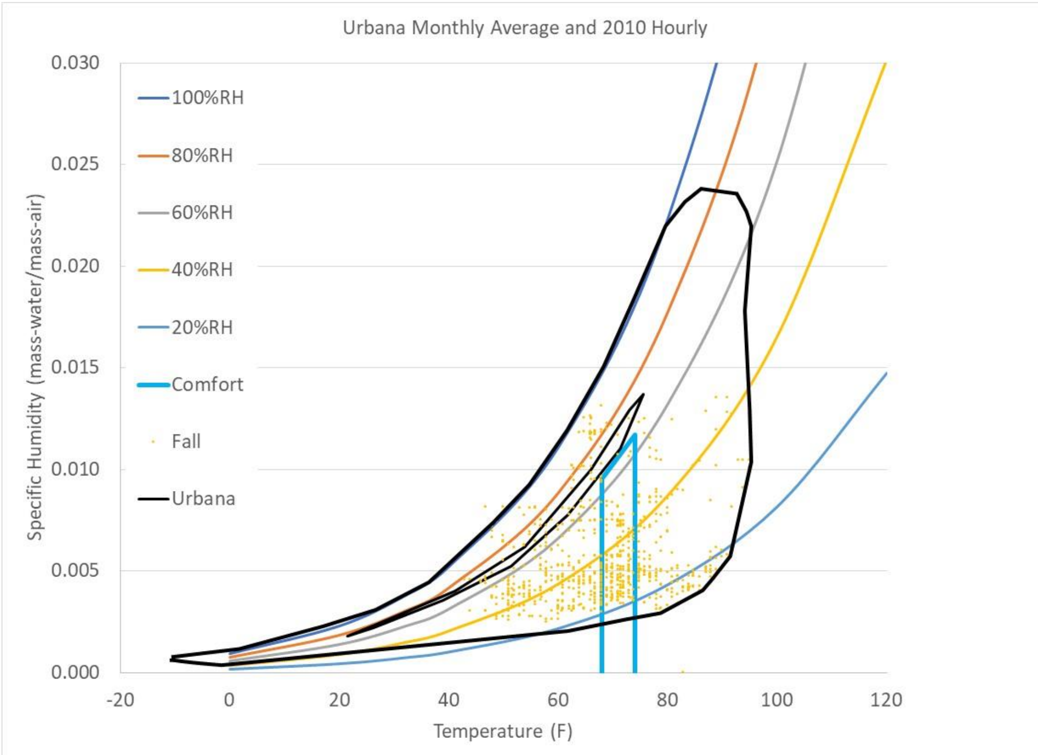



Figure 6B Hourly 2010 fall data for Urbana Champaign IL (September & October)

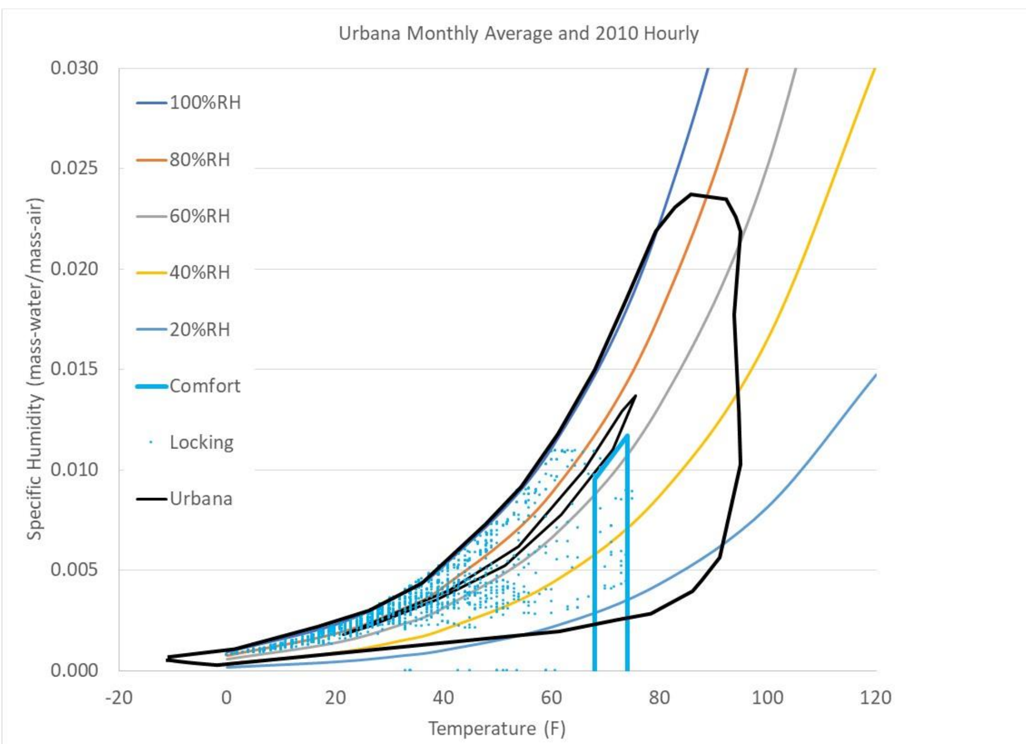



Figure 7B Hourly 2010 “locking” data for Urbana Champaign IL (November & December)

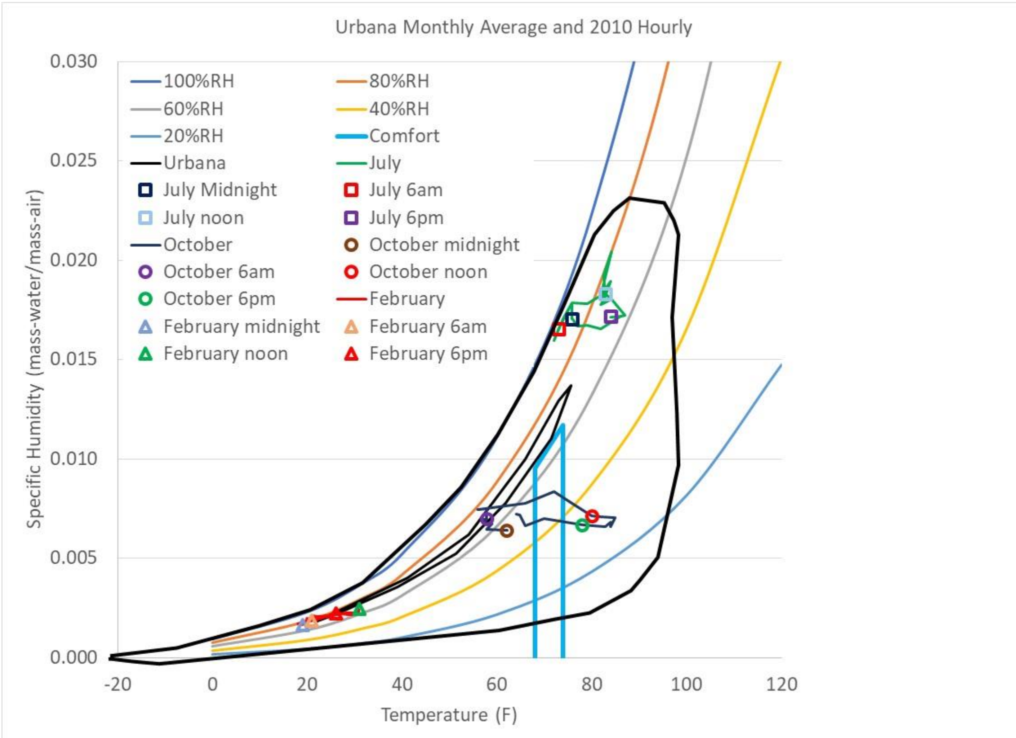



Figure 8B  Diurnal psychrometric paths for summer, fall and winter days.

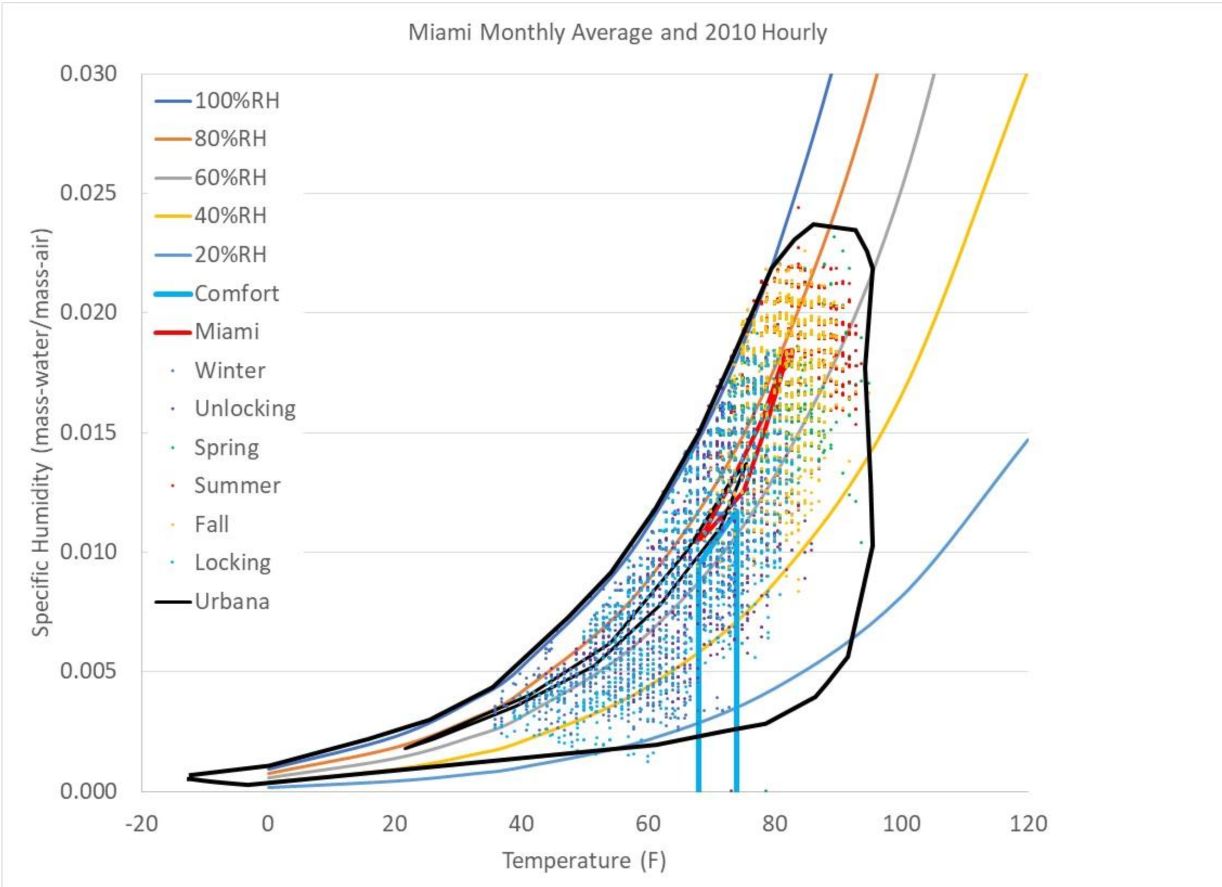
## Appendix C - Hour-by-Hour Weather Variation Characteristics – Lower "48"

Following Appendix B, hourly weather data (2010 weather year) are presented for several locations listed below. Tabular data listing the psychrometric quadrant (H/D, C/D, H/W, C/W) averages for temperature, humidity ratio, and wind speed, and the fraction of the year weather is in each quadrant are included. A boundary envelope for Urbana-Champaign Illinois hourly weather data is drawn on each plot in order to provide a frame of reference for each location's weather variations. Urbana-Champaign has one of the largest weather variation envelopes in the US. Also included on each plot is the monthly average weather condition (from Appendix A) and again for reference, Urbana-Champaign monthly average weather.

Vonnegut season definitions (Winter/Unlocking/Spring/Summer/Fall/Locking) are used to color code hourly weather data.

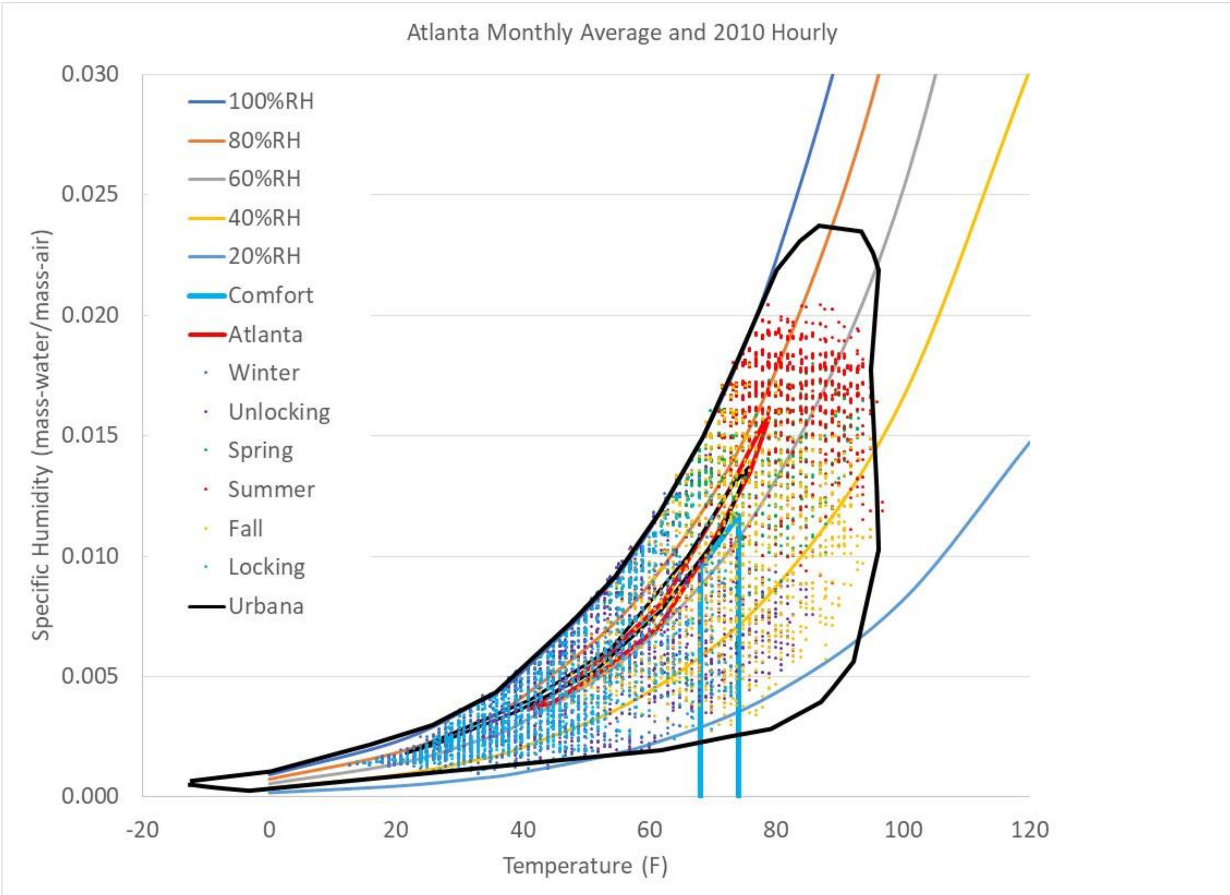
The following is a list of hourly weather data included:

1. Miami FL
2. Atlanta GA
3. New Orleans LA
4. Phoenix AZ
5. Denver CO
6. Los Angeles CA
7. San Francisco CA
8. Seattle WA
9. Minneapolis MN
10. Kansas City MO
11. Boston MA
12. Baltimore-Washington DC



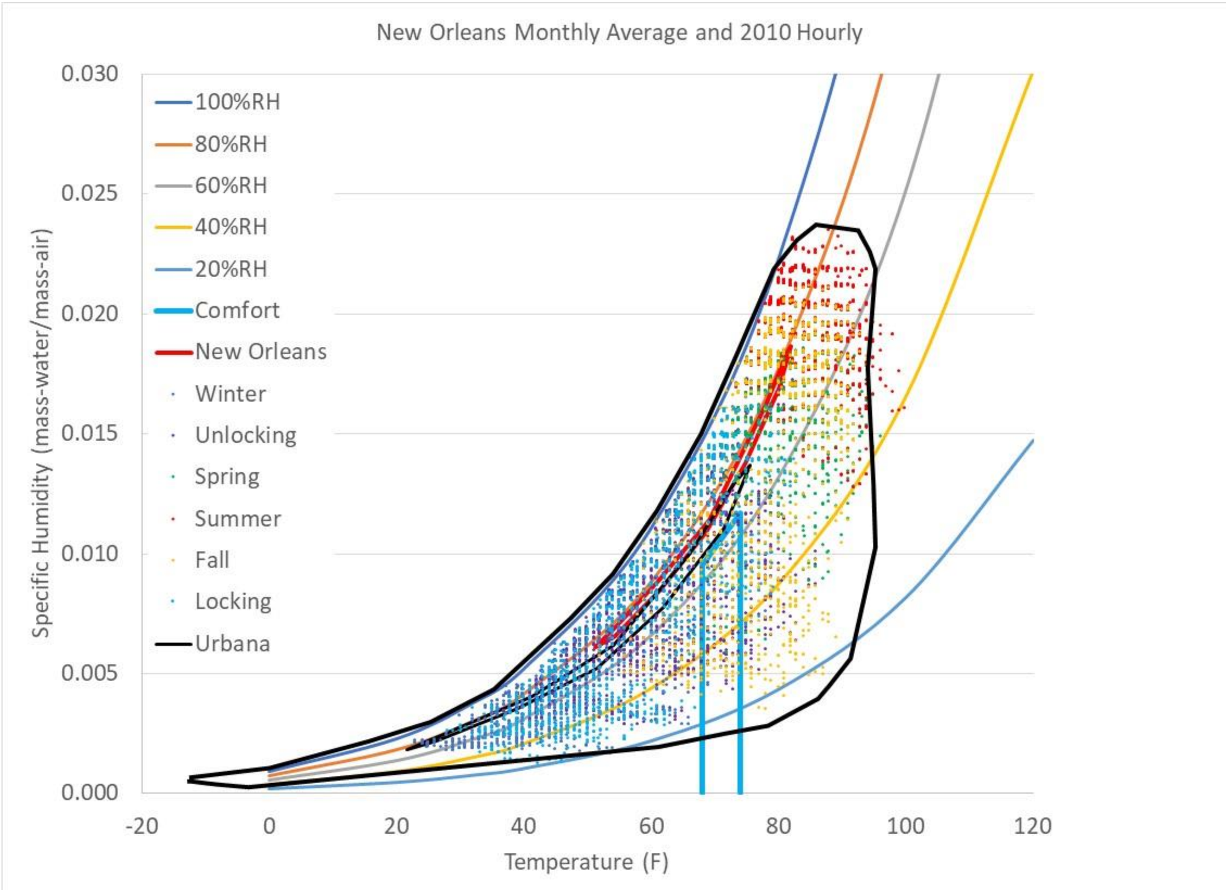

Miami FL; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.138 | ave C/D Tave(F) | 62.7 | ave C/D W(kgw/kga) | 0.005 | ave C/D wind (mph) | 6.93 |
| fraction hot/dry | 0.011 | ave H/D Tave(F) | 74.2 | ave H/D W(kgw/kga) | 0.006 | ave H/D wind (mph) | 7.74 |
| fraction cold/wet | 0.106 | ave C/W Tave(F) | 66.5 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 5.69 |
| fraction hot/wet | 0.744 | ave H/W Tave(F) | 81.2 | ave H/W W(kgw/kga | 0.016 | ave H/W wind (mph) | 8.13 |



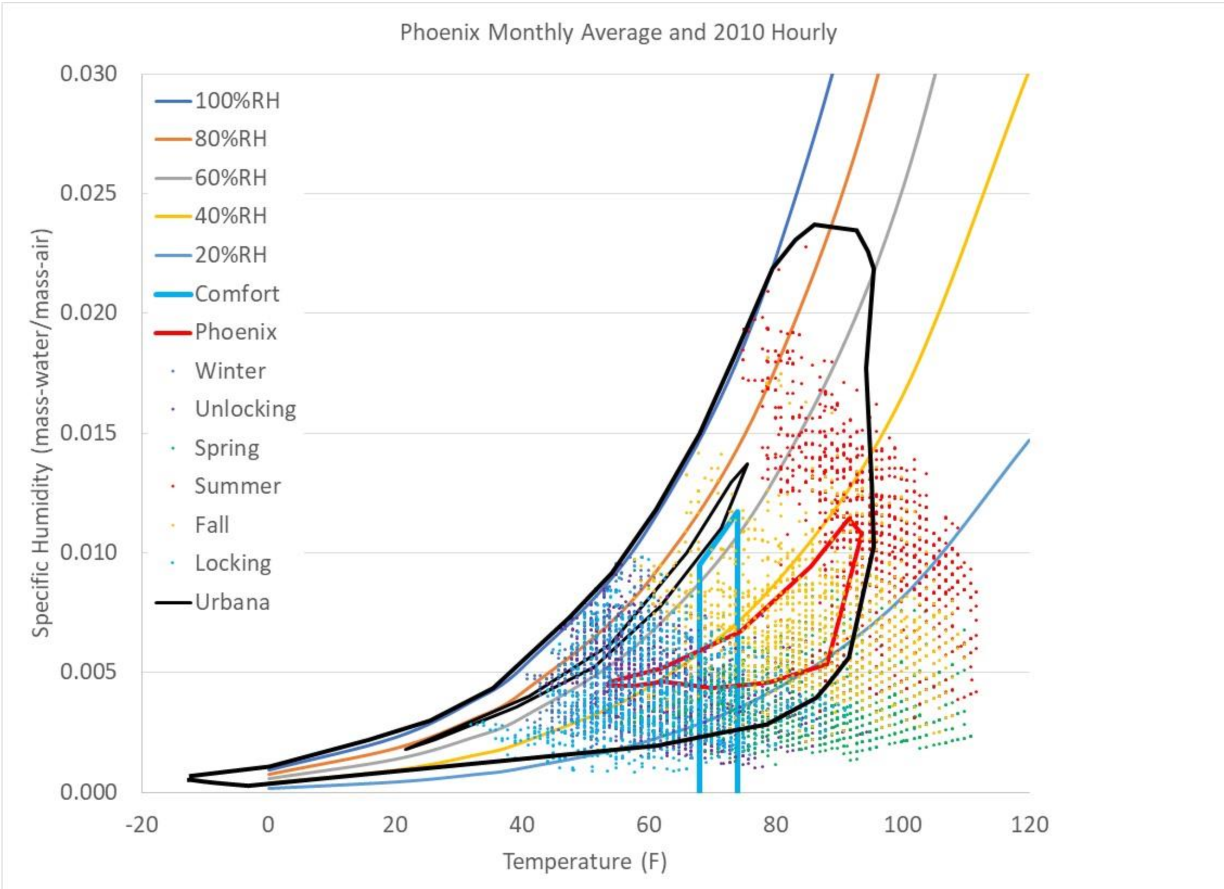

Atlanta GA; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.448 | ave C/D Tave(F) | 50.5 | ave C/D W(kgw/kga) | 0.004 | ave C/D wind (mph) | 9.20 |
| fraction hot/dry | 0.042 | ave H/D Tave(F) | 75.1 | ave H/D W(kgw/kga) | 0.006 | ave H/D wind (mph) | 7.75 |
| fraction cold/wet | 0.144 | ave C/W Tave(F) | 65.2 | ave C/WW(kgw/kga) | 0.012 | ave C/W wind (mph) | 7.94 |
| fraction hot/wet | 0.367 | ave H/W Tave(F) | 79.4 | ave H/W W(kgw/kga | 0.014 | ave H/W wind (mph) | 6.88 |



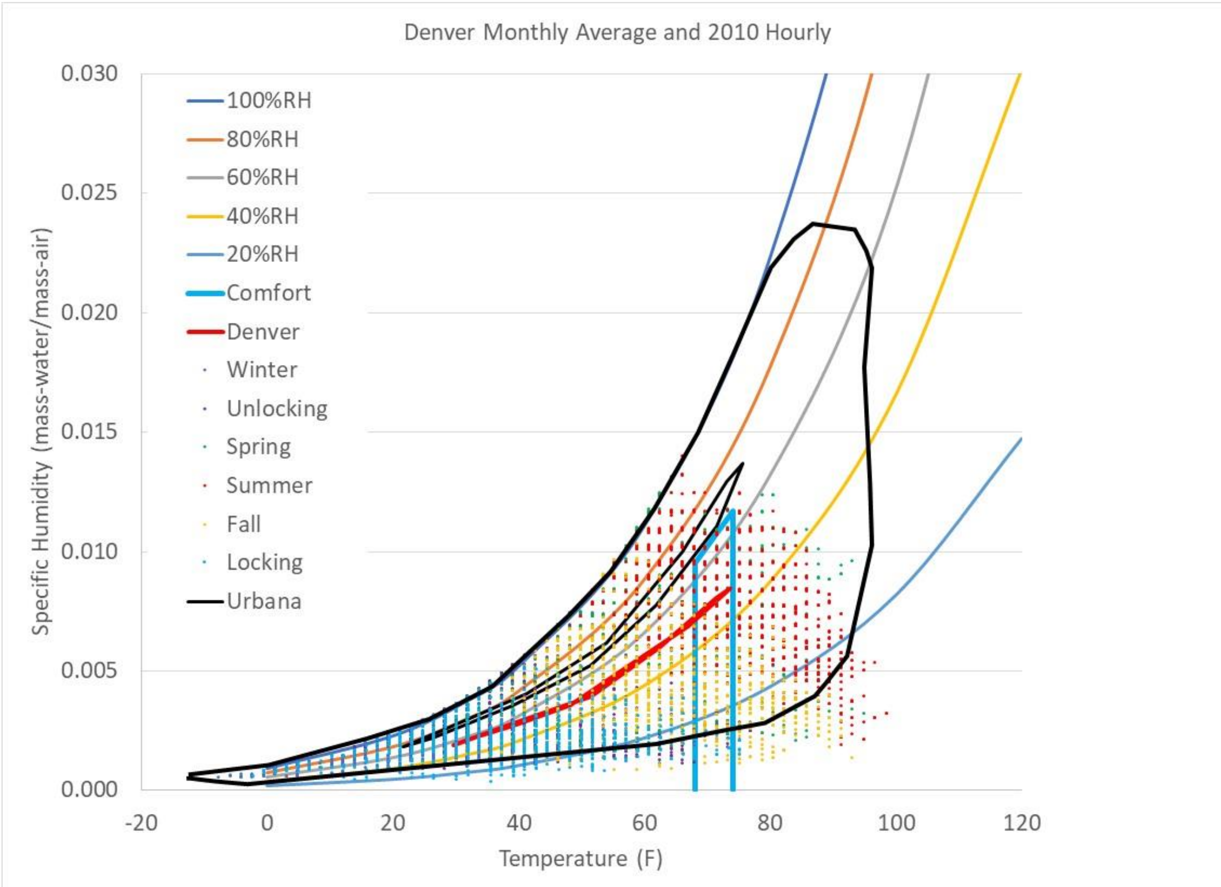

New Orleans LA; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.307 | ave C/D Tave(F) | 56.9 | ave C/D W(kgw/kga) | 0.005 | ave C/D wind (mph) | 9.29 |
| fraction hot/dry | 0.027 | ave H/D Tave(F) | 74.8 | ave H/D W(kgw/kga) | 0.006 | ave H/D wind (mph) | 9.49 |
| fraction cold/wet | 0.159 | ave C/W Tave(F) | 65.8 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 7.65 |
| fraction hot/wet | 0.507 | ave H/W Tave(F) | 80.6 | ave H/W W(kgw/kga | 0.016 | ave H/W wind (mph) | 7.57 |



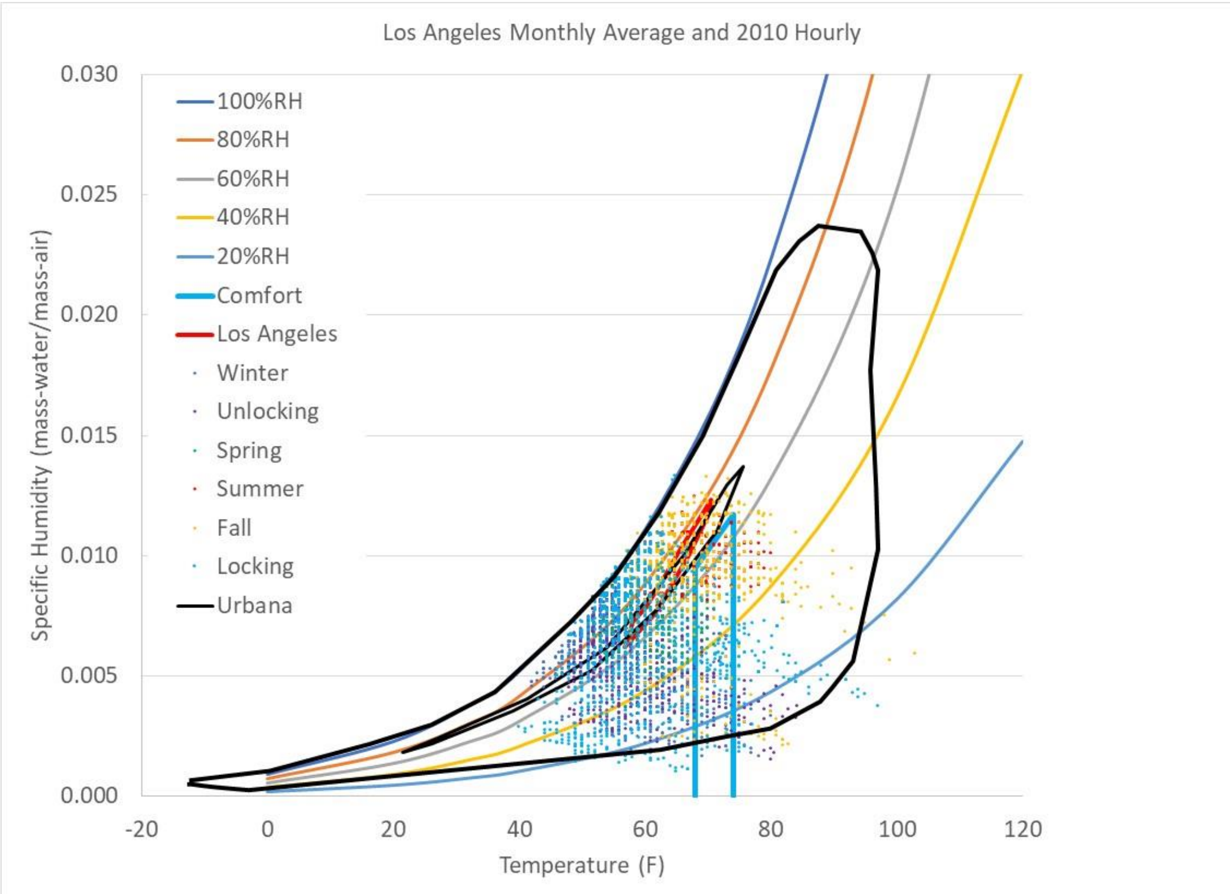

Phoenix AZ; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.420 | ave C/D Tave(F) | 60.3 | ave C/D W(kgw/kga) | 0.004 | ave C/D wind (mph) | 5.45 |
| fraction hot/dry | 0.391 | ave H/D Tave(F) | 84.3 | ave H/D W(kgw/kga) | 0.005 | ave H/D wind (mph) | 6.39 |
| fraction cold/wet | 0.016 | ave C/W Tave(F) | 66.9 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 7.97 |
| fraction hot/wet | 0.173 | ave H/W Tave(F) | 82.4 | ave H/W W(kgw/kga | 0.012 | ave H/W wind (mph) | 7.67 |



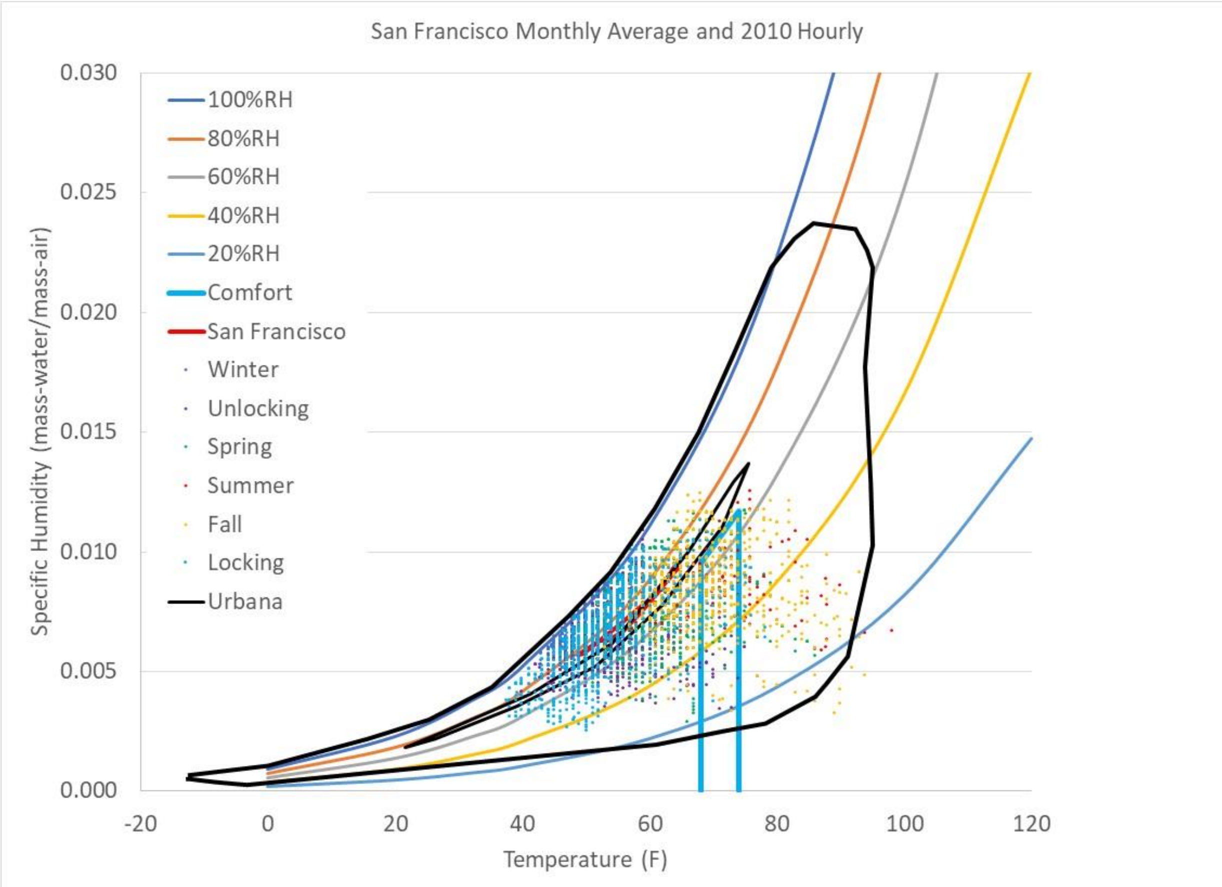

Denver CO; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.752 | ave C/D Tave(F) | 42.3 | ave C/D W(kgw/kga) | 0.003 | ave C/D wind (mph) | 9.15 |
| fraction hot/dry | 0.140 | ave H/D Tave(F) | 77.4 | ave H/D W(kgw/kga) | 0.005 | ave H/D wind (mph) | 10.47 |
| fraction cold/wet | 0.073 | ave C/W Tave(F) | 66.1 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 8.55 |
| fraction hot/wet | 0.035 | ave H/W Tave(F) | 75.1 | ave H/W W(kgw/kga | 0.011 | ave H/W wind (mph) | 10.06 |



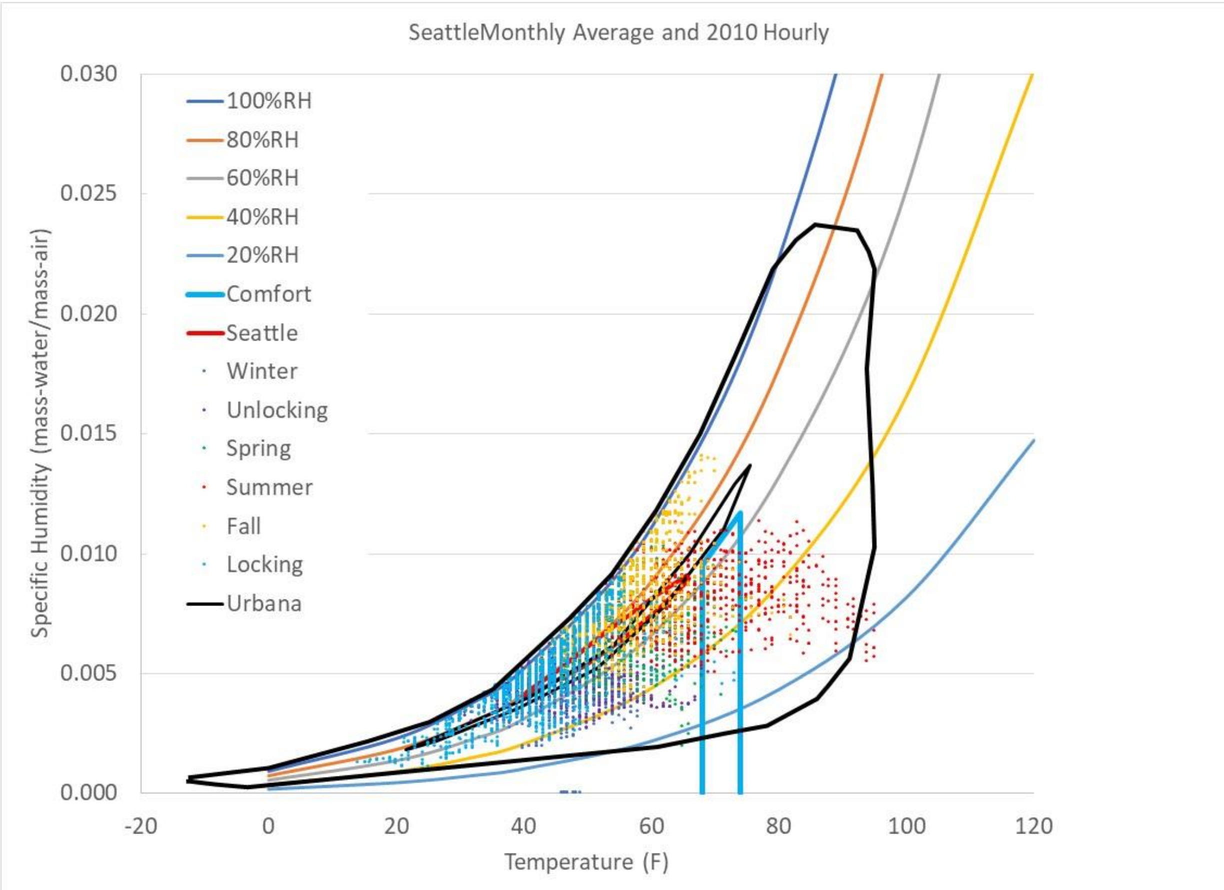

Los Angeles CA; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.420 | ave C/D Tave(F) | 60.5 | ave C/D W(kgw/kga) | 0.005 | ave C/D wind (mph) | 7.34 |
| fraction hot/dry | 0.030 | ave H/D Tave(F) | 75.1 | ave H/D W(kgw/kga) | 0.005 | ave H/D wind (mph) | 7.06 |
| fraction cold/wet | 0.519 | ave C/W Tave(F) | 63.0 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 7.06 |
| fraction hot/wet | 0.030 | ave H/W Tave(F) | 74.6 | ave H/W W(kgw/kga | 0.011 | ave H/W wind (mph) | 9.11 |



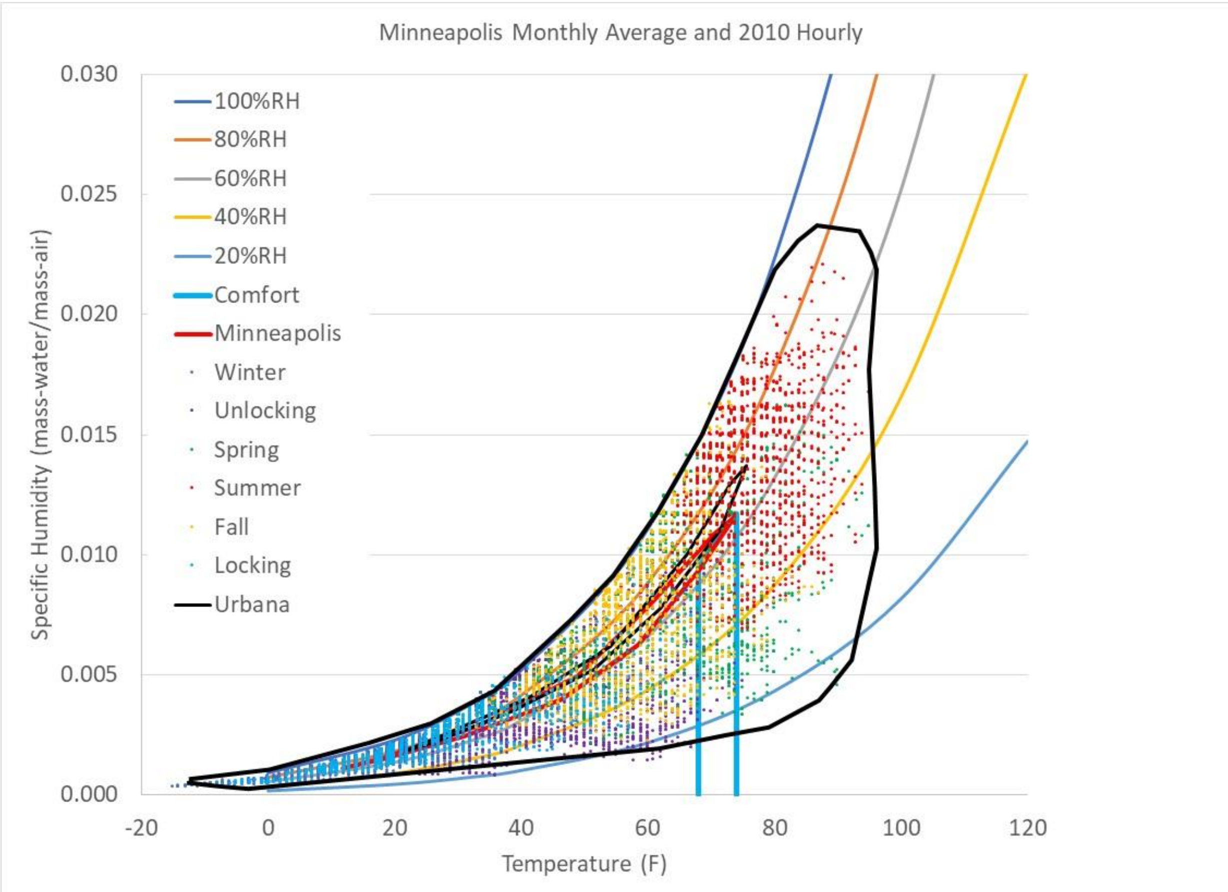

San Francisco CA; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.718 | ave C/D Tave(F) | 55.9 | ave C/D W(kgw/kga) | 0.005 | ave C/D wind (mph) | 9.82 |
| fraction hot/dry | 0.021 | ave H/D Tave(F) | 75.1 | ave H/D W(kgw/kga) | 0.006 | ave H/D wind (mph) | 12.99 |
| fraction cold/wet | 0.232 | ave C/W Tave(F) | 64.0 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 10.29 |
| fraction hot/wet | 0.029 | ave H/W Tave(F) | 74.6 | ave H/W W(kgw/kga | 0.011 | ave H/W wind (mph) | 9.79 |



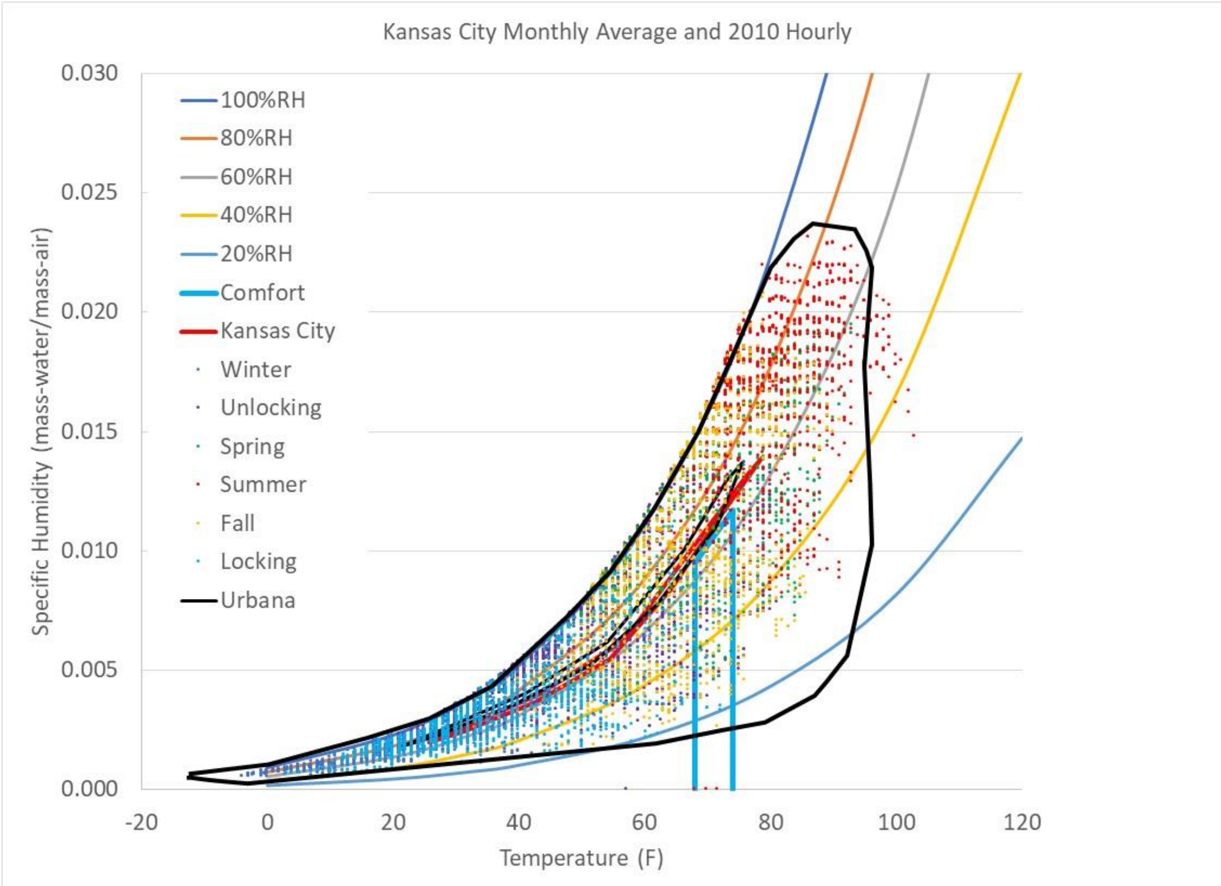

Seattle WA; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.797 | ave C/D Tave(F) | 49.6 | ave C/D W(kgw/kga) | 0.005 | ave C/D wind (mph) | 7.78 |
| fraction hot/dry | 0.015 | ave H/D Tave(F) | 75.1 | ave H/D W(kgw/kga) | 0.006 | ave H/D wind (mph) | 9.52 |
| fraction cold/wet | 0.170 | ave C/W Tave(F) | 64.1 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 6.13 |
| fraction hot/wet | 0.018 | ave H/W Tave(F) | 74.7 | ave H/W W(kgw/kga | 0.011 | ave H/W wind (mph) | 7.38 |



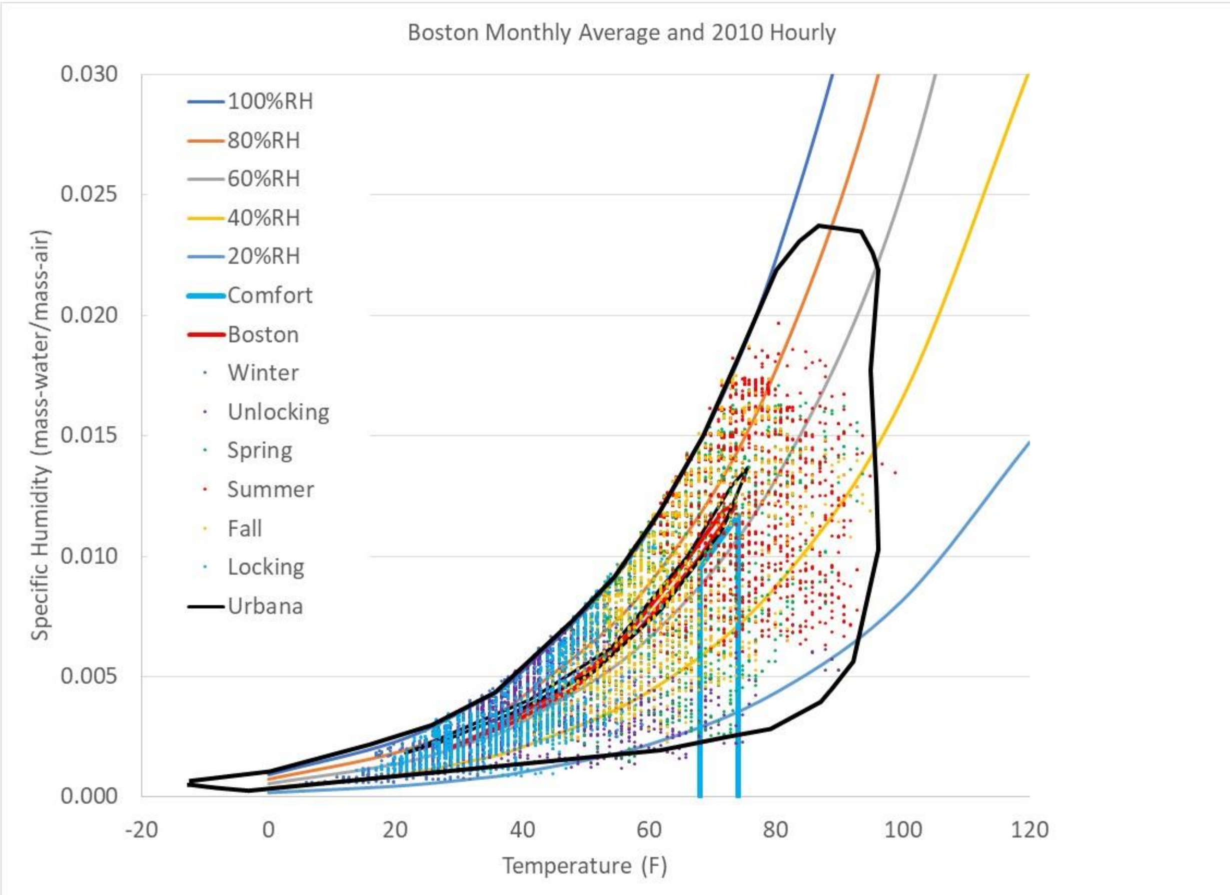

Minneapolis MN; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.671 | ave C/D Tave(F) | 37.0 | ave C/D W(kgw/kga) | 0.003 | ave C/D wind (mph) | 8.67 |
| fraction hot/dry | 0.030 | ave H/D Tave(F) | 74.6 | ave H/D W(kgw/kga) | 0.006 | ave H/D wind (mph) | 9.82 |
| fraction cold/wet | 0.140 | ave C/W Tave(F) | 65.9 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 8.65 |
| fraction hot/wet | 0.160 | ave H/W Tave(F) | 76.8 | ave H/W W(kgw/kga | 0.012 | ave H/W wind (mph) | 8.94 |



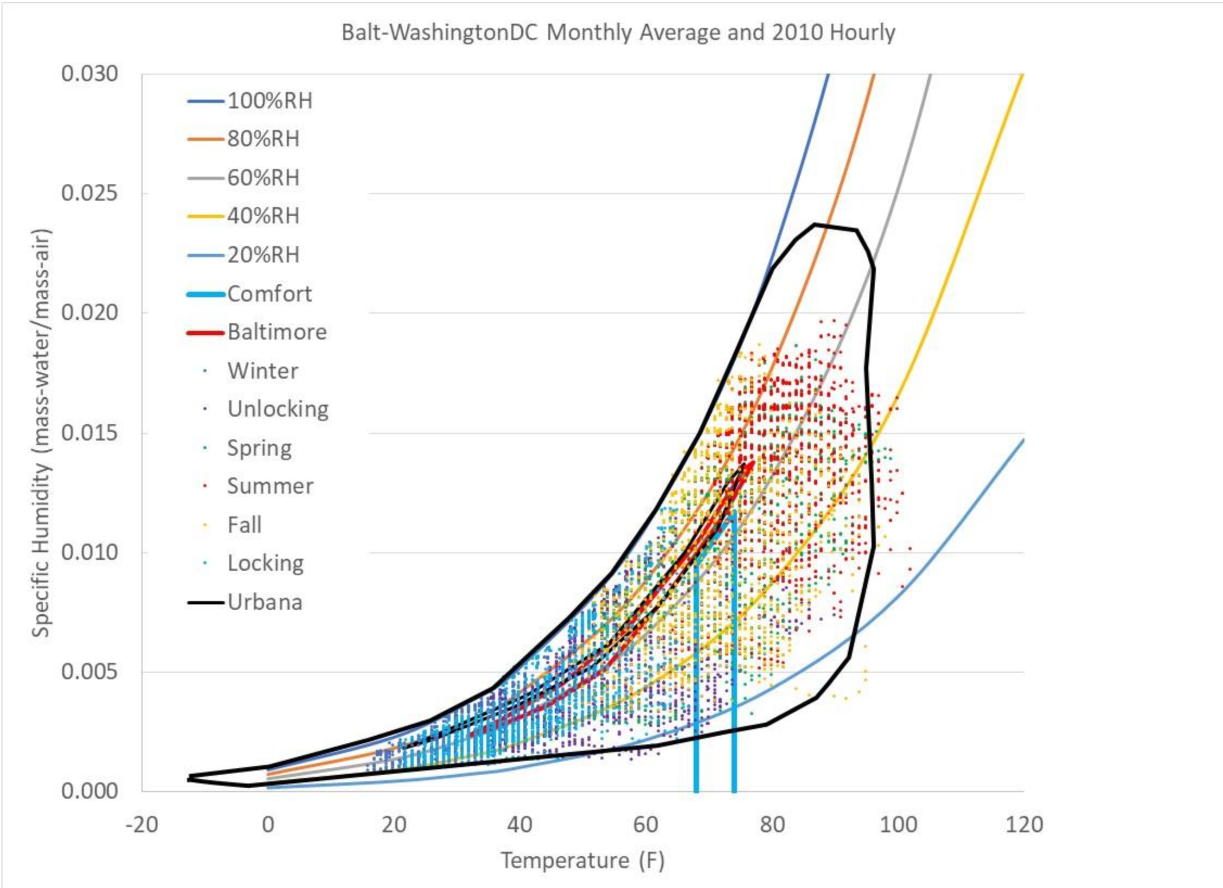

Kansas City MO; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.552 | ave C/D Tave(F) | 43.2 | ave C/D W(kgw/kga) | 0.004 | ave C/D wind (mph) | 9.90 |
| fraction hot/dry | 0.019 | ave H/D Tave(F) | 74.5 | ave H/D W(kgw/kga) | 0.006 | ave H/D wind (mph) | 12.38 |
| fraction cold/wet | 0.159 | ave C/W Tave(F) | 65.1 | ave C/WW(kgw/kga) | 0.012 | ave C/W wind (mph) | 9.44 |
| fraction hot/wet | 0.270 | ave H/W Tave(F) | 78.5 | ave H/W W(kgw/kga | 0.014 | ave H/W wind (mph) | 9.99 |




Boston MA; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.631 | ave C/D Tave(F) | 45.6 | ave C/D W(kgw/kga) | 0.004 | ave C/D wind (mph) | 12.50 |
| fraction hot/dry | 0.031 | ave H/D Tave(F) | 75.1 | ave H/D W(kgw/kga) | 0.006 | ave H/D wind (mph) | 12.91 |
| fraction cold/wet | 0.179 | ave C/W Tave(F) | 64.9 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 9.45 |
| fraction hot/wet | 0.160 | ave H/W Tave(F) | 76.7 | ave H/W W(kgw/kga | 0.012 | ave H/W wind (mph) | 11.38 |




Washington DC; C/D, H/D, C/W, H/W time fraction, average temperature, average humidity ratio and average wind speed

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fraction cold/dry | 0.542 | ave C/D Tave(F) | 48.6 | ave C/D W(kgw/kga) | 0.004 | ave C/D wind (mph) | 9.36 |
| fraction hot/dry | 0.044 | ave H/D Tave(F) | 75.2 | ave H/D W(kgw/kga) | 0.006 | ave H/D wind (mph) | 10.19 |
| fraction cold/wet | 0.107 | ave C/W Tave(F) | 66.1 | ave C/WW(kgw/kga) | 0.011 | ave C/W wind (mph) | 7.89 |
| fraction hot/wet | 0.307 | ave H/W Tave(F) | 79.1 | ave H/W W(kgw/kga | 0.013 | ave H/W wind (mph) | 8.29 |