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Review article

Humidity: A review and primer on atmospheric moisture and human health

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ABSTRACT

Research examining associations between weather and human health frequently includes the effects of atmospheric humidity. A large number of humidity variables have been developed for numerous purposes, but little guidance is available to health researchers regarding appropriate variable selection. We examine a suite of commonly used humidity variables and summarize both the medical and biometeorological literature on associations between humidity and human health. As an example of the importance of humidity variable selection, we correlate numerous hourly humidity variables to daily respiratory syncytial virus isolates in Singapore from 1992 to 1994. Most water-vapor mass based variables (specific humidity, absolute humidity, mixing ratio, dewpoint temperature, vapor pressure) exhibit comparable correlations. Variables that include a thermal component (relative humidity, dewpoint depression, saturation vapor pressure) exhibit strong diurnality and seasonality. Humidity variable selection must be dictated by the underlying research question. Despite being the most commonly used humidity variable, relative humidity should be used sparingly and avoided in cases when the proximity to saturation is not medically relevant. Care must be taken in averaging certain humidity variables daily or seasonally to avoid statistical biasing associated with variables that are inherently diurnal through their relationship to temperature.

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1. Introduction

The health impacts of climate, particularly temperature and humidity, have been of interest for centuries. One area of growing concern is the health effects of heat waves, especially given the likely increased frequency and intensity of extreme temperature events under human-induced climate change (Perkins et al., 2012). The mechanism by which heat impacts humans is complex, and although it is often treated as a sole product of temperature, in reality it is a result of the interactions between temperature, radiation, wind, and humidity.

Of these variables, the most debated (with respect to health outcomes) is humidity, as there is significant inconsistency in how humidity is incorporated and interpreted in human health studies.

Despite its physiological importance, humidity is rarely the explicit focus in health impact studies. Consequently, our goals are to review and summarize the recent literature on how humidity impacts human health, to define and compare a suite of commonly used humidity variables, and to provide guidance to researchers regarding humidity variable selection and implementation.

This paper is organized in the following manner. We begin by presenting an overview of how humidity is examined in the climate/environment and health literature. We then present a primer on atmospheric humidity, which is followed by a review of research that considers humidity either directly or indirectly in health outcomes. Finally, to demonstrate how humidity variable selection may influence the interpretation of the impacts of atmospheric moisture on health, we re-evaluate the analysis of a previously published study on the association between weather and respiratory syncytial virus (RSV) in Singapore. We conclude with recommendations concerning how to incorporate humidity in climate/environment and health studies.

Abbreviations and variable definitions: AT, apparent temperature; COPD, chronic obstructive pulmonary disease; DPD, dewpoint depression; e_s , saturation vapor pressure; hPa, hectopascals; Hx, humidex; LST, local standard time; q , specific humidity; q_s , saturation specific humidity; RH, relative humidity; T , air temperature; T_d , dewpoint temperature; THI, temperature–humidity index; T_w , wet bulb temperature; w , mixing ratio; w_s , saturation mixing ratio; UTC, Universal Time Coordinates; ρ_v , absolute humidity; ρ_{vs} , saturation absolute humidity

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2. Overview of humidity and human health

That the role of humidity in human health outcomes has attracted increasing attention is apparent from a broad analysis of the number of health-related publications. A PubMed search (conducted in September 2015) conducted in English incorporating the terms “humidity,” “human” or “humans,” “epidemiology,” “environment” or “environmental,” produced over 1700 citations starting in 1965 (Derrick, 1965). Over the subsequent 50 years, the number of citations has grown exponentially, covering a diverse range of human conditions. Based on our search parameters, but limiting our analysis to the 260 publications since 2013, we examined the humidity variable(s) used in each publication (Table 1) and the primary research topic(s) of each paper (Table 2).

Relative humidity was used in a significant majority (62%) of studies surveyed (Table 1). Only a small percentage of studies selected humidity variables commonly utilized by atmospheric scientists (e.g., specific humidity) or indices designed to measure heat stress that incorporate humidity (e.g., apparent temperature or energy balance models) (Jendritzky et al., 2012; Steadman, 1979) (Table 1).

Humidity is included as an environmental factor in a wide range of human health topics. The results shown in Table 2 include all topics that were cited at least twice in our search. After air quality (indoor and outdoor), there are similar frequencies across the broad groupings of thermal stress, respiratory diseases, strokes and heart attacks, vector-borne diseases, and gastro-intestinal and urinary disease.

3. Humidity variables

Atmospheric scientists use many variables to characterize atmospheric moisture based on the specific research goals and objectives. Selection of the correct variable is essential because some humidity measures can be highly correlated with other atmospheric variables, particularly temperature, making it difficult to identify the unique contribution of any single variable. The measures discussed here do not represent the full suite of atmospheric

Table 1
Frequency of citations of humidity variables from a PubMed search, 2013–present.

Humidity variable	Frequency	Relative frequency (%)
Relative humidity	163	62.0
Term not used (often “dampness” or “moisture”)	28	10.6
“Humidity”—type not specified	26	9.9
Absolute humidity	14	5.3
Humidifier (interior use)	5	1.9
Apparent temperature	5	1.9
Specific humidity	4	1.5
Heat Index	3	1.1
Dew point temperature	3	1.1
“Saturation deficit”	2	0.8
Energy balance models	2	0.8
Vegetation index	2	0.8
“Humidity index”	1	0.4
Temperature–humidity index	1	0.4
“Humidity sensation”	1	0.4
Vapor pressure	1	0.4
Wet bulb globe temperature	1	0.4
Humidex	1	0.4

263^a

^a Sample size is 260, but some studies included more than one humidity variable.

Table 2

Frequency of citations of various research topics that included humidity based on abstract information from a PubMed search, 2013–present.

Research Topic	Frequency	Relative frequency (%)
Heat-related mortality	4	1.5
Heat stress, morbidity	8	3.0
Exercise-induced stress	3	1.1
Cold-related mortality	3	1.1
ER visits	6	2.2
Hospitalizations	6	2.2
Air quality (outdoor)	21	7.8
Air quality (interior, indoors)	23	8.6
Respiratory, RSV	15	5.6
Asthma	11	4.8
Myocardial infarction, cardio-pulmonary mortality	7	2.6
Aneurysm	5	1.9
Stroke	7	2.6
Influenza	12	4.5
Pneumonia	4	1.5
Legionnaire's disease	2	0.7
Skin, ulcers	9	3.3
Malaria	12	4.5
Dengue	13	4.8
West Nile virus	4	1.5
Leishmaniasis	6	2.2
Tick-borne disease	2	0.7
“Infectious disease”	2	0.7
Gastro-intestinal, diarrhea	9	3.3
Urinary and renal, nephritis	9	3.3
Hand–foot–mouth disease	5	1.9
Ebola	3	1.2
Hemorrhagic fever	4	1.5
Typhus	3	1.1
Epitaxis	2	0.7
Suicide	3	1.2
Testicular torsion	2	0.7
All others	42	15.6

269^a

^a Sample size is 260, but some studies were tallied in more than one category.

humidity variables, but rather serve to represent a subset of those commonly used in epidemiological or environmental health research.

In the atmosphere's gaseous mixture, the amount of water vapor is small and variable. With respect to the atmospheric pressure at sea level (mean = 1013 hectopascals [hPa]), the water vapor component varies from almost zero (in extremely cold, dry climates) to 40 hPa (in some tropical locales). The *vapor pressure* (e [hPa]) is the partial pressure exerted by water vapor in this mixture.

Pressure-based units like vapor pressure are much less commonly used than mass-based measurements so several humidity variables incorporate the actual mass of moisture in the air. The density of water vapor, or *absolute humidity* (ρ_v [g m^{-3}]), is the mass of moisture per total volume of air. It is related to vapor pressure via the ideal gas law for the moist portion of the air:

$$e = \rho_v R_v T \quad (1)$$

where T is the air temperature [K] and R_v is the specific gas constant for moist air [$487 \text{ J kg}^{-1} \text{ K}^{-1}$]. Although the numerator of ρ_v is the mass of moisture, the denominator (volume) varies as a function of pressure and temperature according to the ideal gas law. For example, at sea level, an absolute humidity of 15 g m^{-3} measured at 10°C would increase to 16 g m^{-3} if the air is cooled to 0°C , thereby reducing its volume, despite a constant humidity level (i.e., no change in the actual mass of moisture). Thus, absolute humidity will exhibit some diurnal variation that is inverse with temperature.

More conservative (i.e., less inherently diurnal) measures are *specific humidity* (q [g kg⁻¹]), the mass of moisture per mass of air and *mixing ratio* (w [g kg⁻¹]), the mass of moisture per mass of dry air. Although these variables are unit-less, they are commonly expressed in parts per thousand. The denominator is in units of mass, so they are more conservative with respect to pressure and temperature changes than absolute humidity. Specific humidity and mixing ratio are related to vapor pressure as follows:

$$q = \frac{0.622e}{p - 0.378e} \times 1000 \quad (2)$$

$$w = \frac{0.622e}{p - e} \times 1000 \quad (3)$$

where p is air pressure (hPa). Water vapor accounts for only a trace amount of the total pressure (or volume) of the air, so atmospheric scientists tend to use specific humidity and mixing ratio interchangeably, as they are approximately equal.

Although these measures, to varying degrees, represent the amount of water vapor in the air, they provide no information about saturation. When air is saturated, or converted from vapor to liquid, the number of water molecules evaporating equals the number of molecules condensing, and a dynamic equilibrium is reached. The *saturation vapor pressure* (e_s [hPa]) is simply the vapor pressure of saturated air, and it can be calculated as

$$e_s = 6.108 \exp\left[\frac{17.7T}{T + 237.3}\right] \quad (4)$$

where T is air temperature (°C) and “exp” is the exponential function (e^x). Saturation vapor pressure varies *only* as a function of temperature. Thus, air at 20 °C is exponentially more difficult to saturate than air at 10 °C because it has a higher vapor pressure at saturation. As a result, the most common way to saturate air is to cool it, thereby lowering the air's saturation vapor pressure.

To non-atmospheric researchers (and the general public), the most misunderstood (and as a result, misused) moisture variable is relative humidity. *Relative humidity* (RH [%]) represents the extent to which air is saturated—it quantifies the air's *proximity to saturation*. RH is easily calculated from the previously defined variables as

$$RH = \frac{e}{e_s} \times 100 \approx \frac{w}{w_s} \times 100 \approx \frac{q}{q_s} \times 100 \approx \frac{\rho_v}{\rho_{v_s}} \times 100 \quad (5)$$

where w_s , q_s , and ρ_{v_s} are the mixing ratio, specific humidity, and absolute humidity at saturation, respectively. Although there are small differences between these ratios, they all provide quantitatively similar results. The key to understanding RH is in recognizing that the numerator depends on humidity whereas the denominator varies with air temperature. So RH can change quite markedly while the air's actual moisture content (the number of water vapor molecules) remains constant. RH is highest when the air is closest to saturation. This generally happens in the early morning and in winter—the coldest times when saturation vapor pressure is lowest. Thus, RH is both diurnal and seasonal (in climates with seasonal temperature variations). Because RH depends on both humidity and temperature, it is generally not useful in an environmental health or epidemiological context as a stand-alone humidity variable. For example, adding a relative humidity term in a generalized additive model will not account for atmospheric moisture alone because it is strongly (inversely) correlated with temperature. RH can be interpreted when it is coupled with either a thermal or moisture term, although it should be evident that other humidity variables are better designed for this purpose. Thus, RH is most useful when the researcher is interested in

questions related to saturation alone, independent of possible influences related to temperature.

When unsaturated air is cooled to saturation (at constant pressure and without changing the air's moisture content), that temperature is called the *dewpoint temperature* (T_d [°C]). Dewpoint, therefore, depends on the air's vapor pressure. Like e , w , and q , T_d is conservative with respect to temperature changes, so T_d does not vary diurnally or seasonally unless moisture is added to or removed from the air. T_d is commonly measured at meteorological stations using a dewpoint hygrometer, a device that measures the temperature at which condensation begins to occur on a mirror. T_d can also be calculated from other humidity variables via a series of equations called psychrometric formulae. Despite the name dewpoint temperature, T_d is actually a humidity variable—it is not a measure of the kinetic energy (temperature) of the air but is the temperature at which saturation occurs. It is a humidity variable in temperature units.

The relative dryness of the air can be easily assessed using the *dewpoint depression* (DPD), where

$$DPD = T - T_d \quad (6)$$

DPD is a measure of the proximity of the air to saturation at a given temperature. Because the upper limit of T_d is T , DPD cannot be negative.

The T_d definition assumes that the air's moisture content does not change as air is cooled to condensation. However, if air cools via evaporation then it reaches saturation at a higher temperature than T_d because the evaporated water moistens the air. The temperature at which air becomes saturated by evaporation at constant pressure is the *wet-bulb temperature* (T_w [°C]). Evaporation is a cooling process (heat removed from the surrounding air is used to evaporate liquid water into water vapor), so $T_w \leq T$. Like T_d , T_w is commonly measured at meteorological stations. It is calculated directly using a psychrometer—a thermometer covered with a wet cloth that is aspirated by a fan to speed up evaporation. When T_w is not measured directly, it can be approximated as (Normand, 1946):

$$T_w = T_w + 0.33(T - T_d) \quad (7)$$

Wet-bulb temperature is particularly useful in human health applications associated with heat stress, because evaporation is the primary means by which bodies cool in hot environments; thus, when T_w is high, evaporative cooling is restricted and the body core temperature may rise.

Various indices have been designed to incorporate atmospheric thermal and moisture conditions. One commonly used index, *apparent temperature* (AT [°C]), combines temperature and humidity (and occasionally wind) into a single index for the assessment of human comfort in the warm season. Although AT can be calculated in different ways (Anderson et al., 2013), here we use a parameterization developed by Kalkstein and Valimont (1986):

$$AT = -2.653 + 0.994T + 0.0153T_d^2 \quad (8)$$

where T and T_d are in °C. The *temperature–humidity index* (THI [°F]) (also known as the “discomfort index” Thom, 1959) is calculated as

$$THI = 0.4(T + T_w) + 15 \quad (9)$$

where here only, T and T_w are in degrees Fahrenheit. In the United States, the National Weather Service utilizes the “Heat Index” to express summer comfort levels. The Heat Index is based on a complex multiple regression equation that combines T and RH , but because it is so highly correlated with both AT and THI , it is not shown here.

Canada's version of a comfort index is called the *humidex* (Hx) (Masterton and Richardson, 1979) and it is calculated as

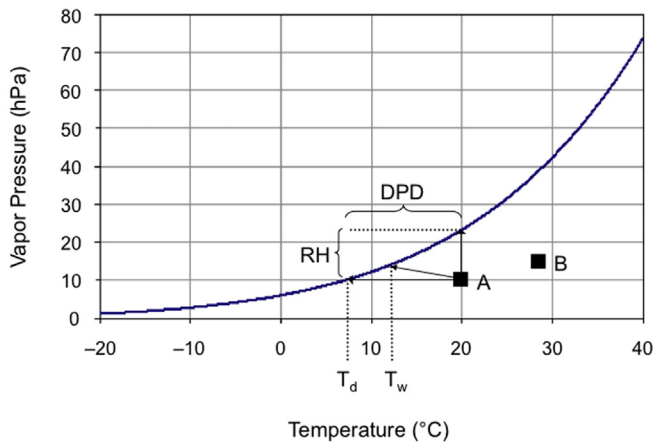


Fig. 1. Graphical depiction of various ways in which an initially unsaturated air parcel (A or B) at different temperature and humidity conditions can become saturated. Variable abbreviations are as defined in the text. See Table 3 for a complete list of all variables associated with parcels A and B.

$$Hx = T + 0.555(e - 10) \quad (10)$$

where T is in degrees Celsius and e is in hPa.

A wide variety of other physiologically based comfort indices have been developed that require additional inputs (e.g., body surface area, radiation load, area of exposed skin), but they are not listed herein. For example, the wet bulb globe temperature, which estimates physical exertion thresholds in hot environments, combines T and T_w with a radiation component (Budd, 2008). Our purpose is to focus on humidity variables specifically, and we include AT , THI , and Hx because these are commonly used and are based on temperature and humidity only.

The relationships between several of the moisture variables are demonstrated in Fig. 1. Assume the air temperature (x -axis) is 20 °C and the vapor pressure (y -axis) is 10 hPa (box A, Fig. 1). The air is unsaturated, since the saturation vapor pressure of air at 20 °C is 23.4 hPa (as indicated by intersection with the saturation curve). The ratio of these two vapor pressures (10.0/23.4) is the relative humidity, which is 42.8% (Fig. 1 and Table 3). Saturation occurs when $RH=100\%$, or when the condition of A is altered so that it reaches the saturation vapor pressure curve, and this can occur in a variety of ways. At $T=20$ °C, air can only be saturated by humidification—by adding air with a vapor pressure of 13.4 hPa, thereby raising the vapor pressure to 23.4 hPa. More commonly, saturation will occur by cooling the air to saturation while maintaining the ambient vapor pressure at 10 hPa. In this scenario, saturation will occur at 7 °C (the dewpoint temperature). The dewpoint depression is therefore 13 °C—the amount of cooling needed to achieve saturation given these initial conditions. If evaporative cooling is expected, the moisture added to the air in the process will allow for saturation to occur at a higher temperature (the wet-bulb temperature, 11.3 °C) (Fig. 1 and Table 3). If the conditions are changed to $T=28$ °C, $e=15$ hPa (box B), the air

is more humid (e is 5 hPa greater) and the RH is lower (15.0/37.8=39.7%, Table 1). This reflects the exponential relationship between saturation vapor pressure and temperature (i.e., in going from A to B, the denominator in RH (e_s) increased more than the numerator (e)). Note that vapor pressure, the ordinate in Fig. 1, could be replaced by specific humidity or mixing ratio without altering these basic principles.

4. Literature review

The medical literature that includes humidity is vast and wide ranging. Space limitations restrict the extent to which we can comprehensively summarize this topic, so we have chosen to emphasize the main research areas identified in Table 2. For each topic, the specific studies we cite are representative of recent research on the role of humidity in health outcomes from both theoretical and empirical perspectives, as well as the possible influence of humidity as a direct or indirect trigger for a number of diseases.

4.1. Humidity and all-cause mortality and morbidity

Conceptually, humidity is linked with anomalous mortality and morbidity levels through its role in affecting heat stress and hydration state. During excessive heat, the body is under considerable duress from a range of heat-stress related physiological reactions (Parsons, 2003). The skin surface loses heat to its surroundings through convection (heat carried away from warm skin via buoyant air currents), long-wave radiation exchange (heat loss from the warm skin to colder air), and evaporation of moisture from the skin surface. These processes are most efficient when strong temperature and humidity gradients are present between the skin surface and the surrounding air. However, in extreme conditions when air temperature is greater than skin temperature, the body can no longer cool via direct heat exchange with the environment—in fact, the opposite can occur. Accordingly, the only mechanism for shedding heat is evaporation, the rate of which depends upon a strong skin–atmosphere humidity gradient. When cooling processes are insufficient, the body core temperature will rise and a range of adverse health outcomes may result. In increasing severity, these are heat rash, heat oedema, heat syncope, heat cramps, heat exhaustion, and heat stroke, the latter of which can be fatal. Increasing dehydration and body core temperature can also exert strain on the cardiovascular system, exacerbating existing heart-related disease. Renal disease and premature death may also result from dehydration.

Although the environmental epidemiology literature is replete with studies linking heat and health that recognize the importance of atmospheric humidity, an explicit humidity variable is rarely incorporated in the research despite its potential direct physiological importance. More often, humidity is treated as a confounding variable that may be related to both the predictor and response variables (Barnett and Tong, 2010; Zhang et al., 2014). This

Table 3
Variables associated with examples A and B in Fig. 1

	T^a	e	e_s	ρ_v	ρ_{vs}	q	q_s	w	w_s	RH	T_w	T_d	DPD	AT	THI	Hx
A	20	10	23.4	7.0	16.2	6.2	14.5	6.1	14.7	42.8	11.3	7	13	17	65	20
B	28	15	37.8	10.2	25.0	9.3	23.5	9.2	24.1	39.7	17.3	12	16	26	75	31

Abbreviations: T , air temperature (°C); e , vapor pressure (hPa); e_s , saturation vapor pressure (hPa); ρ_v , absolute humidity (kg m^{-3}); ρ_{vs} , saturation absolute humidity (kg m^{-3}); q , specific humidity (g kg^{-1}); q_s , saturation specific humidity (g kg^{-1}); w , mixing ratio (g kg^{-1}); w_s , saturation mixing ratio (g kg^{-1}); RH , relative humidity (%); T_w , wet bulb temperature (°C); T_d , dewpoint temperature (°C); DPD , dewpoint depression (°C); AT , apparent temperature (°C); THI , temperature–humidity index (°F); Hx , humidex (°C).

^a Constant sea-level pressure is assumed for all calculations.

approach is a part of the analysis strategy in numerous studies (Cao et al., 2009; Goggins et al., 2012; Guo et al., 2012; Lim et al., 2013; Liu et al., 2011; Vaneckova and Bambrick, 2013; Wang et al., 2009), although this list is certainly not exhaustive. Alternate approaches incorporate humidity in biometeorological indices (such as *AT* or *Hx*) or include it as an input variable in human heat balance models. The extremely common use of *RH* in most climate and health studies (Table 2) is particularly troubling given the confounding influence of temperature, which inherently introduces a number of interpretation problems. This diversity of approaches is emblematic of the difficulty in using atmospheric humidity as an exposure variable in environmental epidemiological research.

In studies that use empirical biometeorological indices such as *Hx* and *AT*, it is difficult to ascertain the unique influence of humidity on health. For example, although increased risk ratios of daily mortality were observed when daily mean *Hx* values were at and above the 95th percentile for a number of cities in Taiwan (Sung et al., 2013), it is unclear whether the humidity or temperature component (or their joint interaction) was driving this association. Others (Fink et al., 2012; Hartz et al., 2012) reported that *Hx* was a better indicator of health impacts than maximum temperature, presumably because of value added by the inclusion of humidity. In a number of studies that used *AT* as the exposure variable, in the United States (Hondula et al., 2012), Taiwan (Lin et al., 2012), Portugal (Almeida et al., 2010), and Denmark (Wichmann et al., 2012), there was little comment on the possible independent role of humidity or the synergistic effects of temperature and humidity—rather, humidity's influence was inferred via its link to temperature. In contrast, on days with high temperatures, high relative humidity increased cardiovascular and respiratory disease admissions in New York (Lin et al., 2009). Similarly, increasing specific humidity was also found to be more dangerous at high temperatures (Barreca, 2012). These results contrast with those for Australia (Vaneckova et al., 2011) and the United States (Barnett and Tong, 2010), where humidity was found to have little to no added effect on temperature-related health outcomes. Montero et al. (2012) suggested temperature and humidity associations should be analyzed separately, acknowledging that humidity may display negative and positive relationships with mortality for hot-dry and warm-humid climate settings, respectively. Clearly the lack of consistency in the selection and application of humidity variables has limited the interpretation of these results.

Some studies have found regional variations in humidity mortality associations. The impact of *RH* on elderly mortality in Sweden varies by region (Rocklöv and Forsberg, 2010). Humidity plays a more noticeable role in increasing mortality in “cold compared to warm counties” in the United States, suggesting that adaptation may be important in moderating the climate and health relationship (Barreca, 2012). The lack of any humidity effects in Brisbane, Australia (Vaneckova et al., 2011) may be related to acclimatization or adaptation of the population to the warm humid climate there.

Synoptic climatological analyses have been used to explore the association between a range of air mass or weather types (nominal classifications of a large number of weather variables) and health outcomes. For example, in Shanghai, high mortality was associated with an extreme maritime tropical (warm and moist) air mass type characterized by exceptionally hot, humid, and cloudy conditions (Tan et al., 2004). Similarly, increased mortality in Philadelphia was associated with maritime tropical air (Kalkstein et al., 1996). In Sydney, Australia, elevated summer mortality levels were associated with both hot-dry and warm-moist air mass types, indicating that humidity extremes at both ends of the atmospheric moisture spectrum may be important (Vaneckova et al., 2008).

Based on findings for California (Sheridan et al., 2012), there appear to be similar air mass type–health associations to those for Sydney. For areas of central Spain, hot, dry air transported over the Iberian Peninsula from northern Africa was extremely important for acute summer mortality events (Montero et al., 2012); low humidity and presumably dehydration was a contributory factor. It is important to note, however, that these air-mass based approaches do not readily allow for the specific examination of humidity effects on health; rather, they suggest dual effects of humidity that are weather-situation dependent.

4.2. Humidity and cardiovascular disease

Cardiovascular disease is often emphasized in climate and health studies because of the potential impacts on cardiac function from high body core temperatures and low hydration levels, both of which can be related to the atmospheric moisture state and increased cardiac function or work (Bouchama and Knochel, 2002). Despite this, no studies have convincingly related atmospheric humidity variations to cardiovascular disease. No association was found between relative humidity and daily hemorrhagic and ischemic stroke counts in Hong Kong (Goggins et al., 2012). Similarly for western Sicily, a mixed relationship was seen between *RH* and angina admissions (Abrignani et al., 2012). A study of elderly patients in 12 U.S. cities found a positive relationship between temperature and hospital admissions for both heart disease and myocardial infarction, but no humidity effect (Schwartz et al., 2004). Conversely, Yang et al. (2013) found a positive association between relative humidity and hypertensive uropathy. Overall, these conflicting results suggest potential confounding for disease process as well as for meteorological variables. Notably, these studies utilized *RH* averaged over a number of lead times, which likely influenced the conclusions and complicated interpretations.

4.3. Humidity and pulmonary disease

Given the continuous exposure of the human respiratory system to the environment, linkage with acute and chronic respiratory illness is biologically plausible. Humidity has been tied to both infectious and non-infectious pulmonary disease. Respiratory viruses, with their seasonal variation in many environments, provide a key example. Higher barometric pressure, more hours of sunshine, and lower humidity in winter were associated with an increase in chronic obstructive pulmonary disease (COPD) exacerbations in Taiwan (Tseng et al., 2013), implying that warm and dry high pressure systems were associated with COPD anomalies. In contrast, Hapcıoğlu et al. (2006) found no relationship between humidity and COPD exacerbations in Istanbul. A study in Trinidad (Ivey et al., 2003) supported the contention that in warm, wet climates, incidence of asthma increased with higher relative humidity in the wet season (May–December). Conversely, a Japanese study demonstrated an association between low relative humidity and hospital admissions for paediatric asthma admissions. Indirect effects of humidity on respiratory disease include the role of moist indoor environments in promoting the growth of mold and the reproduction of mites (Hayes et al., 2013; Richardson et al., 2005; Williamson et al., 1997) and the effects of humidity on pollen dispersal and pollen-related allergens (Bartkova-Scevkova, 2003). In a series of controlled climate chamber studies on exercise performance (Eschenbacher et al., 1992), asthma patients exhibited significantly greater bronchoconstriction after exercise than non-asthmatic subjects as *RH* decreased.

The role of atmospheric moisture in the occurrence of influenza has received increasing attention. The dynamics of this were developed in an animal model in which three regimes of influenza A

virus viability in droplets were identified, as defined by humidity level (Yang et al., 2012). For the United States, absolute humidity was identified as a critical determinant of observed influenza mortality (Barreca and Shimshack, 2012) and anomalously low humidity levels were found to precede the onset of increased wintertime influenza-related mortality in the United States by several weeks (Davis et al., 2012; Shaman et al., 2010). The respiratory impact of low atmospheric humidity was evident in other studies in Belgium (Lander et al., 2012), China (Xiao et al., 2013), Japan (Harata et al., 2004), Israel (Yaari et al., 2010), the Netherlands and Portugal (van Noort et al., 2012), and was inferred in forensic studies of major historical influenza outbreaks in England and Wales (He et al., 2013). Yet in studies that utilized relative humidity, Zhang et al. (2013) found a negative association between RSV and Rodriguez-Martinez et al. (2015) uncovered no relationship. Factors linking low humidity and respiratory viral disease are likely multifactorial, including impacts on virus stability and viability, host susceptibility, and human behavior (e.g., Eccles, 2002; Lofgren et al., 2007; Tamerius et al., 2011).

When climate type or region is considered, there appears to be emerging evidence of a geographical variation in influenza associations with atmospheric moisture. In temperate climates with clear seasonal temperature variations, cold-dry air may enhance airborne influenza virus transmission via prolonged virus survival, whereas in tropical and subtropical climates that have minimal temperature variation, direct contact transmission may be enhanced via indoor crowding during humid-rainy conditions in the wet season (Tamerius et al., 2013). Overall, there is increasing evidence of a humidity linkage to respiratory viruses when the appropriate humidity variable is selected.

4.4. Humidity and zoonotic disease

Humidity is a critical factor in the survival for arthropod disease vectors such as mosquitos and ticks and the development and thus transmission of associated pathogens. Much of the research in zoonotic or vector borne disease has used relative humidity in describing associations between disease and climate. The impact can be either in influencing the vector of disease (e.g. mosquito) or parasite development (e.g. *Plasmodium falciparum*). While most of this research has focused on temperature and rainfall (Gage et al., 2008), several studies (Sena et al. 2015; Zacarias and Majlender, 2011) showed a positive association between increases in malaria and relative humidity, which is often positively correlated with precipitation. A similar association has been seen in zoonotic cutaneous leishmaniasis. Toumi et al. (2012) determined that for each 1% increase in relative humidity above 57.8% there was a 5% increase in disease.

4.5. Humidity and gastrointestinal and urologic illness

Ambient humidity has been associated with infectious enteritis. Studies in Japan, Taiwan, and Peru showed negative relationships between relative humidity and infectious gastroenteritis (Checkley et al., 2000; Chou et al., 2010; Onozuka and Hashizume, 2011). Similar relationships have been uncovered for rotavirus in Australia (D'Souza et al., 2008). The reasons for this are likely similar to those for respiratory virus, that environmental conditions influence virus survival. Urolithiasis (kidney stones) has also been linked (inversely) to relative humidity in a few studies (Lin et al., 2014; Mohit et al., 2014).

4.6. Air quality

Air pollution, along with heat, constitutes an important atmospheric stressor on human health. There is ample evidence in the

literature that a range of atmospheric pollutants have clear acute and chronic impacts on health, with the health effects possibly dependent on the pollutant constituents (Cohen et al., 2005). Diseases such as asthma, rhinosinusitis, COPD and respiratory tract infections, lung cancer and cardiopulmonary problems appear to be the most susceptible to poor air quality (American Thoracic Society, 2000; Cohen et al., 2005; De Sario et al., 2013).

Of the range of atmospheric pollutants, particulate matter—especially PM_{2.5} (particulate matter 2.5 microns diameter or less)—has the most serious effects on health (Atkinson et al., 2015; Cohen et al., 2005; Franck et al., 2011; Fuzzi et al., 2015; Jones et al., 2015), although it is acknowledged that the association between particulate matter and health is complex and wrought with a number of toxicological puzzles (Maynard, 2015). An important constituent of the PM_{2.5} mix is organic aerosol (OA). OA is formed via complex interactions between volatile organic compounds (VOCs) emitted from both natural and anthropogenic sources. Humidity plays an important but complex role in the formation of OA (Li et al., 2015; Mehta et al., 2013) as demonstrated by laboratory- and field-based studies. For example, using a laboratory-based experimental setting, Li et al. (2015), Carlton et al. (2009), and Jia and Xu (2014) highlighted the role of elevated humidity levels in enhancing aerosol formation. Results from a number of field studies have confirmed this. For example, Gao et al. (2015) revealed for Beijing that the size of aerosol particles increases by moisture absorption under high humidity conditions; Markowicz and Larsson (2015) demonstrated rapid increases in indoor VOC concentrations (a precursor of OA) with rises in room humidity; but Wolkoff and Kjaergaard (2007) contended that low relative humidity may directly influence worker health rather than impact it via relationships with poor indoor air quality.

Notwithstanding the vast literature on aerosol formation (Fuzzi et al., 2015) and the wide appreciation of the impacts of air pollutant on health, the number of papers that address whether humidity acts in a synergistic way with air pollution to engender distinct morbidity and mortality responses, or modifies the air pollution health relationship, is sparse. In fact, disentangling the complex relations between weather, air pollution, and health remains a challenge (Zanobetti and Peters, 2015). Despite the meager literature on air pollution–humidity interactions, some interesting results are emerging. For example, Leitte et al. (2009) have shown that the effect of total suspended particles on COPD hospitalizations may increase under low humidity conditions. This supports the results from an earlier extensive study of weather, air pollution, and health relationships for 29 European cities demonstrating that humidity is a significant effect modifier of the PM₁₀ mortality relationship such that as humidity levels decreased the effect of PM₁₀ on mortality increases (Katsouyanni et al., 2001). Non-linear effects of humidity in combination with other variables, including atmospheric pollutants, have also been demonstrated (Hajat et al., 2004; Wanka et al., 2014). McGregor et al. (1999), in considering the relation between air mass physical properties, pollution, and respiratory admissions, pointed to the possible dual role of humidity levels in engendering respiratory morbidity. In an interesting variation on the interactions between humidity and indoor air quality, Giaconia et al. (2013) outlined the role that humidity along with air quality play in determining air passenger comfort. Further, with respect to humidity's influence on the deposition of cigarette smoke derivatives via hygroscopic aerosols in the upper respiratory tract, Xi et al. (2013) showed that the deposition of fine particulate matter is 5–10 times than that of inert particles under high humidity conditions.

There is also some evidence that humidity may modify the health effects of aeroallergens. For example, D'Amato and Cecchi (2008) have shown that low humidity favors the release, dispersion, and transport of pollen with a consequent rise in allergic effects. In

Table 4

Pearson's correlations between all independent variables at (A) 0700 and (B) 1300 local time in Singapore.

(A) ^a	<i>T</i>	<i>T_d</i>	<i>DPD</i>	<i>e_s</i>	<i>e</i>	ρ_v	<i>RH</i>	<i>q</i>	<i>w</i>	<i>T_w</i>	<i>AT</i>	<i>THI</i>
<i>T</i>												
<i>T_d</i>	0.70											
<i>DPD</i>	0.60	0.16										
<i>e_s</i>	1.00	0.69	0.61									
<i>e</i>	0.70	1.00	−0.16	0.69								
ρ_v	0.66	1.00	−0.21	0.65	1.00							
<i>RH</i>	−0.59	0.17	−1.00	−0.60	0.17	0.22						
<i>q</i>	0.69	1.00	−0.16	0.68	1.00	1.00	0.17					
<i>w</i>	0.69	1.00	−0.15	0.69	1.00	1.00	0.16	1.00				
<i>T_w</i>	0.87	0.96	0.13	0.87	0.96	0.94	−0.12	0.95	0.96			
<i>AT</i>	0.96	0.87	0.34	0.96	0.87	0.85	−0.33	0.87	0.88	0.98		
<i>THI</i>	0.97	0.84	0.41	0.97	0.84	0.81	−0.40	0.83	0.84	0.96	1.00	
<i>Hx</i>	0.94	0.90	0.29	0.94	0.90	0.88	−0.28	0.90	0.90	0.99	1.00	0.99
(B)	<i>T</i>	<i>T_d</i>	<i>DPD</i>	<i>e_s</i>	<i>e</i>	ρ_v	<i>RH</i>	<i>q</i>	<i>w</i>	<i>T_w</i>	<i>AT</i>	<i>THI</i>
<i>T</i>												
<i>T_d</i>	0.20											
<i>DPD</i>	0.84	−0.36										
<i>e_s</i>	1.0	0.20	0.84									
<i>e</i>	0.21	1.00	−0.35	0.21								
ρ_v	0.12	1.00	−0.44	0.12	1.00							
<i>RH</i>	−0.85	0.34	−1.00	−0.84	0.33	0.42						
<i>q</i>	0.26	1.00	−0.28	0.26	1.00	0.99	0.26					
<i>w</i>	0.26	1.00	−0.28	0.26	1.00	0.99	0.26	1.00				
<i>T_w</i>	0.73	0.82	0.24	0.73	0.82	0.76	−0.26	0.82	0.82			
<i>AT</i>	0.99	0.54	0.59	0.93	0.55	0.47	−0.61	0.57	0.57	0.92		
<i>THI</i>	0.97	0.45	0.67	0.96	0.46	0.37	−0.69	0.49	0.88	0.99	0.99	
<i>Hx</i>	0.89	0.62	0.51	0.89	0.63	0.55	−0.52	0.64	0.65	0.96	1.00	0.98

Abbreviations: *T*, air temperature (°C); *e*, vapor pressure (hPa); *e_s*, saturation vapor pressure (hPa); ρ_v , absolute humidity (kg m^{−3}); ρ_{vs} , saturation absolute humidity (kg m^{−3}); *q*, specific humidity (g kg^{−1}); *q_s*, saturation specific humidity (g kg^{−1}); *w*, mixing ratio (g kg^{−1}); *w_s*, saturation mixing ratio (g kg^{−1}); *RH*, relative humidity (%); *T_w*, wet bulb temperature (°C); *T_d*, dewpoint temperature (°C); *DPD*, dewpoint depression (°C); *AT*, apparent temperature (°C); *THI*, temperature–humidity index (°F); *Hx*, humidex (°C).

^a All correlations are statistically significant ($\alpha \leq 0.01$). The period of record is January 1, 1992 through September 24, 1994 and the maximum sample size is 979 days.

contrast, a build-up in atmospheric moisture, often leading to thunderstorm formation, may cause short-term increases in asthma epidemics through the release of allergens caused by pollen grain rupture via osmotic shock (D'Amato et al., 2013; Zhang et al., 2015).

4.7. Indoor vs. outdoor humidity

It is quite common to use weather observations from standard, outdoor weather observation networks as the independent variables in environmental epidemiological studies. These data are usually collected from regionally representative weather stations that are often located at airports. A topic of interest is whether these outdoor measurements are representative of the true exposure of individuals, particularly given that the susceptible population is often elderly individuals who spend much more time indoors (Hoppe and Martinac, 1998; Loughnan et al., 2015; Quinn et al., 2014). Most of the relevant literature has examined temperature rather than humidity (e.g., Iddon et al., 2015; Lomas and Giridharan, 2012), although a few studies have incorporated a humidity comparison. In an evaluation of 285 low- and middle-income homes in New York City, Quinn et al. (2014) found a strong relationship between hourly internal and external dewpoint temperature, with indoor dewpoint increasing by 0.66 °C for every 1 °C increase in outdoor dewpoint. A study in Boston found a strong year-round correlation between indoor and outdoor absolute humidity but a much weaker relationship with relative humidity. These admittedly limited studies suggest that mass-based humidity variables provide a better measure of exposure to different humidity levels than the more commonly-used relative humidity variable. Given this, researchers need to not only take into account the 'best' measure of humidity in terms of the posited

research question, but should also consider the representativeness of the humidity variable for their study environment.

5. A worked example

5.1. Methods

To demonstrate the importance of humidity variable selection in epidemiological research, we re-evaluate the analysis of Chew et al. (1998), who found a statistically significant inverse relationship between the frequency of daily isolates of respiratory syncytial virus (RSV) and daily *RH* in Singapore from 1990 to 1994 (Fig. 2c in Chew et al. (1998)). These data represent laboratory analyses of RSV isolates acquired from two large general hospitals in Singapore, most of which (71%) were acquired from inpatient admissions. Our purpose here is not to study the relationship between humidity and RSV but to simply use these data, which were kindly provided to us by Dr. F.T. Chew, as an example of how humidity variable selection and treatment can influence the conclusions in an epidemiological analysis.

Hourly meteorological data were acquired from Changi Airport, Singapore, from 1992 to 1994. These data included *T*, *T_d*, and surface pressure, from which all other humidity variables were calculated using Eqs. (1)–(10). To examine the diurnal aspects of humidity, we acquired weather data at 0700 Local Standard Time (LST) and 1300 LST, corresponding to 2300 Universal Time Coordinates (UTC) and 0500 UTC, respectively. We identified the observation closest to that time, but in the few cases with missing data, observations up to one hour earlier or later were used—otherwise, that day was coded as missing for that variable.

The analysis consists of contemporary (non-lagged) Pearson's correlation between humidity variables as well as between each humidity variable and one-day lagged daily RSV counts with statistical significance based on a Type I error rate of 0.01. Although lagging and smoothing are often useful in epidemiological research, our purpose here is to compare the various humidity measures, not to identify the strongest statistical relationship to RSV isolates, so we did not manipulate the raw hourly observations. We employed a one-day lag with RSV to eliminate the possibility of the response variable preceding that putative effect; however, the non-lagged results were quite comparable because of the temporal autocorrelation inherent in the weather variables.

5.2. Results

Correlations between the various humidity variables for 0700 and 1300 LST are shown in Table 4. The correlations are so high between dewpoint temperature, vapor pressure, absolute humidity, specific humidity, and mixing ratio that these variables are virtually interchangeable. This is true independent of time of day. These variables are essentially slightly different representations of the mass of water vapor in a given sample of air, and as such they are effectively measuring the same humidity characteristic.

Relative humidity is only highly (inversely) correlated with dew-point depression. This is expected, as RH is calculated from e and e_s , which are derived from T_d and T , respectively. Thus, RH has weak negative correlations with the thermally based variables (T , e_s , T_w) and weak positive correlations with the mass-based humidity variables (T_d , q , and w).

The various comfort indices (AT , THI , and Hx) are nearly identical and are highly correlated with temperature, because temperature influences these variables much more than humidity. These indices are particularly highly correlated with wet-bulb temperature—a logical relationship given that the comfort indices were developed to account for the body's ability to cool under high thermal stress, the primary means of which is via evaporative cooling, as dictated by T_w .

Temperature has high positive correlations with every variable (except RH) in the morning, but many of the relationships are much weaker in the afternoon. In a humid, tropical climate like Singapore's (and in many other, non-tropical locations), T approaches T_d in the evening and early morning, often resulting in dew formation via condensation. Since T_d varies little diurnally, T_d is often close to the morning minimum temperature and effectively limits how low T can drop overnight. However, there is no similar upper limit to T in the afternoon, so afternoon temperatures rise without a corresponding increase in atmospheric water vapor content. The correlation between T and mass-based variables such as T_d , q , and w is still positive at the warmest time of day, but the relationship is much weaker than in the morning. Conversely, RH is now more strongly (inversely) related to T , demonstrating the clear dependence (and inherent diurnality) of RH .

The correlations between daily RSV isolates in Singapore and each humidity variable are shown in Fig. 2. At 0700 LST, there is essentially no difference between any of the mass-based measures, all of which exhibit similar, positive relationships to RSV counts. The relationship to the two thermal variables is lower, and the correlation with RH is almost zero. These results suggest that RSV is more related to the mass of water vapor in the air than it is to temperature or the proximity of the air to saturation. At 1300 LST, however, the overall relationships are somewhat weaker, although the mass-based variables are still most highly correlated. At this time of day, T_w and the comfort indices (AT , THI , and Hx) begin to separate from the moisture mass variables, and the thermal variables and RH/DPD exhibit very low (non-significant) correlations. Comparison of Fig. 2a and b clearly demonstrates how time of day can influence those humidity

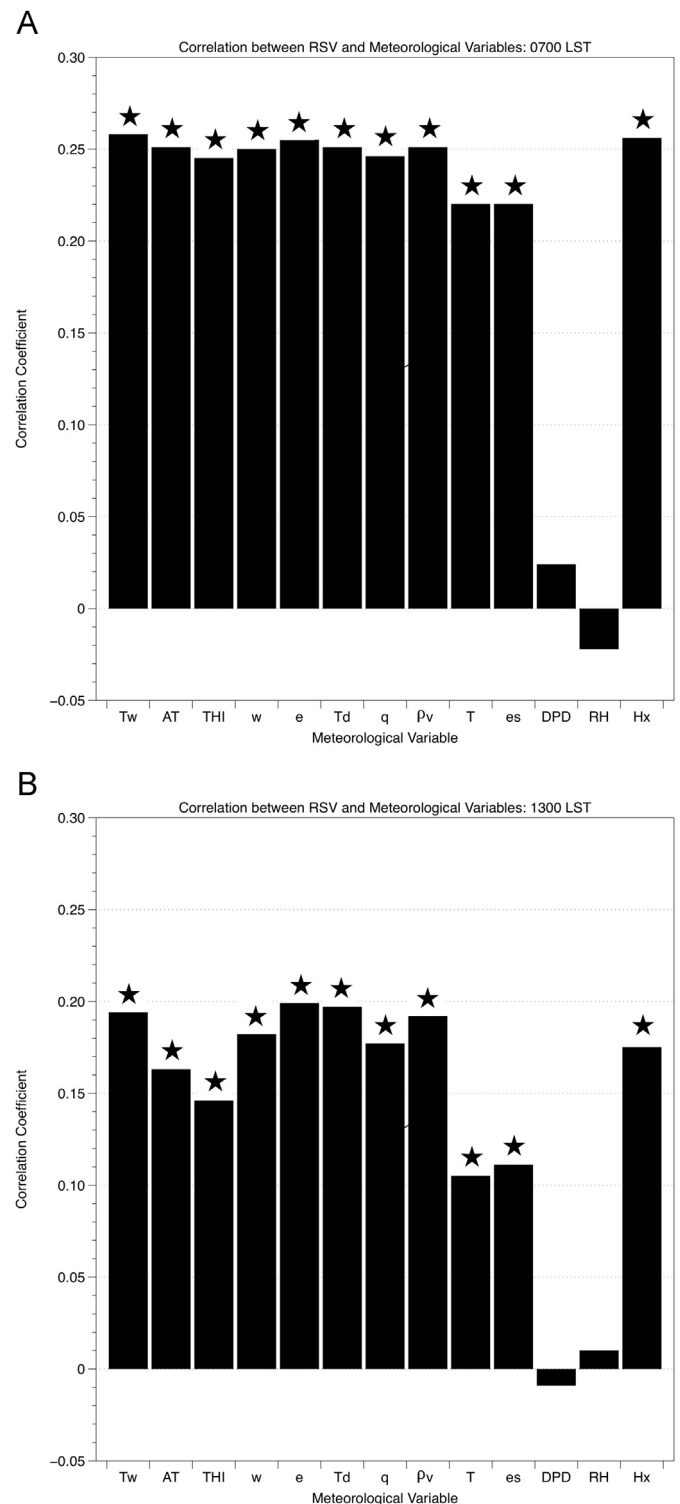


Fig. 2. Linear correlation between respiratory syncytial virus isolates and various meteorological variables in Singapore at (A) 0700 LST and (B) 1300 LST. Statistically significant correlations ($\alpha \leq 0.01$) are indicated by a star. Weather variable abbreviations are listed in the text and Table 3.

variables that are not conservative over a 24-h period via their relationship to temperature.

6. Discussion and conclusions

From the perspective of an epidemiologist or environmental

Table 5
Humidity variable groupings and suggested epidemiological applications.

Variable group	Applications	Cautions	Example condition
<i>Mass-based variables</i>			
Absolute humidity	Most studies concerned with the amount of atmospheric moisture; e.g., respiratory processes, exposure to ambient environment, micro-organism survival	Some residual correlation with air temperature exists	Infectious disease
Dewpoint temperature			Pulmonary disease
Mixing ratio			
Specific humidity			
Vapor pressure			
<i>Relative variables</i>			
Dewpoint depression	Proximity to saturation; dampness, mold	Highly inversely correlated with temperature; vary diurnally and (often) seasonally	Avoid
Relative humidity			
<i>Comfort indices</i>			
Apparent temperature	Human comfort in warm environments related to evaporative cooling	Applicable only in warm conditions; not possible to examine humidity effect independent of temperature	Sudden cardiac death
Temperature–humidity index			Exposure-related research
Humidex			
Wet-bulb temperature			

health professional, atmospheric scientists use a dismaying array of variables to characterize atmospheric humidity. These various measures are designed for specific purposes, so a researcher's variable choice should be dictated by how humidity is fundamentally related to the process or condition of interest. In cases when the air's actual moisture content is important, any of the mass-based variables (vapor pressure, mixing ratio, specific humidity, absolute humidity) can be used interchangeably given their very high inter-correlation (Table 5). If the research question is based upon the degree of saturation, then relative humidity or dew-point depression are appropriate, but their dependence on time of the day or changing weather situations should be acknowledged. If human comfort in hot environments is the primary focus, then wet-bulb temperature or a comfort index, such as apparent temperature, are best.

Although relative humidity is the most commonly used moisture variable in epidemiological and environmental health research, in many cases it is inappropriate and it should always be used with caution. Because relative humidity varies as a function of both water vapor content and air temperature, one cannot make inferences about how either relates to the dependent variable. Furthermore, relative humidity varies diurnally and (often) seasonally, and the use of mean relative humidity does not necessarily represent average moisture content of the air, since temperature diurnality and seasonality are also variable. These complexities associated with relative humidity may account for some of the contradictions in the epidemiological literature regarding how humidity influences health outcomes (Barnett et al., 2010; Gao et al., 2014; Zhang et al., 2014).

Based upon our review of atmospheric moisture variables and their intercorrelations, and the related climate and health literature, we make the following recommendations. First, the humidity variable should be selected based on whether the primary medical consideration is (a) atmospheric moisture content (e.g., specific humidity), (b) proximity to saturation (e.g., relative humidity), or (c) thermal stress (e.g., apparent temperature). Second, it is more informative to use a humidity variable for a specific time or

multiple times of day (when available) rather than a daily mean. This is especially true in middle to high latitude locations where there can be large diurnal and seasonal variations in humidity associated with frontal passages and air mass changes. Although maximum and minimum values are preferable to a daily mean, in many cases it is difficult to identify the time of day when these observations occur, particularly where frontal passages—and thus significant short-term humidity changes—are commonplace. Lastly, although inter-humidity variable correlations will be site-specific, as shown here for Singapore, the fundamental relationships between the humidity variables are generic and will be present and consistent regardless of location.

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This research was undertaken without the use of grant-related funding support. As our research only involved the retrospective examination of de-identified summary data, no human or animal subjects were involved in the conduct of this research nor was IRB approval required.

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