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Int J Biometeorol. Author manuscript; available in PMC 2017 February 01.

Published in final edited form as:

Int J Biometeorol. 2016 February ; 60(2): 221–229. doi:10.1007/s00484-015-1019-5.

Daily indoor-to-outdoor temperature and humidity relationships: a sample across seasons and diverse climatic regions

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Abstract

The health consequences of heat and cold are usually evaluated based on associations with outdoor measurements at the nearest weather reporting station. However, people in the developed world spend little time outdoors, especially during extreme temperature events. We examined the association between indoor and outdoor temperature and humidity in a range of climates. We measured indoor temperature, apparent temperature, relative humidity, dew point, and specific humidity (a measure of moisture content in air) for one calendar year (2012) in a convenience sample of eight diverse locations ranging from the equatorial region (10°N) to the Arctic (64°N). We then compared the indoor conditions to outdoor values recorded at the nearest airport weather station. We found that the shape of the indoor-to-outdoor temperature and humidity relationships varied across seasons and locations. Indoor temperatures showed little variation across season and location. There was large variation in indoor relative humidity between seasons and between locations which was independent of outdoor, airport measurements. On the other hand, indoor specific humidity, and to a lesser extent dew point, tracked with outdoor, airport measurements both seasonally and between climates, across a wide range of outdoor temperatures. Our results suggest that, depending on the measure, season, and location, outdoor weather measurements can be reliably used to represent indoor exposures and that, in general, outdoor measures of actual moisture content in air better capture indoor exposure than temperature and relative humidity. Therefore, absolute measures of water vapor should be examined in conjunction with other measures (e.g. temperature, relative humidity) in studies of the effect of weather and climate on human health.

Keywords

airport; humidity; indoor; outdoor; temperature; weather

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Introduction

Most studies of the association between weather and health events use measurements made at a nearby outdoor weather station as an indicator of population exposure. However, in developed countries people spend most of their time indoors where temperature is controlled within a much narrower range compared to the outdoors (Höppe and Martinac 1998). This disagreement between outdoor and indoor temperatures may introduce bias into studies of weather-related health effects. Despite this potential for bias, associations of outdoor temperature with acute adverse events are consistently reported across different climatic regions. Two natural questions arise from these observations: 1) how well is outdoor temperature representing indoor/personal temperature exposure, and 2) what other environmental parameters are correlated with outdoor temperature, and how well do these other parameters represent indoor/personal exposure?

Temperature and humidity (i.e., water vapor) are important determinants for maintaining a comfortable, healthy indoor environment. They impact the efficiency with which we condition inspired air to body temperature and 100% saturation with water in the airways and affect the physiologic response to heat. The amount of heat removed from the skin depends on the latent heat evaporation of water and the rate of evaporative cooling, with the latter being mainly determined by the amount of sweat secreted and evaporated, ambient temperature and humidity, and clothing (Givoni et al. 1962; Shapiro et al. 1982). Alternative measures of temperature have been proposed that incorporate the effect of water vapor. The wet-bulb temperature is the lowest temperature that can reached under ambient conditions through evaporative cooling. Apparent temperature is a measure of what a given temperature, humidity, and wind combination “feels like” to the typical human (Steadman 1979).

Water vapor content is reported by multiple alte rnative measures. Relative humidity is the ratio of the amount of water vapor present in the air relative to the amount of water vapor needed for saturation at a given temperature, expressed as a percentage, and is thus a temperature-dependent measure. Other measures of water vapor content in the air include absolute humidity (g/m^3), the mixing ratio (g/kg dry air), and specific humidity (g/kg moist air). Absolute humidity changes with air parcel volume, which can change with temperature or pressure. Specific humidity does not depend on air parcel volume (Byers 1959), and can be used to directly compare air parcels at different temperatures and pressures (and implicitly, latitude and altitude). The mixing ratio and specific humidity are nearly equivalent. We propose that the water vapor content of air may be informative, in addition to temperature and relative humidity, in assessing personal exposures and potential health effects of day-to-day changes in weather.

Two recent studies of the associations of indoor environment with outdoor temperature and humidity in the northeast United States reported a weak relationship between outdoor and indoor temperature in cold seasons, but much closer tracking of indoor and outdoor temperatures during the warm season. In contrast, indoor absolute humidity was strongly and linearly correlated with outdoor measurements at nearby airports in all seasons (Nguyen et al. 2014; Tamerius et al. 2013). These season-specific relationships may reflect the

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heating and cooling practices of the northeast United States, where heating is near universal but air conditioning is not (American Community Survey, American Housing Survey). We undertook the present study to examine if the indoor and outdoor temperature and humidity relationships identified in the northeast United States could be extrapolated to other climatic regions. In a convenience sample of locations across a range of latitudes, we examined the relationship between daily indoor conditions and outdoor weather observations made at airport weather stations using five weather parameters – temperature, apparent temperature, relative humidity, dew point, and specific humidity.

Materials and methods

Study sites

We identified a sample of indoor locations from colleagues, friends, and family distributed across a wide range of latitudes and climates globally. We provided participants with a passive temperature and humidity data logger to be placed in their home (or in one case, an office) for the full 2012 calendar year. All sampled locations were constructed using modern building-construction techniques and were typical for the location. There were no restrictions on heating, ventilation, or air conditioning (HVAC) systems. Participants completed a brief questionnaire characterizing the indoor environment (residential or office), the type of heating or cooling systems in place, and presence and use of humidifiers or de-humidifiers.

Indoor measurements

Temperature (°C) and relative humidity (%) were measured hourly from January 1, 2012 to December 31, 2012 using HOBO U12-011 Data Loggers (Onset Corporation; Bourne, MA, USA). These loggers measure temperature from −20°C to 70°C with accuracy of ± 0.35°C and relative humidity from 5% to 95% with accuracy of ± 2.5%. Each of the loggers were validated against a National Institute of Standards and Technology traceable instrument (EDGETECH Model DS2 Dew Point Hygrometer) in our Boston laboratory prior to and following the one year sampling period.

The data loggers were delivered or express mailed to the participants in December 2011. Participants placed the data logger in their residential living room or in a central location in their office away from sources of heat, cold, or moisture. One measurement was recorded per hour. At this sampling rate, the data logger can store up to 2 ½ years of data without overwriting memory or replacing batteries. We periodically contacted the participants to check that the logger was indicating that it was recording data. In January 2013, participants returned their data logger to our laboratory, where the data were downloaded. Dew point (°C) was automatically calculated from temperature and relative humidity when exporting the recorded data.

For each hourly measurement, we calculated the apparent temperature from the measured temperature and relative humidity using the US National Weather Service algorithm (National Weather Service). This algorithm applies corrections for low temperature and very low and high relative humidity, and does not consider the effects of wind. We calculated the

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specific humidity from the measured dew point and outdoor atmospheric pressure using the following equations (Saucier 2003):

$$e = 6.11 \times 10^{(7.5 \times \mathrm{Td})/(237.7 + \mathrm{Td})} \quad (1)$$

$$\mathrm{SH} = 1000 \times (0.622 \times e)/[\mathrm{P} - (0.378 \times e)], \quad (2)$$

where *e* is actual vapor pressure (mb), T_d is dew point temperature (°C), SH is specific humidity (g/kg), and P is atmospheric pressure (mb). Daily mean temperature, apparent temperature, relative humidity, dew point, and specific humidity were calculated as the average of the 24 hourly measurements.

Airport measurements

We identified the closest airport weather station to each participating site. We downloaded hourly outdoor ambient temperature (dry bulb, °C), RH (%), dew point (°C), and atmospheric pressure (mb) measured at these airports from the Weather Underground website (www.wunderground.com). Weather Underground receives data directly from automated weather stations; all airport data retrieved for this study came from airports operated and maintained by government agencies (Weather Underground). Apparent temperature and specific humidity were computed from the temperature, relative humidity, dew point, and atmospheric pressure measurements, as above.

Statistical analysis

We calculated means, standard deviations (SD), Pearson correlation coefficients (*r*) and 95% confidence intervals (CIs) between the indoor and airport daily averages. We constructed scatterplots and boxplots to compare the magnitude and variability in temperature and humidity measurements at the airports versus indoors across study sites. We used ordinary least squares regression to quantify the annual and season-specific relationships between indoor and outdoor conditions at each site. The cool and warm seasons for each city were defined as the six consecutive months in 2012 with the lowest and highest average monthly temperatures, respectively. To estimate overall relationships, we used random effects regression models with a random intercept per city in order to account for the clustering of measurements within a city. Results are reported per site in order of increasing distance from the equator (latitude). Analyses were carried out in SAS version 9.3 (SAS Institute; Cary, NC, USA) and R version 2.15.3 (R Foundation for Statistical Computing; Vienna, Austria); plots were generated using the *ggplot2* graphing package and line graphs used loess smoothing.

Results

Nine participants from eight cities participated in this study (Table 1). Sampling sites ranged from the Tropic of Capricorn (São Paulo, Brazil) to close to the Arctic Circle (Nuuk, Greenland). There was one tropical site (Ho Chi Minh City, Vietnam) and six sites distributed across the mid-latitudes (Kuwait City, Kuwait; Atlanta, Georgia; Athens, Greece; Boston, Massachusetts; and Dublin, Ireland) (Figure 1). Most sites were single family

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homes, two were apartments (São Paulo and one Kuwait City site), and one was an office (Dublin). All sites had some type of heating system except in Ho Chi Minh City and São Paulo. Four sites had air conditioning (Ho Chi Minh City, both Kuwait City sites and Atlanta). Only one site used a humidifier and no sites used de-humidifiers. All participating sites were located < 25 km away (mean: 11 km) from the nearest airport weather station.

Mean indoor and airport temperature and humidity were calculated for each day of the 2012 calendar year. Although the sampler in Ho Chi Minh City indicated the data logger was continuously operational throughout the year, upon downloading the data, we found the logger only contained measurements prior to April 5, 2012. Because of the limited seasonal variation of outdoor temperatures and humidity in Ho Chi Minh City, the results for this brief recording period compared well to the year-long distribution (mean outdoor temperature (SD) = 27.9°C (1.2) vs. 28.2°C (1.2) and mean relative humidity (SD) = 72% (7) and 78% (8), for January – March 2012 and the entire 2012 year, respectively). We therefore included this restricted period as representative of the annual conditions.

We observed apparently anomalous days at two of the indoor sampling sites. Indoor temperature recordings at the two Kuwait City sites indicated sporadic, large spikes in temperature in August and September lasting at most a few days, although never on the same days. Study participants confirmed that the dates of the temperature spikes coincided with power outages that shut off their air conditioning units. At the participating office in Dublin, the central heat was turned off during the winter holiday periods (i.e., Christmas through New Year’s Day) and also during the weekends. As this study was designed to measure indoor conditions at the selected locations, not personal exposure, we retained all indoor measurements recorded in Kuwait City and Dublin in our analyses.

Indoor temperatures correlated moderately ($r = 0.53$, $p<0.0001$) between the two Kuwait City sites. This weaker correlation may be explained by the limited range of indoor temperature values (Ware et al. 2013). The range of indoor temperatures was only about 10°C at these two sites, with 90% of the measurements falling within an interval of less than 6°C. Relative humidity displayed a stronger correlation between the two sites ($r = 0.70$). The absolute differences between the two Kuwait City sites were small (by 1.4°C for average temperature and 2.2% for average relative humidity) and both sites correlated moderately, and similarly, with outdoor temperature (r’s = 0.44 and 0.51) and outdoor relative humidity (r’s = 0.65 and 0.63). For this analysis of indoor versus outdoor associated, we averaged the two daily indoor measurements for each parameter.

Average outdoor airport temperature ranged between 0° and 28°C (Table 2). There was comparatively small variation in the airport temperature at the low latitude sites (Ho Chi Minh City and São Paulo) compared to the mid- and high-latitude sites (Table 2, Figure 2). On the other hand, all sites had a narrow range of indoor average temperature compared with the airport measurements (Table 2, Figure 2). Across all eight sites, there was a strong correlation between airport and indoor daily temperature ($r = 0.64$, 95% CI: 0.61, 0.66), although there was considerable variation in the site-specific correlations (Table 2). The lowest correlations were observed in the coldest (Nuuk, $r = 0.48$) and hottest (Kuwait City, $r = 0.54$) sites. In linear regression analyses, adjusting for clustering by site, we found that

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average daily indoor temperature only increased 0.21 (±0.004) °C for each 1°C increase in airport temperature. The site-specific regression coefficients (Table 3) were heterogeneous. In the mid-latitude sites, the regression coefficients were modest (0.24 to 0.44), that is, positive but substantially less than a one-to-one-association. As would be expected, in the extreme climatic sites (Nuuk and Kuwait City) there were very weak associations between airport and indoor daily mean temperatures (Table 3, Figure 3). In analyses stratified by cold versus warm seasons (Table 3), the association of indoor with airport daily temperature was weaker in the cold season, except again in the extreme climate sites - Nuuk and Kuwait City.

Apparent temperature was very similar to temperature in terms of airport and indoor daily means (Table 2, Figure 2), and also similar to temperature in the associations and correlations between indoor and airport daily means by site (Tables 2 and 3, Figures 2 and 3). Average daily indoor apparent temperature increased by 0.27 (±0.005)°C for each 1°C increase in airport apparent temperature.

The measures of water vapor content at the airport and the indoor sites showed a very different pattern (Table 2, Figure 2). Distributions of relative humidity had limited differences compared with temperature, other than in Kuwait City. Similar to indoor temperature, indoor relative humidity was less variable than airport relative humidity, both between sites and day-today within sites (Table 2, Figure 2). Across the sites, there was a weak correlation between airport and indoor daily relative humidity (r = 0.32, 95% CI: 0.29, 0.36). Site-specific correlations generally were lower than for temperature (Table 2). The overall regression coefficient (0.29 ± 0.01) was modestly larger than for temperature. The site-specific regression coefficients for relative humidity were heterogeneous and had larger uncertainty than the temperature coefficients (Table 2, Figure 3).

The means and distributions of indoor dew point and specific humidity were generally similar to the mean and distribution of the airport measurements (Table 2, Figure 2). The correlations between airport and indoor daily dew point (r = 0.88, 95% CI: 0.87, 0.89) and specific humidity (r = 0.93, 95% CI: 0.92, 0.93) were both high, as were the site-specific correlations (r's ≥ 0.77, Table 2). The overall regression coefficient for indoor dew point compared to airport (0.50 ± 0.01) was larger than for the temperature measures, as were the site-specific regression coefficients (Table 3). The specific humidity regression coefficients were the largest overall (0.65 ± 0.01) and largest in site-specific regression analyses (Table 3). In linear regression models stratified by season, the regression coefficients for specific humidity were lower in the warm compared to the cold season in the two sites with air conditioning (Kuwait City and Atlanta), but also in non-air conditioned sites (Nuuk and Athens). The scatterplots and fitted curves for specific humidity (Figure 3), and less so for dew point, suggested the strongest associations between indoor and airport daily measurements of all the temperature and water vapor parameters considered.

Discussion

Despite differences in building characteristics, climate control, and outdoor weather conditions, we observed several characteristics that were similar across all study sites. First, indoor temperatures were quite similar, with annual average temperatures between 19°–

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30°C with limited daily variation. These findings could be a reflection of the middle- to upper-class participants of this study; one would reasonably expect indoor conditions to vary by income class or access to resources. However, indoor residential temperature in New York City lower- and middle-income homes displays a very similar distribution to the range reported here. In the cool season, New York City residential temperatures range from 16°–28°C, and in the warm season, 20°–31°C (Tamerius et al. 2013). Second, the indoor-to-outdoor relationship is similar for temperature and apparent temperature, which is expected since temperature is the primary determinant of apparent temperature. Third, outdoor, airport relative humidity tracks poorly with indoor relative humidity. This finding is also expected since relative humidity is dependent on both water vapor content and temperature. Lastly, absolute measures of ambient moisture – specific humidity and dew point - track more closely indoor-to-outdoors than temperature or relative humidity.

Our results are consistent with two previous studies conducted in Boston and New York City characterizing the relationship between indoor and outdoor temperature and water vapor levels. Notably, the relationship between indoor and outdoor temperature during the warm seasons is very consistent across the two previous studies and our current results. For each 1°C increase in outdoor temperature during the warm seasons, the average indoor residential temperature was found to increase by 0.41°C in Boston (Nguyen et al. 2014) and by 0.43°C in New York City (Tamerius et al. 2013). In our study, we found similar estimated increased indoor temperatures in São Paulo (0.43°C), Boston (0.41°C), Dublin (0.37°C), and Atlanta (0.29°C). Similarly, the water vapor relationship previously reported in Boston is consistent with the relationship observed here. In Boston, each 1 g/m^3 increase in outdoor absolute humidity is associated with an average indoor increase of 0.69 g/m^3 (Nguyen et al. 2014). With the exception of Kuwait City, we observed similar increases at each site, ranging from 0.51 g/m^3 in Atlanta to 0.86 g/m^3 in Boston. (The coefficients reported in Table 3 will differ slightly when converted from g/kg to g/m^3).

There is currently no consensus on the preferred measure for relating weather to health (Barnett and Astrom 2012). Most weather-related health studies have focused on outdoor mean daily temperature. Reported adverse effects of extreme (both hot and cold) temperatures include increased mortality, cardiovascular- and respiratory-related morbidity, and adverse birth outcomes (preterm birth, stillbirth and low birth weight) (Anderson and Bell 2009; Basu 2009; Strand et al. 2011; Turner et al. 2012; Ye et al. 2012). Studies have reported heterogeneity in vulnerability to hotter or cooler temperatures across climates (i.e., in temperate as well as less moderate climates) (Bhaskaran et al. 2009; Braga et al. 2002; Healy 2003; Medina-Ramon and Schwartz 2007; The Eurowinter Group 1997). One reason for this heterogeneity may be differences in how populations have adapted to climatic conditions. For example, the cold Nordic countries of Sweden, Norway and Finland have high home energy efficiency standards, while homes in southern and western Europe have lower thermal efficiency (e.g., less insulation, fewer double-glazed windows) (Healy 2003). Air conditioning use may also reduce the effect of high temperature on health (Ostro et al. 2010). Another contributing factor to the observed heterogeneity in health effects may be differences in how outdoor weather measures relate to one another and to indoor conditions in different locations and across seasons. We observed low correlations between indoor and outdoor temperatures during the warm season in two cities with very different climates -

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Kuwait City and Nuuk - and temperature correlations that were positive or negative depending on the outdoor conditions. This suggests that indoor-to-outdoor thermal relationships are complex and difficult to accurately predict.

The biological mechanisms for how temperatures may influence human health are generally understood. Exposure to cold temperatures increases vasoconstriction, which limits heat loss by redistributing blood to the core (Castellani et al. 2002). Cold extremities and the lowering of core body temperature can induce increases in heart rate, blood pressure, blood viscosity, hemoconcentration and arterial thrombosis that could lead to triggering of acute cardiac events (Collins 1986). The human body responds to high temperatures by increasing heat loss through the skin surface via blood circulation (Höppe and Martinac 1998). Loss of salt and water results in hemoconcentration that strains the cardiovascular and respiratory systems, and combined with increased blood viscosity and cholesterol levels, may increase the risk of cardiorespiratory deaths (Keatinge 2002; Medina-Ramon and Schwartz 2007).

The current findings and our previous work suggest that measures of water vapor in air track most closely indoors-to-outdoors. The biological mechanisms for how the human body responds to changes in air moisture are generally understood in relation to the respiratory system. Cold and/or dry inspired air must be warmed to body temperature and saturated with water in the airways. This process results in substantial heat and water loss in the airways and can induce reflex-mediated bronchoconstriction (Koskela 2007; Larsson et al. 1998). Cold, dry air also promotes respiratory infection by drying the mucosal surface (Reinikainen and Jaakkola 2003) and by decreasing the ability of cilia to remove airway contaminants before they can be absorbed in the respiratory mucosa (Castellani et al. 2002; Collins 1986). Several studies have linked low absolute water vapor levels to increased rates of influenza infection (Shaman et al. 2010; Shoji et al. 2011; van Noort et al. 2011).

A particular strength of our study is the heterogeneity in latitude and outdoor climate covered by our sampling sites. We continuously collected data for one year from study sites chosen to capture a wide range of weather conditions. Nevertheless, the sampled sites may not be representative of the range of indoor conditions in the sampled sites. However, this small convenience sample of selected locations is not meant to inform on broader population patterns. Indeed, occupant behavior is complex and individual exposure can only be accurately measured through personal monitoring. Heating, air conditioning use, and fenestration undoubtedly depend on occupancy and have major effects on indoor temperature and humidity levels. The geometry of the built structure, the construction age, and the type of insulation also determine the indoor conditions (Mavrogianni et al. 2012). Determining the most appropriate exposure variable - in terms of both biological relevance and accuracy in representing exposure - is very important to defining the effects of weather on health and to enabling the comparison of studies performed in different locations. This work adds to the limited available evidence regarding the extent to which weather-related health studies that have been generally conducted in mid-latitude locations can be extrapolated to other geographical areas. These results show that day-to-day variation in indoor temperature and relative humidity - significant contributors to human exposure - are not well represented by routinely collected outdoor, airport weather station measurements. On the other hand, daily indoor water vapor content measured as specific humidity, and to a

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lesser extent dew point temperature, was linearly and consistently related to outdoor airport weather station measurements across a wide range of seasonal and climatic conditions. Therefore, absolute measures of outdoor water vapor content should be included in assessments of the acute effects of weather on human health.

Acknowledgments

We thank all study volunteers for their participation. This work was supported in part by National Institute of Environmental Health Sciences (NIEHS) grants ES000002, R21ES020194, and T32ES023770. JLN also received support from the Benjamin Greely Ferris, Jr. Fellowship Fund at the Harvard School of Public Health.

References

American Community Survey. United States Census Bureau. [Accessed 1/24/2015] Physical housing characteristics for occupied housing units. American Community Survey 1-year estimates. 2013. http://www.census.gov/acs/www/

American Housing Survey. United States Census Bureau. [Accessed 1/24/2015] National summary tables – AHS. 2013. http://www.census.gov/programs-surveys/ahs/data/2013/national-summary-report-and-tables---ahs-2013.html

Anderson BG, Bell ML. Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. Epidemiology. 2009; 20:205–213. [PubMed: 19194300]

Barnett AG, Astrom C. Commentary: What measure of temperature is the best predictor of mortality? Environ Res. 2012; 118:149–151. [PubMed: 22854320]

Basu R. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. Environ Health. 2009; 8:40.10.1186/1476-069X-8-40 [PubMed: 19758453]

Bhaskaran K, Hajat S, Haines A, Herrett E, Wilkinson P, Smeeth L. Effects of ambient temperature on the incidence of myocardial infarction. Heart. 2009; 95:1760–1769. [PubMed: 19635724]

Braga AL, Zanobetti A, Schwartz J. The effect of weather on respiratory and cardiovascular deaths in 12 U.S. cities. Environ Health Persp. 2002; 110:859–863.

Byers, HR. General meteorology. 3. McGraw-Hill; New York: 1959.

Castellani JW, Brenner MIK, Rhind SG. Cold exposure: human immune responses and intracellular cytokine expression. Med Sci Sports Exerc. 2002; 34:2013–2020. [PubMed: 12471310]

Collins KJ. Low indoor temperatures and morbidity in the elderly. Age Ageing. 1986; 15:212–220. [PubMed: 3751747]

Givoni, B.; Belding, HS. The cooling efficiency of sweat evaporation. In: Tromp, SW., editor. Biometeorology: proceedings of the second international bioclimatological congress. Pergamon Press; London: 1962.

Healy JD. Excess winter mortality in Europe: a cross country analysis identifying key risk factors. J Epidemiol Comm H. 2003; 57:784–789.

Höppe P, Martinac I. Indoor climate and air quality. Review of current and future topics in the field of ISB study group 10. Int J Biometeorol. 1998; 42:1–7. [PubMed: 9780844]

Keatinge WR. Winter mortality and its causes. Int J Circumpol Heal. 2002; 61:292–299.

Koskela HO. Cold air-provoked respiratory symptoms: the mechanisms and management. Int J Circumpol Heal. 2007; 66:91–100.

Larsson K, Tornling G, Gavhed D, Muller-Suur C, Palmberg L. Inhalation of cold air increases the number of inflammatory cells in the lungs in healthy subjects. Eur Respir J. 1998; 12:825–830. [PubMed: 9817153]

Mavrogianni A, Wilkinson P, Davies M, Biddulph P, Oikonomou E. Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings. Build Environ. 2012; 55:117–130.

Medina-Ramon M, Schwartz J. Temperature, temperature extremes, and mortality: a study of acclimatization and effect modification in 50 United States cities. Occup Environ Med. 2007; 64:827–833. [PubMed: 17600037]

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National Weather Service. Weather Prediction Center. [Accessed 10/3/2014] The heat index equation. http://www.hpc.ncep.noaa.gov/html/heatindex_equation.shtml

Nguyen JL, Schwartz J, Dockery D. The relationship between indoor and outdoor temperature, apparent temperature, relative humidity, and absolute humidity. Indoor Air. 2014; 24:103–112. [PubMed: 23710826]

Ostro B, Rauch S, Green R, Malig B, Basu R. The effects of temperature and use of air conditioning on hospitalizations. Am J Epidemiol. 2010; 172:1053–1061. [PubMed: 20829270]

Reinikainen LM, Jaakkola JJ. Significance of humidity and temperature on skin and upper airway symptoms. Indoor Air. 2003; 13:344–352. [PubMed: 14636228]

Saucier, WJ. Principles of meteorological analysis. Dover Publications; Mineola, NY: 2003.

Shaman J, Pitzer VE, Viboud C, Grenfell BT, Lipsitch M. Absolute humidity and the seasonal onset of influenza in the continental United States. PLoS Biol. 2010; 8:e1000316. [PubMed: 20186267]

Shapiro Y, Pandolf KB, Goldman RF. Predicting sweat loss response to exercise, environment and clothing. Eur J Appl Physiol Occup Physiol. 1982; 48:83–96. [PubMed: 7199457]

Shoji M, Katayama K, Sano K. Absolute humidity as a deterministic factor affecting seasonal influenza epidemics in Japan. Tohoku J Exp Med. 2011; 224:251–256. [PubMed: 21705850]

Steadman R. The assessment of sultriness. Part I: a temperature-humidity index based on human physiology and clothing science. J Appl Meteorol. 1979; 18:874–885.

Strand LB, Barnett AG, Tong S. The influence of season and ambient temperature on birth outcomes: a review of the epidemiological literature. Environ Res. 2011; 111:451–462. [PubMed: 21333980]

Tamerius JD, Perzanowski MS, Acosta LM, Jacobsen JS, Goldstein IF, Quinn JW, Rundle AG, Shaman J. Socioeconomic and outdoor meteorological determinants of indoor temperature and humidity in New York City dwellings. Weather Clim Soc. 2013; 5:168–179. [PubMed: 24077420]

The Eurowinter Group. Cold exposure and winter mortality from ischaemic heart disease, cerebrovascular disease, respiratory disease, and all causes in warm and cold regions of Europe. Lancet. 1997; 349:1341–1346. [PubMed: 9149695]

Turner LR, Barnett AG, Connell D, Tong S. Ambient temperature and cardiorespiratory morbidity: a systematic review and meta-analysis. Epidemiology. 2012; 23:594–606. [PubMed: 22531668]

van Noort SP, Aguas R, Ballesteros S, Gomes MG. The role of weather on the relation between influenza and influenza-like illness. J Theor Biol. 2011; 298C:131–137. [PubMed: 22214751]

Ware, WB.; Ferron, JM.; Miller, BM. Introductory statistics: a conceptual approach using R. Routledge; New York, NY: 2013.

Weather Underground. [Accessed October 3, 2014] http://www.wunderground.com/about/data.asp

Ye X, Wolff R, Yu W, Vaneckova P, Pan X, Tong S. Ambient temperature and morbidity: a review of epidemiological evidence. Environ Health Persp. 2012; 120:19–28.

Fig. 1.
Map of study cities

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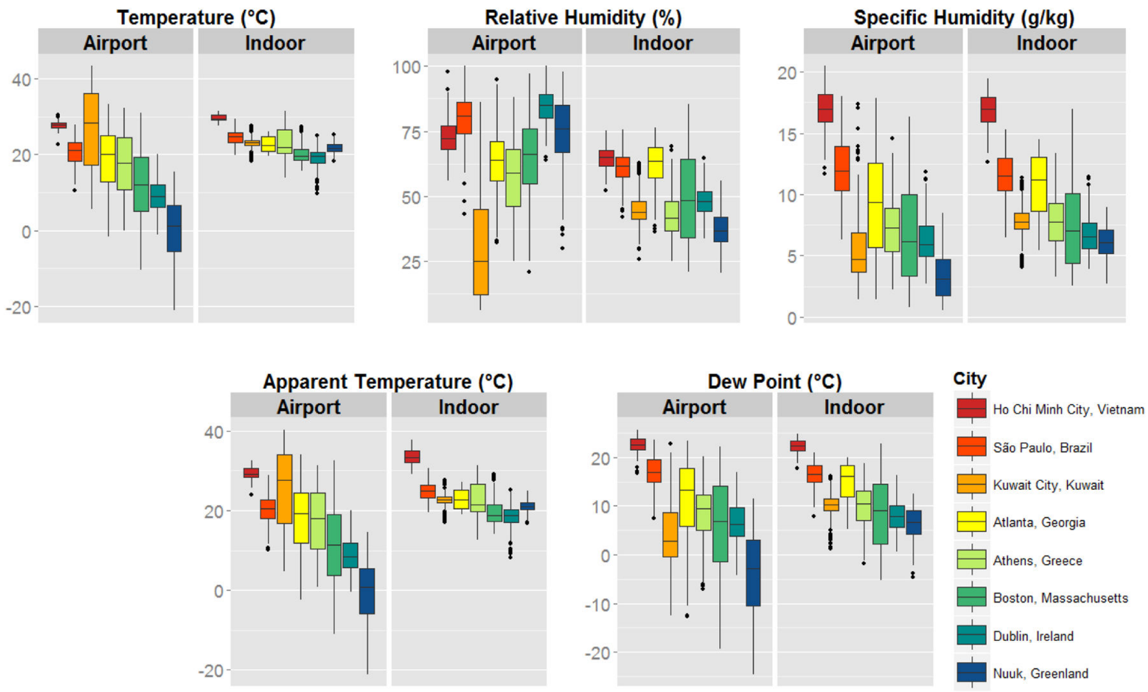

Fig. 2.

Boxplots comparing airport and indoor measurements of temperature and humidity at each study site. Cities are listed in order of increasing distance from the equator (latitude). Top whisker, Q3 + 1.5 × IQR; bottom whisker, Q1 − 1.5 × IQR. Q3, 3rd quartile; Q1, 1st quartile; IQR, interquartile range

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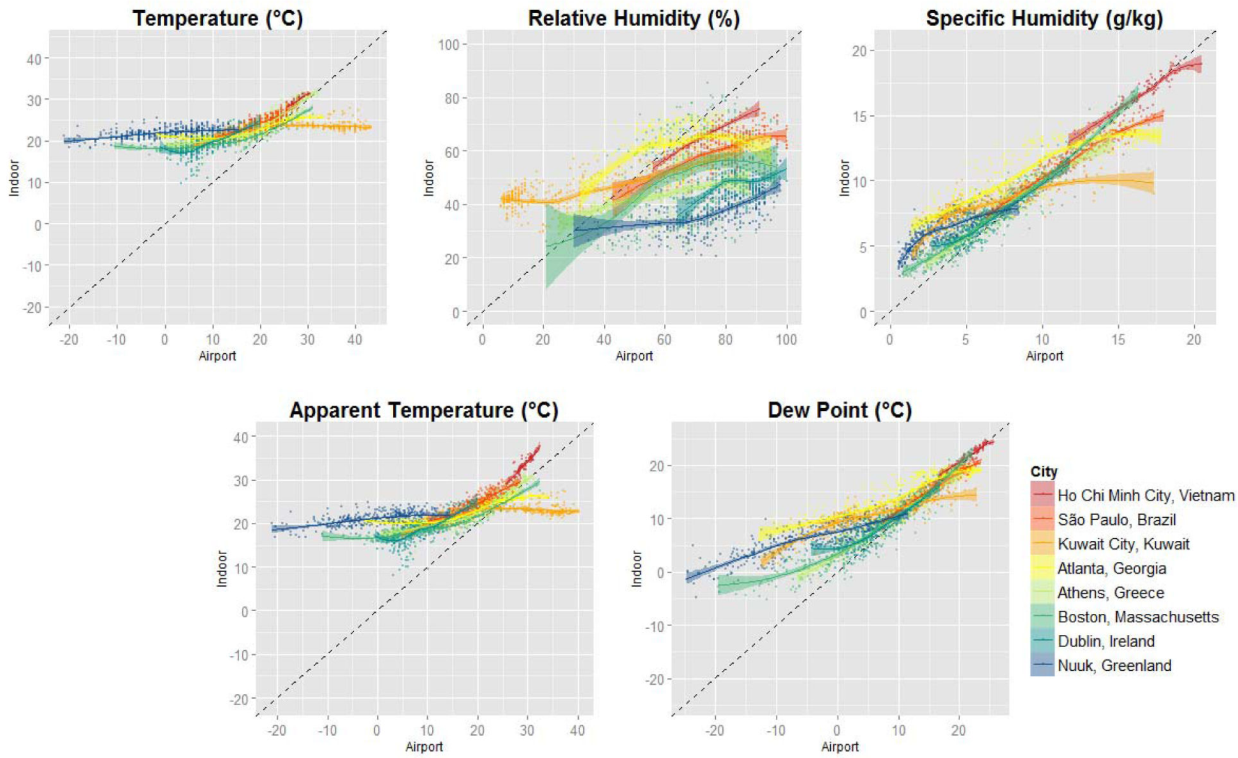

Fig. 3.

Scatterplots and line graphs (loess curves) relating indoor-to-airport weather measurements at each study site. Cities are listed in order of increasing distance from the equator. Black dashed line, y = x (45°) reference line

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Table 1

Study cities, airports, and indoor climate control characteristics of the participating sites

City	Airport Latitude	IATA Code	Building Type	Distance between Airport and Site	Heating System	Cooling System	Use of a Humidifier	Use of a De-humidifier
Ho Chi Minh City, Vietnam	10°49′N	SGN	House	2 km	None	Wall AC	No	No
São Paulo, Brazil	23°26′S	GRU	Apartment	23 km	None	None	No	No
Kuwait City, Kuwait	29°13′N	KWI	House	11 km	Space heaters	Central AC	No	No
			Apartment	3 km	Space heaters	Central AC	Yes	No
Atlanta, Georgia, USA	33°38′N	ATL	House	23 km	Forced hot air	Central AC	No	No
Athens, Greece	37°56′N	ATH	House	14 km	Radiator	None	No	No
Boston, Massachusetts, USA	42°21′N	BOS	House	11 km	Radiator/Baseboard	None	No	No
Dublin, Ireland	53°25′N	DUB	Office	10 km	Central	None	No	No
Nuuk, Greenland	64°11′N	GOH	House	2 km	Radiators	None	No	No

AC, air conditioning; IATA, International Air Transport Association

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Table 2

Means (SD) of the daily average airport and indoor temperature, apparent temperature, relative humidity, dew point, and specific humidity and Pearson correlation coefficients (r)* between the airport and indoor averages by study city

Measure	Ho Chi Minh City	São Paulo	Kuwait City	Atlanta	Athens	Boston	Dublin	Nuuk
Temperature (°C)								
Airport	27.8 (1.3)	20.6 (3.3)	26.9 (10.1)	18.8 (7.4)	17.6 (7.8)	12.5 (8.7)	9.1 (4.1)	0.1 (7.8)
Indoor	29.7 (1.0)	24.6 (1.8)	22.9 (1.5)	22.8 (2.0)	23.5 (3.7)	20.2 (2.4)	19.3 (2.6)	21.8 (1.3)
r	0.84	0.82	0.54	0.90	0.90	0.86	0.69	0.48
Apparent temperature (°C)								
Airport	29.2 (1.6)	20.4 (3.5)	25.5 (9.4)	18.1 (7.9)	17.5 (8.1)	11.7 (8.8)	8.9 (4.2)	−0.4 (7.4)
Indoor	33.4 (2.0)	24.9 (2.3)	22.4 (1.6)	22.8 (2.4)	22.9 (3.9)	19.6 (3.1)	18.6 (2.8)	21.0 (1.5)
r	0.91	0.85	0.56	0.91	0.92	0.89	0.73	0.56
Relative humidity (%)								
Airport	72.6 (7.4)	80.2 (9.2)	30.4 (21.2)	63.1 (12.2)	57.2 (14.7)	65.8 (14.9)	84.6 (6.5)	75.1 (12.7)
Indoor	65.3 (5.1)	61.0 (5.9)	44.9 (6.6)	61.9 (8.3)	42.9 (8.4)	49.5 (16.8)	48.3 (5.8)	37.2 (6.9)
r	0.91	0.60	0.70	0.41	0.44	0.41	0.31	0.54
Dew point (°C)								
Airport	22.3 (1.7)	16.9 (3.1)	4.2 (6.5)	11.4 (8.2)	8.4 (5.3)	6.0 (9.5)	6.6 (4.1)	−3.9 (8.4)
Indoor	22.4 (1.4)	16.5 (2.4)	10.2 (2.6)	15.1 (3.7)	9.9 (4.0)	8.6 (7.0)	8.0 (3.1)	6.3 (3.2)
r	0.93	0.94	0.81	0.88	0.95	0.93	0.88	0.84
Specific humidity (g/kg)								
Airport	16.9 (1.7)	12.1 (2.4)	5.6 (2.7)	9.3 (4.2)	7.1 (2.3)	6.8 (3.9)	6.2 (1.8)	3.3 (1.8)
Indoor	16.9 (1.4)	11.6 (1.7)	7.8 (1.3)	10.8 (2.5)	7.7 (2.0)	7.6 (3.6)	6.8 (1.5)	6.1 (1.2)
r	0.93	0.94	0.77	0.88	0.94	0.96	0.91	0.80

* All correlations were statistically significant ($p < 0.05$).

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Table 3

Annual and season-specific (cool vs. warm) linear regression beta coefficients (standard errors) relating the change in the average indoor value per one unit increase in the airport value, by study city*

Me asure	Ho Chi Minh City	São Paulo	Kuwait City	Atlanta	Athens	Boston	Dublin	Nuuk
Temperature (°C)								
Annual	---	0.44 (0.02)	0.08 (0.01)	0.24 (0.01)	0.44 (0.01)	0.24 (0.01)	0.42 (0.02)	0.08 (0.01)
Cool Season	0.72 (0.05)	0.41 (0.03)	0.20 (0.02)	0.11 (0.01)	0.16 (0.02)	0.13 (0.01)	0.26 (0.06)	0.08 (0.01)
Warm Season	---	0.43 (0.03)	−0.03 (0.02)	0.29 (0.01)	0.71 (0.03)	0.41 (0.02)	0.37 (0.03)	0.04 (0.02)
Apparent temperature (°C)								
Annual	---	0.55 (0.02)	0.10 (0.01)	0.27 (0.01)	0.46 (0.01)	0.31 (0.01)	0.50 (0.02)	0.11 (0.01)
Cool Season	1.2 (0.06)	0.48 (0.03)	0.23 (0.02)	0.15 (0.01)	0.21 (0.02)	0.18 (0.01)	0.32 (0.07)	0.10 (0.02)
Warm Season	---	0.54 (0.03)	−0.05 (0.02)	0.31 (0.01)	0.73 (0.02)	0.47 (0.02)	0.47 (0.03)	0.07 (0.03)
Relative humidity (%)								
Annual	---	0.38 (0.03)	0.22 (0.01)	0.27 (0.03)	0.25 (0.03)	0.47 (0.05)	0.28 (0.04)	0.29 (0.02)
Cool Season	0.64 (0.03)	0.43 (0.04)	0.33 (0.02)	0.24 (0.04)	0.30 (0.06)	0.20 (0.04)	0.22 (0.05)	0.17 (0.03)
Warm Season	---	0.33 (0.04)	0.28 (0.02)	0.24 (0.02)	0.52 (0.02)	0.18 (0.05)	0.39 (0.06)	0.26 (0.03)
Dew point (°C)								
Annual	---	0.71 (0.01)	0.32 (0.01)	0.40 (0.01)	0.77 (0.01)	0.69 (0.01)	0.68 (0.02)	0.31 (0.01)
Cool Season	0.75 (0.03)	0.72 (0.02)	0.44 (0.02)	0.32 (0.02)	0.72 (0.02)	0.41 (0.03)	0.43 (0.05)	0.30 (0.02)
Warm Season	---	0.72 (0.03)	0.20 (0.01)	0.32 (0.02)	0.66 (0.03)	0.68 (0.03)	0.71 (0.02)	0.27 (0.03)
Specific humidity (g/kg)								
Annual	---	0.70 (0.01)	0.36 (0.02)	0.51 (0.01)	0.82 (0.02)	0.86 (0.01)	0.76 (0.02)	0.54 (0.02)
Cool Season	0.77 (0.03)	0.72 (0.02)	0.57 (0.02)	0.51 (0.03)	0.79 (0.03)	0.51 (0.03)	0.49 (0.05)	0.61 (0.06)
Warm Season	---	0.68 (0.03)	0.23 (0.01)	0.33 (0.02)	0.68 (0.03)	0.81 (0.03)	0.76 (0.02)	0.38 (0.04)

* All coefficients were statistically significant ($p < 0.0001$). Three months of data (January-March) were available for Ho Chi Minh City.