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Comparison of single-point and continuous sampling methods for estimating residential indoor temperature and humidity

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Abstract

Residential temperature and humidity are associated with multiple health effects. Studies commonly use single-point measures to estimate indoor temperature and humidity exposures, but there is little evidence to support this sampling strategy. This study evaluated the relationship between single-point and continuous monitoring of air temperature, apparent temperature, relative humidity, and absolute humidity over four exposure intervals (5-min, 30-min, 24-hrs, and 12-days) in 9 northern Utah homes, from March – June 2012. Three homes were sampled twice, for a total of 12 observation periods. Continuous data-logged sampling was conducted in homes for 2-3 wks, and simultaneous single-point measures (n = 114) were collected using handheld thermo-hygrometers. Time-centered single-point measures were moderately correlated with short-term (30-min) data logger mean air temperature ($r = 0.76$, $\beta = 0.74$), apparent temperature ($r = 0.79$, $\beta = 0.79$), relative humidity ($r = 0.70$, $\beta = 0.63$), and absolute humidity ($r = 0.80$, $\beta = 0.80$). Data logger 12-day means were also moderately correlated with single-point air temperature ($r = 0.64$, $\beta = 0.43$) and apparent temperature ($r = 0.64$, $\beta = 0.44$), but were weakly correlated with single-point relative humidity ($r = 0.53$, $\beta = 0.35$) and absolute humidity ($r = 0.52$, $\beta = 0.39$). Of the single-point RH measures, 59 (51.8%) deviated more than ±5%, 21 (18.4%) deviated more than ±10%, and 6 (5.3%) deviated more than ±15% from data logger 12-day means. Where continuous indoor monitoring is not feasible, single-point sampling strategies should include multiple measures collected at prescribed time points based on local conditions.

Keywords

Temperature; Humidity; Indoor; Monitoring; Thermo-hygrometer; Exposure Misclassification

Introduction

The relationship between health and environmental hazards found in the home is a growing public health concern.[1,2] Air temperature and relative humidity (RH) are among the most common environmental parameters measured in residential studies due to their direct and indirect health effects.[1-11] Air temperature and RH can also be used to derive other important indoor environmental quality measures, such as apparent (perceived) temperature and absolute humidity. However, sampling strategies for measuring temperature and humidity vary widely, with little empirical research to support preferred methods. Some studies have used centralized outdoor monitoring data as a surrogate measure of residential exposure, but recent findings show that outdoor measures may be poor indicators of indoor conditions.[12-14] Direct indoor assessment may be necessary to accurately characterize residential temperature and humidity exposures.

Common indoor sampling strategies include instantaneous single-point measurements collected with handheld (pen-type) thermo-hygrometers, and continuous monitoring with data logging instruments. Single-point sampling is attractive because measurements can be easily collected during home visits. However, instantaneous measures only reflect conditions at the moment monitoring was conducted. If used to represent long-term exposures, one must assume static or inappreciable temporal variation in environmental conditions within the home. Occupant time-activity patterns, local weather, seasonal influences, and home HVAC systems contribute to daily and long-term fluctuations that are likely not represented by single-point measures. Despite this risk, single-point sampling is commonly used to assess environmental conditions in residential health studies.[15-20]

Continuous monitoring provides longer-term mean exposures and allows for home-specific trend analysis, but requires more time for data collection than single-point sampling, and incurs additional study costs related to instrument return. Single-point sampling may be a valid alternative to continuous monitoring if shown to correlate highly with longer-term indoor exposures, but the relationship between these two sampling methods has not been established. The purpose of this study was to compare single-point and continuous monitoring strategies for estimating indoor air temperature, apparent temperature, RH, and absolute humidity in homes in northern Utah, USA.

Methods

Study population

Study homes were recruited from among employees at the Utah State University, National Children's Study (NCS) office in Logan, Utah. Employee volunteers were NCS environmental monitoring specialists (n = 5), lab technician (n = 1), and research faculty (n = 2). Employees sampled their own homes, and one employee also sampled a family member's home. The final sample size included nine homes, three of which were sampled twice, for a total of 12 unique observation periods. Prior to data collection, employees were trained on instrument use and study protocols. Employees also completed a 10-item survey regarding home characteristics, including type of home, humidifier use, dehumidifier use, heating system, cooling system, number of occupants, size of home, number of bathrooms with a shower or tub, number of mechanically vented bathrooms, and use of a kitchen hood venting to outdoors. Utah State University's Institutional Review Board approved this study.

Continuous monitoring

Data collection was performed over a 93-day period from March – June 2012. Continuous temperature and RH monitoring was conducted for multiple days (range = 13.8 – 26.1) in each home. Four data logging thermo-hygrometers were used: two Campbell Scientific CR200X-CS215 instruments (Campbell Scientific, Inc., Logan, UT) and two Tip-Temp EL-USB-2-LCD instruments (Tip Temperature Products, Burlington, NJ). Before each data collection event, instruments were initialized, cleared of any previous data, and programmed to record air temperature and RH every 5 minutes using the respective manufacture's software. Employees were instructed to place the instrument in a main living area of the home (e.g. family room). Following data collection, instruments were returned to the NCS laboratory where temperature and RH data were downloaded. Tip-Temp instruments were calibrated prior to data collection by National Institute of Standards and Technology (NIST)-traceable Thunder Scientific 1200 humidity generator, Eutechnics 4500 thermometer and sensor and Cincinnati subzero chamber at 20.0% and 80.0% RH and 23.0°C. Both Tip-Temp data loggers were within manufacturer's tolerances of ±3% RH and ±0.9°C. Campbell Scientific instruments were verified by NIST-traceable CR3000 data logger and Vaisala HMT337 temperature and RH probe at 20.0%, 50.0%, and 90.0% RH. Both instruments were within manufacturer's specifications of ±2% RH and ±1.00°C.

Single-point sampling

Single-point air temperature and RH measurements were collected with 10 Extech model 445580 handheld electronic thermo-hygrometers (Extech Instruments Corp., Waltham, MA). Single-point sampling was conducted intermittently on multiple days and at different times of day while data loggers were running in homes. Single-point measurements were collected using the following procedure: (1) Instruments were unpacked from field data collection bags, powered on, and placed in the same room and same location as the data-logging instruments. (2) Instruments were allowed to equilibrate for five minutes. (3) Employees recorded date, time, temperature & RH, and instrument identification numbers on a standard data collection form. (4) Instruments were turned off and packed in the field bag. All measures for a given home were collected by the same person, but Extech instruments were systematically rotated through homes. Following data collection, single-point measurements for each home were matched by date and time to continuous measurements collected with data logging instruments. Extech instruments were calibrated to NIST-traceable Edgetech RH-Cal prior to data collection at 33.0% and 75.0% RH and 21.0 °C. All instruments were within manufacturer's tolerances of ±5% RH and ±1.00°C.

Instrument validation

Prior to field implementation, all data logging instruments and two randomly selected Extech thermo-hygrometers were compared side-by-side to a Vaisala HMP 110 (Agilent Technologies, Santa Clara, CA) temperature and RH probe in an environmentally controlled laboratory (50% RH, 28°C). The Vaisala HMP 110 was chosen as a comparison standard based on temperature and RH accuracies (±0.2°C and ±1.7% RH). The Vaisala underwent

NIST-traceable calibration prior to data collection. Single-point, time-matched comparisons (n = 17) were made over a 16-day period in January 2012, and differences were calculated as the Vaisala reading subtracted from the instrument reading. The overall mean data logger deviations from the Vaisala were 3.9% RH and 0.10°C, and the overall mean Extech deviations from the Vaisala were 3.2% RH and 0.05°C. When using the absolute value of the differences, the overall data logger deviations from the Vaisala were 3.9% RH and 0.17°C, and the overall mean Extech deviations from the Vaisala were 3.2% RH and 0.12°C. Following data collection, a final verification step of all 10 Extech instruments was performed using a mixed model analysis of variance (ANOVA) blocking on home. Validation was performed by comparing differences between single-point Extech measurements and time-matched continuous monitoring measurements for both RH and air temperature. Differences were not significant for either RH ($F(9,86) = 0.74$, $p = 0.67$) or air temperature ($F(9,86) = 0.66$, $p = 0.74$), suggesting consistency between the 10 Extech instruments.

Analysis

Overall mean air temperature and RH for each of the 12 data collection events were calculated from the data logger data. Air temperature and RH are known to fluctuate throughout the day; therefore, to determine the typical pattern for each household, mean air temperature and RH were calculated by time intervals. Time was divided into 5-minute increments such that 288 time points were identified per 24-hour period (00:00 – 23:55). Mean air temperature and RH was calculated for each of these 288 time points, allowing us to estimate averages for a given time of day across the 13.8 – 26.1 days of data collection for each household. These 288 time-point means were compared to the household average, and deviations were calculated and plotted.

Apparent temperature (AT) was calculated from air temperature and RH for both single-point and continuous reading instruments using the following formula: $AT = -2.653 + (0.994 \times T_c) + (0.0153 \times T_d^2)$, where T_d is dew point temperature, and T_c is air temperature in °C.[21] Dew point temperature was calculated as $T_d = (RH/100)^{1/8} \times (112 + 0.9T_c) + (0.1T_c - 112)$.[22] AH was calculated using the following formula: $AH = C \times (P_w/T_K)$, where C = 2.16679 gk/J, P_w = vapor pressure of water in Pa, and T_K = temperature in Kelvin.

To compare single-point measurements to continuous monitoring, continuous monitor means were first calculated for 5-min, 30-min, 24 hours, and 12 days for air temperature, AT, RH, and AH. The 5-min mean was the time-matched data logger reading closest in time to when the single-point measure was collected. The 30-min, 24-hr, and 12-day means were calculated by centering the data logger measures as closely as possible to when the single-point measure was collected. Pearson's correlation coefficients were then calculated to compare single-point measures to the 5-min, 30-min, 24-hr, and 12-day means from the continuous monitors. Linear regression was used to evaluate the relationship between single-point measures and the four interval period means from the continuous monitors for all four measures of temperature and humidity. Differences between single-point and continuous monitors were calculated by subtracting the continuous monitor means from the time-centered single-point measure. Linear regression, means, standard deviations, correlations, differences, and ANOVA were calculated in SAS (Version 9.3, SAS institute Inc., Cary, NC, USA). Histograms, quantiles, and box-plots of the differences were calculated in JMP (Version 11.0, SAS Institute Inc., Cary, NC, USA).

Results

Of the nine households, seven were single-family dwellings and two were apartments. Households 1, 7, and 11 were sampled twice, for a total of 12 data collection periods. Homes were an average of 15.6 miles (25.1 km) from the National Children's Study office (range: 0.9, 39.5 miles). Home characteristics and mean air temperature and RH are shown in Table 1. The overall mean data logger air temperature and AT for the 12 observation periods were 20.0°C (range = 5.5 - 30°C) and 17.8°C (range = 5.6 – 27.4°C), respectively. The overall mean data logger RH and AH were 38.0% (range = 11.9 - 61.0%) and 6.6 g/m^3 (range = 1.7 – 11.6 g/m^3), respectively. Mean data logger air temperature and RH within individual observations ranged from 17.1 - 23.0°C and 29.9 - 49.3%, respectively. A total of 114 single-point measurements were taken over the 12 observation periods while the data loggers were operating. Of the single-point measurements, 93 (81%) were collected between the hours of 8 AM – 8 PM. Overall mean air temperature and RH, when calculated by averaging single-point measurements across observations, were 20.2°C and 38.1% RH, respectively. Overall mean AT and AH derived from single-point measurements were 18.0°C and 6.6 g/m^3, respectively.

Figure 1 shows the temperature and humidity deviations from the household mean for a given time of day, where zero represents the data logger household mean, and fluctuations are shown by time of day. Observed deviations were larger for RH than for AH. The average spread of deviations about the mean across observations was 4.4% RH and 0.42 g/m^3 AH, respectively. Households with large deviations fluctuated as much as 8.9% RH and 1.15 g/m^3 AH over the 24-hr period, and homes with low deviations fluctuated as little as 3.0% RH and 0.39 g/m^3 AH. The overall mean indoor air temperature and apparent temperature fluctuated 1.6°C and 1.7°C, respectively. The observed variation differed between houses with the largest spread for a single household being 3.8°C (-1.9 to 1.9°C) for both air temperature and AT. The most temperature stable houses varied less than 1.0°C from the household mean.

Linear regression and Pearson's correlation were used to evaluate the relationship between single-point sampling and continuous monitoring. Single-point RH and AH measures centered on data logger 30-min and 12-day means 30-min are shown in Figure 2. Single-point readings were moderately correlated with data logger 30-min means for RH (r = 0.70, 95% CI: 0.51, 0.75, β = 0.63, SE (β) = 0.06) and AH (r = 0.8, 95% CI: 0.69, 0.91, β = 0.80, SE (β) = 0.06). Single-point readings were weakly correlated with data logger 12-day means for RH (r = 0.53, 95% CI: 0.24, 0.45, β = 0.35, SE (β) = 0.05) and AH (r = 0.52, 95% CI: 0.27, 0.51, β = 0.39, SE (β) = 0.06). For temperature (Figure 3), single-point readings were moderately correlated with data logger 30-min means for both air temperature (r = 0.76, 95% CI: 0.62, 0.86, β = 0.74, SE (β) = 0.06) and AT (r = 0.79, 95% CI: 0.68, 0.90, β = 0.79, SE (β) = 0.06). Single-point measures were also moderately correlated with 12-day air temperature (r = 0.64, 95% CI: 0.33, 0.52, β = 0.43, SE (β) = 0.05) and 12-day AT (r = 0.64, 95% CI: 0.34, 0.54, $\beta = 0.44$, SE (β) = 0.05). Pearson's correlation coefficients between single-point and continuous measures averaged over the four time intervals (5-min, 30-min, 24-hr, and 12-day) are shown in Table 2.

The distribution of differences between single-point measures and data logger household means are shown in Figure 4. For single-point measures centered on data logger 30 min and 12-day means, half of the data points fell within -5.1 to 3.0% RH and -5.7 to 4.9% RH, respectively. Results for AH were more conserved, where for single-point measures centered on data logger 30-min and 12-day means, half of the data points fell within -0.6 to 0.5 g/m^3 and -0.9 to 0.8 g/m^3, respectively. Differences between air temperature and AT were negligible. For single-point air temperature and AT centered on data logger 30 min and 12-day means, half of the data points fell within -0.5 to 1.2 °C and -1.0 to 1.2 °C, respectively. For RH, the measure with the largest deviations, we calculated practically useful margins-of-error. Of the single-point measures, 59 (51.8%) deviated more than ±5% RH from the 12-day data logger mean, 21 (18.4%) deviated more than ±10%, and 6 (5.3%) deviated more than ±15%. One-way ANOVA was used to evaluate differences between single-point measures and continuous monitor 30 min means by household Figure 5). Results showed significant variability between observations for both RH ($p < 0.001$) and air temperature ($p < 0.001$). Differences in single-point and continuous monitor 30-min means for both RH and air temperature for the 12 observation periods are shown in Appendix 1. For RH, the largest deviations occurred in homes 1, 3, and 6, and for air temperature the largest deviations were seen in homes 3, 5, and 6.

Discussion

This study shows that residential indoor temperature and humidity exposures can be misclassified when using single-point measures to assess the home. Single-point sampling was only moderately correlated with continuous monitoring when assessing short-term exposures (5 – 30-min), and the strength of this relationship decreased as time intervals were increased to 24-hrs and 12 days. This finding was most pronounced for RH and absolute humidity. These findings support previous research showing that exposure estimates vary widely depending on the sampling strategy used. Nguyen et al. (2014) reported an 18.4% difference between annual mean indoor and outdoor RH, and a weak correlation between indoor and outdoor air temperature on cool days, in homes in the Greater Boston, MA area.[(12)] Likewise, White-Newsome et al. (2012) found a 13.8°C difference between average maximum indoor and outdoor air temperature in homes in Detroit, MI during summer months.[(13)] Our findings, taken in the context of these previous studies, suggest that accurate assessment of residential indoor temperature and humidity requires not only direct measurement of indoor conditions, but measurement using a continuous monitoring strategy.

The diurnal pattern observed in study homes may be partially explained by occupant time-activity patterns. Lower temperatures, showering, and cooking activities probably explain the universal morning RH peak across all 12 households. Increasing temperatures and lower occupant densities during daytime hours, and higher occupant densities and cooking activities during evening hours may explain the daytime and evening trends. One advantage of continuous monitoring is that long-term means and trends can be identified, whereas estimates based on single-point samples inherently assume static environmental conditions in the home. For instance, exposure to house dust mite (HDM) allergens is associated with the development of asthma.[23,24] HDMs reach a maximum population size at 80% RH, but can survive at levels as low as 50% if excursions >65% occur periodically.[8] Single-point sampling is unlikely to detect temporal humidity fluctuations in the home that contribute to HDM growth unless multiple measures are collected throughout the day and across multiple days. If handheld thermo-hygrometers are used to collect single-point measures in studies related to HDMs or other humidity-sensitive exposures, we recommend leaving the instrument with participants and asking them to record measurements at several prescribed time points during non-sleeping hours over the course of a set observation period.

For environmental samples that are relativley easy to collect, participant-based monitoring strategies may offer a valid alternative to technician-based sampling.[25, 26] For indoor temperature and humidity measurements, data logging instruments could be prepared at the study center and delivered to the home with instructions on where to place the instrument and how to initiate data collection. After the sampling period, instruments could be returned by mail to the study center. An alternative sampling strategy would be to establish temperature and RH trends across a limited sample of homes in a given locale and climate using data logging instruments, and to use this data to estimate the best time(s) of day to collect single-point measures. This strategy would work best in homes where humidifiers or other artificial moisture sources are absent. Based on the findings of this study, minimum and maximum RH levels occur in evening (5:00 – 8:00 PM) and morning (6:30 – 9:00 AM) hours, respectively. To estimate mean temperature and RH for homes in this study, 2:00 – 3:00 PM appears to be the best time of day during spring months to collect single-point measures. Similar trends can be identified for homes in other locales and climates, and recommended time schedules for single-point measurements can be developed.

Modern handheld thermo-hygrometers most often use negative temperature coefficient (NTC) thermistors and thin-film capacitance-based sensors to measure air temperature and RH, respectively.[27-29] These sensors can achieve accuracies within ±1°C and ±5% RH, which are sufficient for most health study applications as long as instrument margins-of-error are considered when interpreting monitoring results.[30] The risk of exposure misclassification, therefore, resides primarily in the single-point sampling strategy rather than in limitations in handheld thermo-hygrometer accuracies. Among the homes in this study, the risk of misclassification appears to be greater when measuring RH than air temperature. Prior to data collection, we compared study instruments against the Vaisala and found a small 0.7% RH mean difference between the data loggers and the handheld thermo-hygrometers. This finding suggests the study instruments were reading closely to each other and that deviations between single-point and continuous monitors were likely not due to instrument differences, but rather due to temporal fluctuations within the home that are not captured by the single-point sampling strategy.

In addition to fluctuations caused by occupant time-activity patterns, we hypothesize that deviations between single-point and continuous measurements observed in this study are partially attributable to data collection error. One long-recognized challenge with using handheld instruments for RH measurement is that moisture from the operator's body, particularly from exhaled air, can influence measurement results.[31] We found a significant difference in deviations between single-point and continuous measurements by home, suggesting the sample collection technique used by individual data collectors may have introduced measurement error. All data collectors were trained to hold the handheld thermo-hygrometer away from the breathing zone when taking measurements, but we were unable to assess compliance with this recommendation in the field. Due to the fast response times and high sensitivity of modern handheld thermo-hygrometers, data collection error may be significantly reduced by initializing the instrument, placing it the room to be sampled, and leaving the room or area for at least 5 min while the sensor equilibrates. This procedure may help eliminate error introduced by moisture or heat from the data collector's body or breath. After 5 min, the data collector should return to the room or area but stand at a distance to record measurements.

The results of this study may not be applicable to homes in non-arid climates or to homes in arid climates during different seasons of the year. This study was limited to a small sample of homes in Northern Utah that were chosen based on convenience of data collection, rather than on specific home characteristics, such as type of dwelling, occupant density, or use of evaporative coolers, humidifiers, or dehumidifiers. In arid climates, these factors can drastically influence indoor RH.[32] This study was also limited to a relatively short sampling period. Comparisons were made between single-point sampling and continuous monitoring over 12-day time intervals. Correlations between the two sampling methods dropped as the time intervals were increased, but additional research is needed to evaluate the representativeness of single-point sampling for estimating indoor conditions spanning longer time periods over multiple seasons.

Conclusions

Indoor temperature and humidity exposures are commonly estimated in residential health studies using handheld (pen-type) thermo-hygrometers in a single-point sampling strategy. Findings from this study demonstrate that single-point measures can vary widely from overall household means estimated by continuous monitors. This study also showed that single-point sampling is less accurate for predicting long- rather than short-term exposures, particularly for humidity. These results suggest continuous indoor monitoring or multiple-point sampling is preferred over single-point measurements in residential health studies.

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References

1. Krieger J, Higgins DL. Housing and health: Time again for public health action. Am J Public Health. 2002; 92(5):758–768. [PubMed: 11988443]
2. Braubach M. Key challenges of housing and health from WHO perspective. Int J Public Health. 2011; 56:579–580. [PubMed: 21894569]
3. Arundel AV, Sterling EM, Biggin JH, Sterling TD. Indirect health effects of relative humidity in indoor environments. Environ Health Persp. 1986; 65:351–361.

4. Butler S, Williams M, Tukuitonga C, Paterson J. Problems with damp and cold housing among Pacific families in New Zealand. New Zeal Med J. 2003; 116(1177):U494–U494. [PubMed: 12861308]
5. Ormandy D, Ezratty V. Health and thermal comfort: From WHO guidance to housing strategies. Energ Policy. 2012; 49:116–121.
6. Semenza JC, Rubin CH, Falter KH, Selanikio JD, Flanders WD, Howe HL, Wilhelm JL. Heat-related deaths during the July 1995 heat wave in Chicago. New Engl J Med. 1996; 335(2):84–90. [PubMed: 8649494]
7. Yip FY, Flanders WD, Wolkin A, Engelthaler D, Humble W, Neri A, Lewis L, Backer L, Rubin C. The impact of excess heat events in Maricopa County, Arizona: 2000—2005. Int J Biometeorol. 2008; 52(8):765–772. [PubMed: 18607646]
8. Arlian LG, Confer PD, Rapp CM, Vyszenski-Moher DL, Chang JC. Population dynamics of the house dust mites *Dermatophagoides farinae*, *D. pteronyssinus*, and *Euroglyphus maynei* (Acari: Pyroglyphidae) at specific relative humidities. J Med Entomol. 1998; 35(1):46–53. [PubMed: 9542344]
9. Gunnbjörnsdóttir MI, Franklin KA, Norback D, Bjornsson E, Gislason D, Lindberg E, Svanes C, Omenaas E, Norrman E, Joqi R, Jensen EJ, Dahlman-Hoglund A, Janson C. RINE Study Group. Prevalence and incidence of respiratory symptoms in relation to indoor dampness: the RHINE study. Thorax. 2006; 61(3):221–225. [PubMed: 16396946]
10. Clark, NM.; Ammann, HM.; Brunekreef, B.; Eggleston, PA.; Fisk, WJ.; Berkeley, L.; Fullilove, RE.; Guernsey, J.; Nevalainen, A.; Von Essen, SG. Institute of Medicine of the National Academies. Washington D.C.: National Academies Press: 2004. Damp Indoor Spaces and Health.
11. Koskinen OM, Husman TM, Meklin TM, Nevalainen AI. The relationship between moisture and mould observations in houses and the state of health of their occupants. Eur Respir J. 1999; 14:1363–1367. [PubMed: 10624768]
12. Nguyen JL, Schwartz J, Dockery DW. The relationship between indoor and outdoor temperature, apparent temperature, relative humidity, and absolute humidity. Indoor Air. 2014; 24:103–112. [PubMed: 23710826]
13. White-Newsome JL, Sanchez BN, Jolliet O, Zhang Z, Parker EA, Dvonch JT, O'Neill MS. Climate change and health: indoor heat exposure in vulnerable populations. Environ Res. 2012; 112:20–27. [PubMed: 22071034]
14. Ozbalta TG, Sezer A, Yildiz Y. Models for prediction of daily mean indoor temperature and relative humidity: Education Building in Izmir, Turkey. Indoor Built Environ. 2012; 21(6):772–781.
15. Cho SH, Reponen T, LeMasters G, Levin L, Huang J, Meklin T, Ryan P, Villareal M, Bernstein D. Mold damage in homes and wheezing in infants. Ann Allergy, Asthma & Immunology. 2006; 97(4):539–545. [PubMed: 17069111]
16. Grimsley LF, Chulada PC, Kennedy S, White L, Wildfire J, Cohn RD, Mitchell H, Thornton E, El-Dahr J, Mvula MM, Sterling Y, Martin WJ, Stephens KU, Lichtveld M. Indoor environmental exposures for children with asthma enrolled in the HEAL study, post-Katrina New Orleans. Environ Health Persp. 2012; 120(11):1600–1606.
17. Martin SB, Coffey CC. An indoor environmental quality investigation of the Fayette County (Pennsylvania) courthouse. Indoor Built Environ. 2007; 16(5):456–464.
18. Perry TT, Vargas PA, Bufford J, Field C, Flick M, Simpson PM, Hamilton RG, Jones SM. Classroom aeroallergen exposure in Arkansas head start centers. Asthma & Immunology. 2008; 100(4):358–363.
19. Rabito FA, Iqbal S, Holt E, Grimsley LF, Islam TMS, Scott SK. Prevalence of indoor allergen exposures among New Orleans children with asthma. J Urban Health. 2007; 84(6):782–792. [PubMed: 17917814]
20. Ren P, Jankun TM, Belanger K, Bracken MB, Leaderer BP. The relation between fungal propagules in indoor air and home characteristics. Allergy. 2001; 56(5):419–424. [PubMed: 11350305]
21. Kalkstein LS, Valimont KM. An evaluation of summer discomfort in the United States using a relative climatological index. B Am Meteorol Soc. 1986; 67(7):842–848.

22. Wanielista, M.; Kersten, R.; Eaglin, R. Hydrology: Water Quantity and Quality Control, 2nd edition. John Wiley & Sons, Inc; 1997. p. 68-72.

23. Sporik R, Holgate ST, Platts-Mills TAE, Cogswell JJ. Exposure to house-dust mite allergen (*Der p I*) and the development of asthma in childhood. New Engl J Med. 1990; 323:502–507. [PubMed: 2377175]

24. Lodge CJ, Lowe AJ, Gurrin LC, Hill DJ, Hosking CS, Khalafzai RU, Hopper JL, Matheson MC, Abramson MJ, Allen KJ, Dharmage SC. House dust mite sensitization in toddlers predicts current wheeze at age 12 years. J Allergy Clin Immunol. 2011; 128(4):782–788. [PubMed: 21820717]

25. Johnson M, Hudgens E, Williams R, Andrews G, Neas L, Gallagher J, Özkaynak H. A participant-based approach to indoor/outdoor air monitoring in community health studies. J Expo Sci Environ Epid. 2009; 19(5):492–501.

26. Arbes SJ Jr, Sever M, Vaughn B, Mehta J, Lynch J, Mitchell H, et al. Feasibility of using subject-collected dust samples in epidemiologic and clinical studies of indoor allergens. Environ Health Persp. 2005; 113(6):665–669.

27. Rittersma ZM. Recent achievements in miniaturised humidity sensors – a review of transduction techniques. Sensor Actuator. 2002; A96:196–210.

28. Visscher GJW, Kornet JG. Long-term tests of capacitive humidity sensors. Meas Sci Technol. 1994; 5:1294–1302.

29. Childs PRN, Greenwood JR, Long CA. Review of temperature measurement. Rev Sci Instrum. 2000; 71(8):2959–2978.

30. Johnston JD, Magnusson BM, Eggett D, Mumford K, Collingwood SC, Bernhardt SA. Sensor drift and predicted calibration intervals of handheld temperature and relative humidity meters under residential field use conditions. J Environ Health. 2014; 77(3):22–28.

31. Marvin CF. Psychrometric tables for obtaining the vapor pressure, relative humidity, and temperature of the dew-point. US Government Printing Office. 1900 Bulletin No 235.

32. Ellingson AR, LeDoux RA, Vedanthan PK, Weber RW. The prevalence of Dermatophagoides mite allergen in Colorado homes utilizing central evaporative coolers. J Allergy Clin Immun. 1995; 96(4):473–479. [PubMed: 7560657]

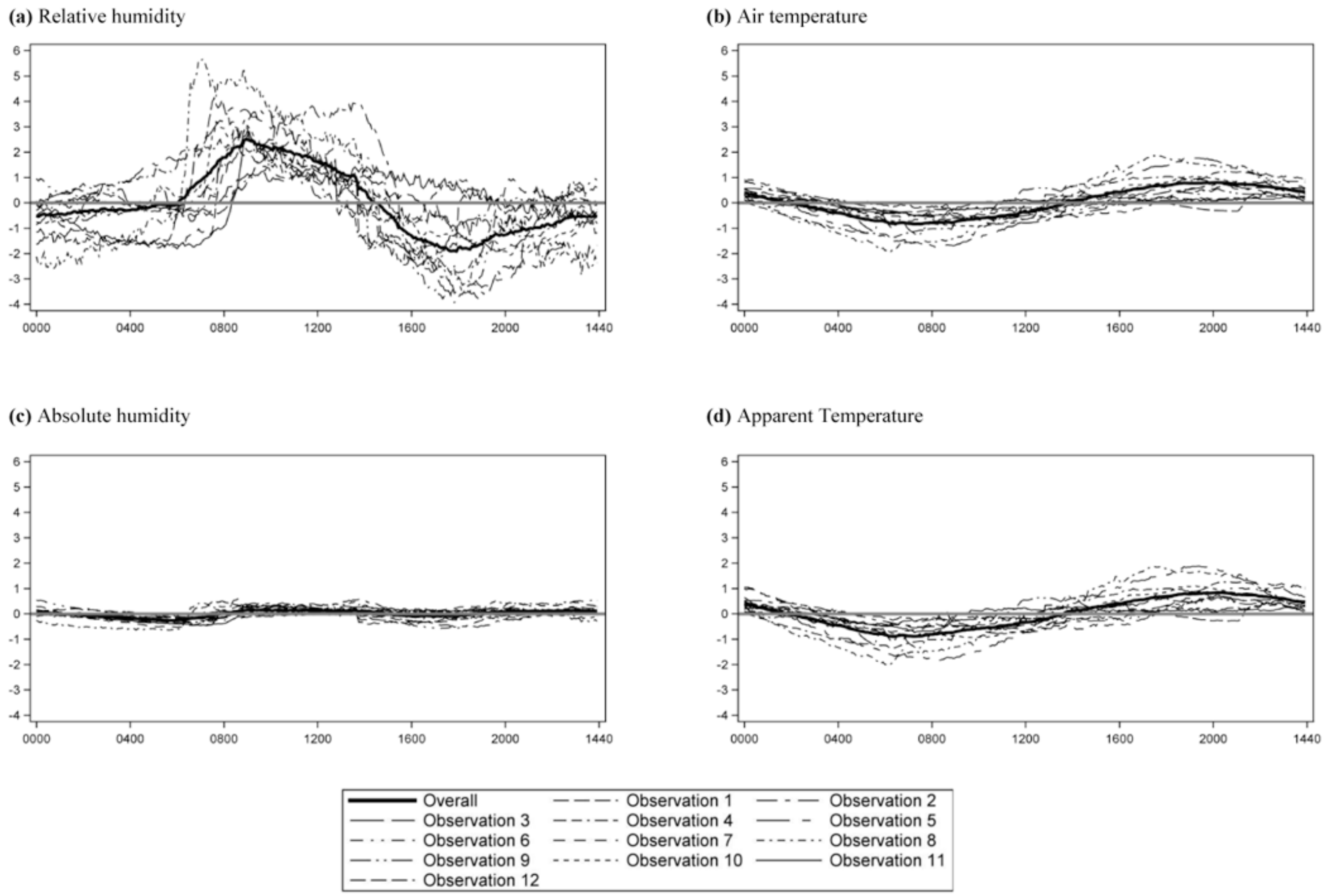

Figure 1.

Deviations from data logger observation means for (a) RH (%), (b) air temperature (°C), (c) absolute humidity (g/m^3), and (d) apparent temperature (°C) by time-of-day averages across the sampling period. Time of day is shown in 288 5-min intervals over a 24-hr period. Deviations were calculated by subtracting the household data logger mean from the average RH, air temperature, absolute humidity, and apparent temperature at each time interval.

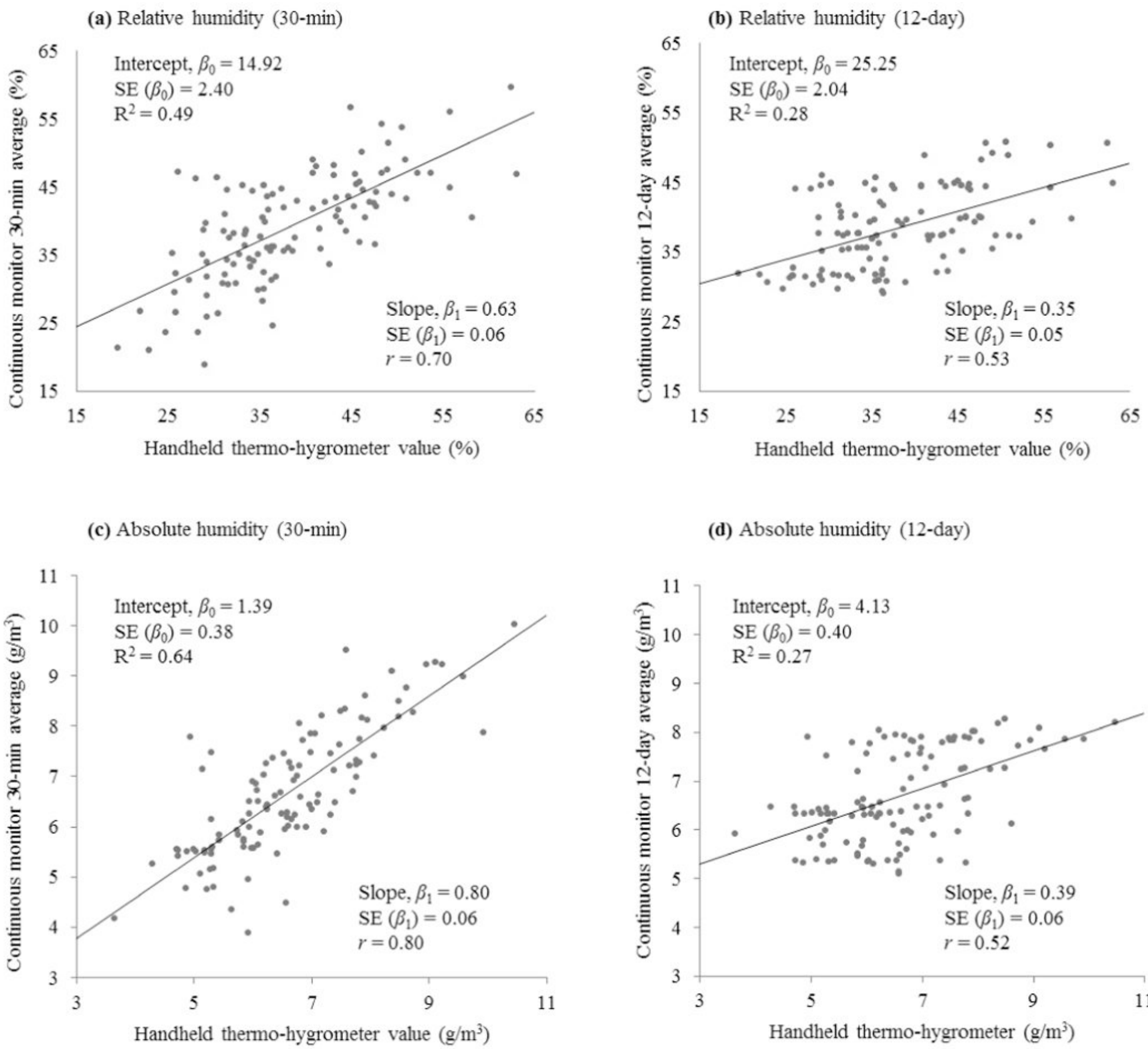

Figure 2.

Linear regression of relative and absolute humidity collected with handheld thermo-hygrometers and continuous data logging instruments from March – June 2012. Single-point relative humidity measures were collected by recording an instantaneous reading from the handheld thermo-hygrometer 5 minutes after the instrument was powered on. Absolute humidity was derived from relative humidity and air temperature readings from handheld and data logging instruments. Single-point measures were matched by date and time to continuous monitoring data. Continuous readings were averaged from data loggers for 30 minutes (a & c) and 12 days (b & d).

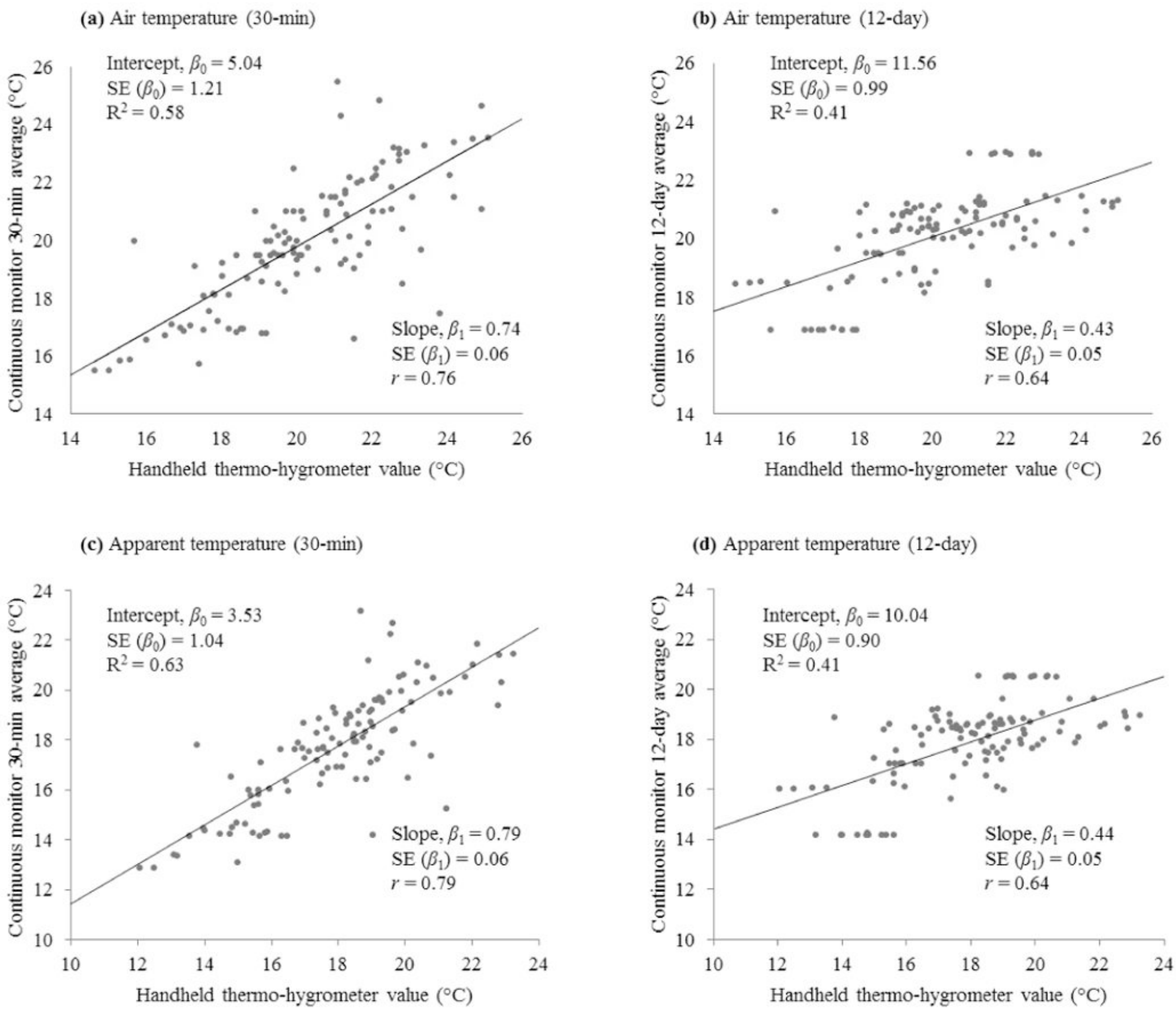

Figure 3.

Linear regression of air and apparent temperature (°C) collected with handheld thermo-hygrometers and continuous data logging instruments from March – June 2012. Single-point air temperature measures were collected by recording an instantaneous reading from the handheld thermo-hygrometer 5 minutes after the instrument was powered on. Apparent temperature was derived from air temperature and relative humidity readings from handheld and data logging instruments. Single-point measures were matched by date and time to continuous monitoring data. Continuous readings were averaged from data loggers for 30 minutes (a & c) and 12 days (b & d).

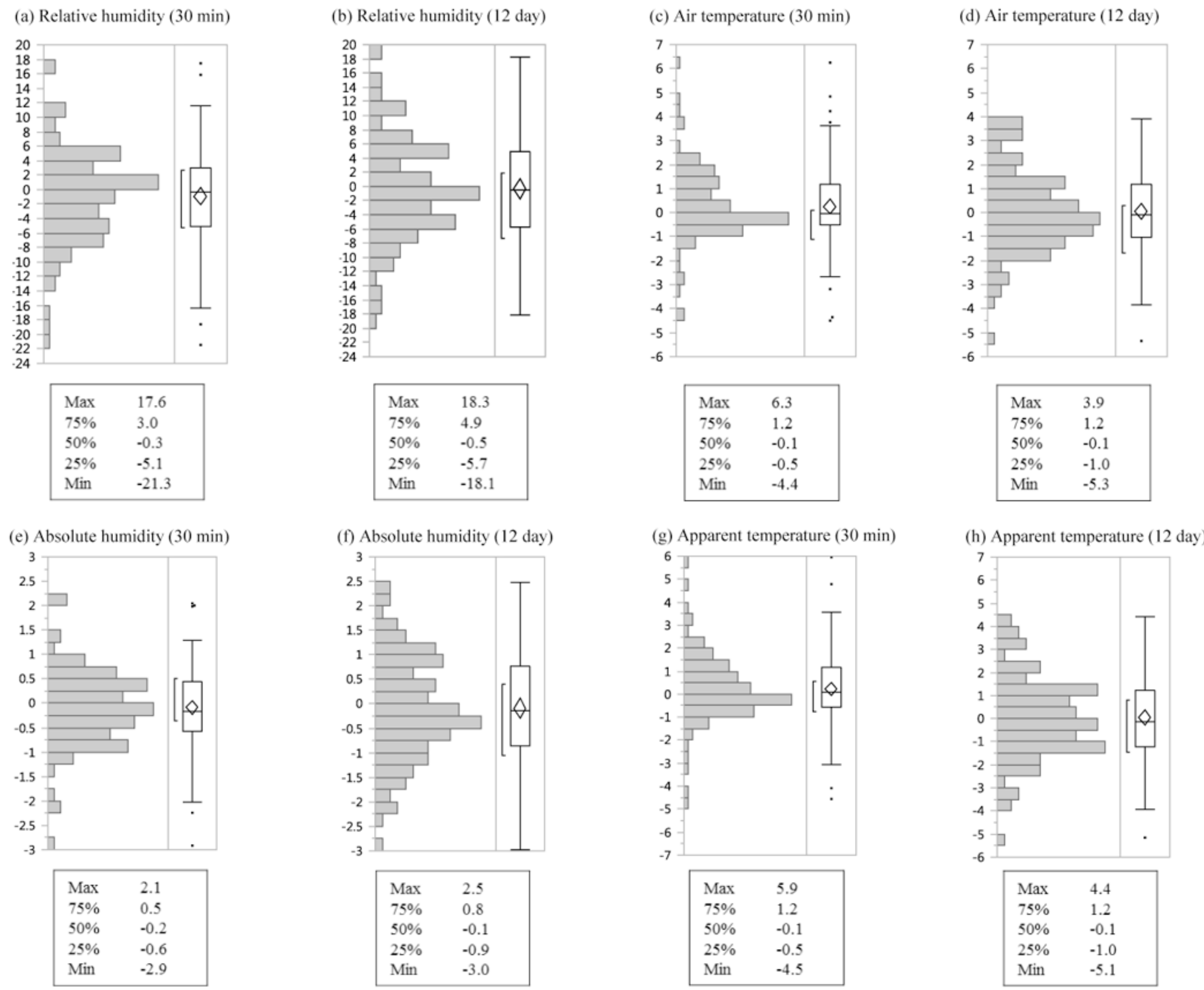

Figure 4.

Distribution of differences in single-point and continuous measures of indoor RH (%) (a & b), air temperature (°C) (c & d), absolute humidity (g/m^3) (e & f), and apparent temperature (°C) (g & h) March – June 2012. Differences calculated as handheld thermo-hygrometer reading – continuous monitor average (30 min and 12 day means).

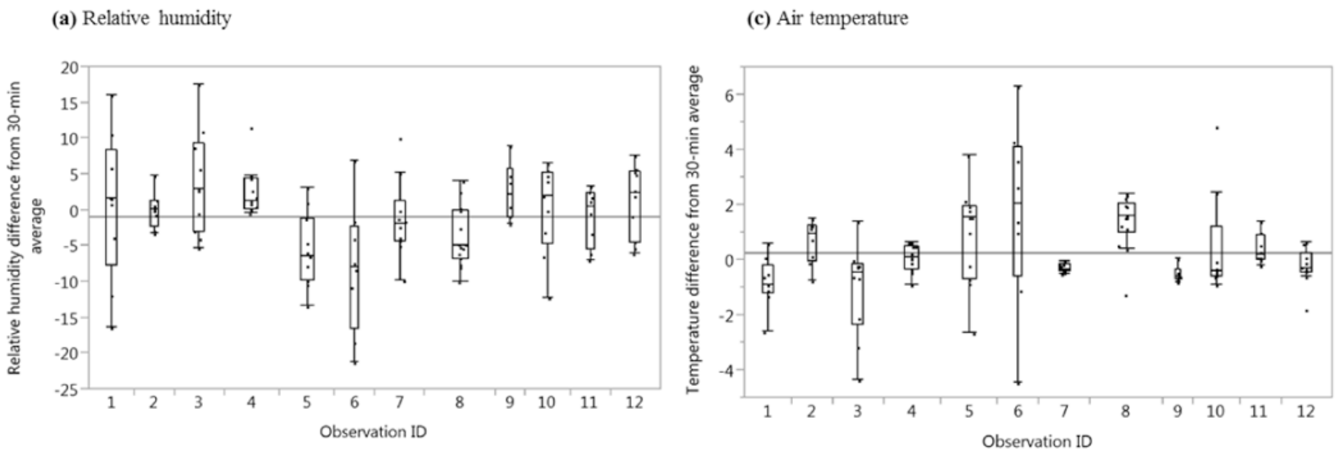

Figure 5.
Distribution of differences in single-point and continuous measures by observation. Differences were calculated as handheld thermo-hygrometer reading – continuous monitor average based on 30-min data logger mean.

Table 1

Characteristics and mean indoor RH and air temperature for continuous and single-point sampling in Northern Utah homes, March – June 2012

							Continuous monitoring			Single-point monitoring	
Observation ID	Residence Type	Central AC	#Baths/ #vented[A]	Range vented[B]	Room Sampled[C]	#days sampled	%RH (mean, SD)	Temp °C (mean, SD)	#Single-point measures	%RH (mean, SD)	Temp °C (mean, SD)
1	Single Family	No	2/0	No	Living	13.9	44.7 (6.3)	20.5 (0.9)	9	46.4 (9.0)	19.5 (0.6)
2	Single Family	No	2/0	No	Living	17.9	33.7 (7.7)	21.1 (1.7)	8	34.3 (4.9)	22.1 (2.5)
3	Single Family	No	2/1	No	Living	26.1	37.4 (5.6)	20.3 (2.4)	10	42.3 (7.4)	19.8 (1.7)
4	Single Family	Yes	4/4	Yes	Living	26.0	29.9 (4.1)	20.5 (2.1)	11	32.2 (5.4)	21.4 (1.8)
5	Single Family	No	2/2	No	Dining	23.1	43.7 (5.5)	20.3 (2.5)	11	36.4 (5.4)	21.6 (1.9)
6	Single Family	Yes	2/0	No	Living	17.1	44.4 (3.5)	19.8 (1.4)	8	35.9 (7.8)	22.2 (1.6)
7	Apartment	No	1/0	No	Living	13.9	31.6 (4.1)	23.0 (1.0)	10	29.6 (4.6)	22.2 (0.6)
8	Apartment	No	1/0	No	Living	17.8	34.0 (8.3)	20.0 (2.3)	14	34.7 (6.5)	19.6 (1.6)
9	Single Family	Yes	3/2	No	Living	13.8	31.4 (5.4)	21.3 (1.4)	6	33.6 (9.5)	20.5 (1.5)
10	Single Family	No	2/0	No	Living	21.8	40.0 (3.1)	18.0 (1.6)	9	41.4 (8.8)	17.8 (2.7)
11	Apartment	Yes	2/2	No	Dining	17.5	49.3 (3.2)	18.6 (0.9)	8	50.6 (6.2)	19.1 (1.1)
12	Apartment	Yes	2/2	No	Dining	13.8	37.0 (4.5)	17.1 (1.3)	10	42.5 (6.7)	17.1 (0.7)

[A] Bathrooms counted as “vented” if a working mechanical system venting to the outdoors was present. Recirculating fans and natural window ventilation were not counted.

[B] Kitchen range hood counted as “vented” if a working mechanical system venting to the outdoors was present. Recirculating fans were not counted.

[C] All single-point measures collected in the same room where the continuous monitor was located.

Table 2

Pearson correlation coefficients[a] for single-point and continuous monitoring of indoor humidity and temperature in Northern Utah homes, March – June, 2012

	Continuous monitoring			
Single-point sampling	**5 min**	**30 min**	**24 hv**	**12 day**
Relative humidity (%)	0.70	0.70	0.66	0.53
Absolute humidity (g/m^3)	0.80	0.80	0.76	0.52
Air temperature (°C)	0.75	0.76	0.70	0.64
Apparent temperature (°C)	0.78	0.79	0.73	0.64

[a]All P-values < 0.0001

Table 3

Distribution of differences between single-point and continuous monitoring of indoor temperature and apparent temperature in Northern Utah homes, March – June, 2012

Observations	Min	10%	25%	Median	75%	90%	Max
Air Temperature (°C)							
1	-2.6	-2.6	-1.2	-0.9	-0.2	0.6	0.6
2	-0.76	-0.76	-0.03	0.96	1.26	1.52	1.52
3	-4.33	-4.21	-2.37	-0.43	-0.14	1.25	1.39
4	-0.89	-0.8	-0.35	0.11	0.51	0.66	0.66
5	-2.66	-2.29	-0.72	1.56	1.95	3.48	3.81
6	-4.44	-4.44	-0.58	2.05	4.11	6.28	6.28
7	-0.5	-0.5	-0.42	-0.34	-0.17	-0.06	-0.05
8	-1.23	-0.42	0.98	1.58	2.06	2.37	2.39
9	-0.8	-0.8	-0.7	-0.56	-0.33	0.05	0.05
10	-0.91	-0.91	-0.58	-0.3 S	1.21	4.87	4.87
11	-0.19	-0.19	0.02	0.21	0.89	1.42	1.42
12	-1.82	-1.7	-0.46	-0.28	0.24	0.65	0.66
Apparent Temperature (°C)							
1	-2.33	-2.33	-1.38	-0.97	-0.62	0.78	0.78
2	-0.69	-0.69	0.05	1.10	1.31	1.76	1.76
3	-4.04	-3.55	-1.72	-0.53	0.15	0.69	1.23
4	-0.71	-0.42	-0.22	0.30	0.60	0.72	0.81
5	-2.72	-1.10	-0.93	1.17	LSI	1.87	3.36
6	-4.54	-4.54	-0.42	1.99	3.49	5.99	5.99
7	-0.74	-0.70	-0.62	-0.44	-0.22	-0.05	-0.01
8	-1.43	0.45	0.83	1.52	2.08	2.31	2.37
9	-0.73	-0.73	-0.68	-0.31	-0.17	0.06	0.06
10	-0.82	-0.82	-0.40	-0.23	-0.12	4.82	4.82
11	-0.28	-0.28	0.19	0.25	0.76	1.21	1.21
12	-1.76	-1.13	-0.40	-0.28	0.28	0.54	0.56

Differences calculated as Extech reading – continuous monitor 30-min average.

Table 4

Distribution of differences between single-point and continuous monitoring of indoor relative humidity (RH) and absolute humidity in Northern Utah homes, March – June, 2012

Observations	Min	10%	25%	Median	75%	90%	Max
Relative Humidity (%)							
1	-16.3	-16.3	-7.84	1.62	8.3	16	16
2	-3.22	-3.22	-2.28	0.06	1.24	4.84	4.84
3	-5.38	-5.23	-3.1	2.89	9.33	16.93	17.6
4	-0.47	-0.37	0.08	1.24	4.41	10.28	11.64
5	-13.4	-12.78	-9.9	-6.4	-1.1	2.78	3.2
6	-21.33	-21.33	-16.49	-7.875	-2.23	6.95	6.95
7	-9.9	-9.4	-4.38	-1.95	1.23	9.52	10
8	-9.91	-8.9	-6.81	-4.94	-0.04	3.27	4.01
9	-1.94	-1.94	-1.06	2.19	5.83	8.87	8.87
10	-12.29	-12.29	-4.73	1.93	5.1	6.51	6.51
11	-6.98	-6.98	-5.41	0.47	2.34	3.27	3.27
12	-6.05	-5.97	-4.62	2.3	5.41	7.45	7.65
Absolute Humidity							
1	-2.88	-2.88	-0.89	-0.17	0.58	2.02	2.02
2	-0.13	-0.13	-0.02	0.31	0.52	0.60	0.60
3	-0.81	-0.69	-0.43	0.27	0.76	0.94	0.99
4	0.02	0.06	0.09	0.38	0.57	0.96	2.07
5	-1.28	-1.07	-1.06	-0.81	-0.24	-0.21	-0.21
6	-2.21	-2.21	-0.91	-0.73	-0.26	-0.03	-0.03
7	-2.02	-1.51	-0.87	-0.56	-0.15	1.44	2.00
8	-0.88	-0.83	-0.58	-0.28	-0.07	0.94	1.27
9	-0.55	-0.55	-0.36	0.26	0.74	1.30	1.30
10	-0.49	-0.49	-0.22	0.22	0.43	0.63	0.63
11	-0.75	-0.75	-0.35	0.10	0.44	0.51	0.51
12	-0.83	-0.77	-0.44	0.19	0.50	0.82	1.06

Differences calculated as Extech reading – continuous monitor 30-min average.