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Biometeorology for cities

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Abstract Improvements in global sustainability, health, and equity will largely be determined by the extent to which cities are able to become more efficient, hospitable, and productive places. The development and evolution of urban areas has a significant impact on local and regional weather and climate, which subsequently affect people and other organisms that live in and near cities. Biometeorologists, researchers who study the impact of weather and climate on living creatures, are well positioned to help evaluate and anticipate the consequences of urbanization on the biosphere. Motivated by the 60th anniversary of the International Society of Biometeorology, we reviewed articles published in the Society's *International Journal of Biometeorology* over the period 1974–2017 to understand if and how biometeorologists have directed attention to urban areas. We found that interest in urban areas has rapidly accelerated; urban-oriented articles accounted for more than 20% of all articles published in the journal in the most recent decade. Urban-focused articles in the journal span five themes: measuring urban climate, theoretical foundations and models, human thermal comfort, human morbidity and mortality, and ecosystem impacts. Within these themes, articles published in the journal represent a sizeable share of the total academic literature. More explicit attention from urban biometeorologists publishing in the journal to low- and middle-income countries, indoor environments, animals, and the impacts of climate change on human health would help ensure that the distinctive perspectives of biometeorology reach the places, people, and processes that are the foci of global sustainability, health, and equity goals.

Keywords Urban · Climate · Weather · Ecology · Health · Comfort

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Introduction

Cities have emerged as a key focus area for biometeorological inquiry over the past 60 years. The interest in cities among biometeorologists, along with scientists from related disciplines with an interest in the intersection of weather, climate, people, and ecosystems, is valuable at a time when urban areas—and their societal and environmental impacts—are growing at a rapid pace (Seto et al. 2011). Improvements in global sustainability, health, and equity, such as those envisioned in the United Nations' Sustainable Development Goals, will largely be determined by the extent to which cities are able to become more efficient, hospitable, and productive places. This manuscript summarizes the role of the biometeorology community in pursuing such improvements, as documented in the *International Journal of Biometeorology* (*IJB*).

The International Society of Biometeorology defines biometeorology as an interdisciplinary science that considers how weather and climate impact the well-being of all living creatures (Gosling et al. 2014). Extending this definition to the context of cities, biometeorologists are equipped to ask two different questions. First, how do weather and climate impact the well-being of living creatures in urban environments? More narrowly, biometeorologists might ask how cities modify weather and climate, and what are the subsequent impacts of those changes on the well-being of all living creatures? Answers to both questions can create biometeorological knowledge *for* cities (analogizing Childers et al. 2015). The first question might be considered the study of biometeorology *in* cities, while the latter represents a more holistic study of the biometeorology *of* cities. Researchers examining the second question are not only examining the impacts of weather and climate on people and ecosystems in urban areas but also intentionally examining how the city itself directly and indirectly modifies weather and climate and the subsequent impacts of those modifications on the well-being of all living creatures.

The 60th anniversary of *IJB* provides an opportunity to reflect on the contributions that the biometeorology community has made to the study of cities and the interactions between weather, climate, people, and ecosystems therein. We conducted a review of articles published in the society's journal to understand the extent to which urban biometeorological research has been conducted *in* or *of* cities. We also sought to characterize urban biometeorological research in *IJB* by major themes, common methodologies, emerging trends, and geographical areas of study and contextualize the scholarship published in *IJB* to the scientific literature more broadly. By examining this literature and its dominant themes and methodological contributions, we intend to provide recommendations for future biometeorological inquiry that can help cities around the world pursue and achieve continuing improvements with respect to sustainability and health.

Materials and methods

We used Web of Science to search for articles published in the electronically accessible history of *IJB* (January 1974–February 2017, inclusive) that contained the terms "urban," "city," or "cities" in the title or keywords. The initial search returned 324 articles, of which the abstracts were subsequently randomly assigned to and screened by several authors of this manuscript. Papers were eligible to be included in the review if they met any one of the following criteria: (1) they were related to observations of weather and climate in urban areas, (2) they were related to models and indices used for bridging urban weather and climate and physiological processes, (3) they were related to understanding the impacts of weather and climate on human thermal comfort, (4) they were related to understanding the impacts of weather and climate on morbidity and mortality, or (5) they were related to understanding the impacts of weather and climate on ecosystems in cities. These themes emerged iteratively as authors reviewed titles and abstracts. After the articles were initially tagged as matching one or more of the five themes, a second author also evaluated the suitability of articles within each theme for inclusion. In total, 216 articles were reviewed. We then used bibliometric data available from Web of Science including keywords, titles, and abstracts, as well as the manuscripts themselves, to identify patterns and trends within each theme.

To provide additional perspective on the placement and significance of *IJB* in the broader academic literature concerning urban biometeorology, we conducted an additional series of Web of Science searches. First, we searched for all articles published over the same time period as described above that met the first search criteria and included the keyword "biometeorology," to assess the extent to which *IJB* accounts for publications on the theme of urban biometeorology. Then, we identified the five most common keywords from the *IJB* articles identified within each of the five themes of our review and conducted a search for articles including those keywords. We sorted the initial search returns (which often contained more than one million articles) by the Web of Science Relevance option. Web of Science determines article relevance based on the degree to which search terms (in this case, five keywords) appear in article titles, abstracts, and keywords (Thomson Reuters 2012). We extracted the 500 most relevant articles within each theme for subsequent review of citation counts and source titles. We then assessed the frequency with which *IJB* was represented among all 500 articles and among the 25 most highly cited articles within each theme.

Results

Urban biometeorology has accounted for an increasingly large share of articles published in *IJB* over the past four decades (Fig. 1). Over the period 1974–1983, less than 3% of all *IJB* articles met the review criteria. In contrast, over the most recent decade, more than 20% of articles have been on the topic of urban biometeorology. Review of keywords and article titles revealed a dominant focus of urban biometeorological literature in *IJB* on human thermal comfort and health, specifically concerning heat exposure. The terms temperature, heat, thermal, climate, and mortality comprised the five most frequently used keywords among the articles we reviewed.

The interdisciplinary nature of urban biometeorology is evident from the reference lists of the articles included in our review. Papers commonly cited within the articles we reviewed come from fields including meteorology and climatology (e.g., *International Journal of Climatology*, *Bulletin of the American Meteorological Society*, *Theoretical and Applied Climatology*), environmental health and epidemiology (e.g., *Environmental Health Perspectives*, *Journal of the American Medical Association*, *Journal of Epidemiology and Community Health*), and building science and planning (e.g., *Building and Environment*, *Landscape and Urban Planning*,

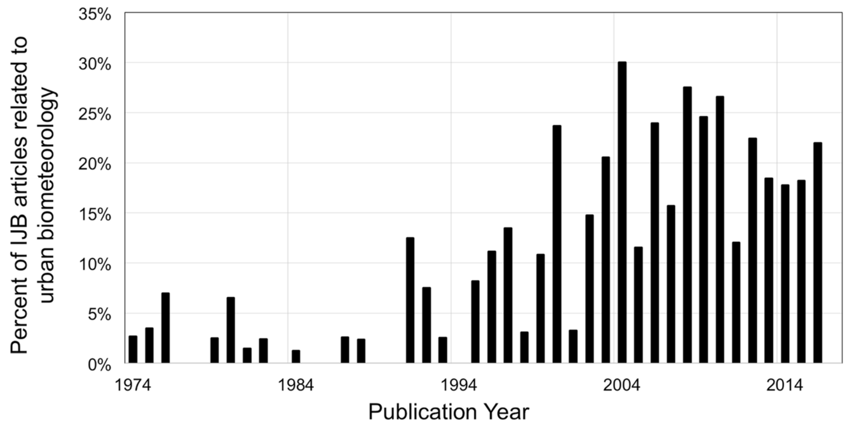

Fig. 1 The percentage of articles published in *IJB* on the topic of urban biometeorology over the period 1974–2016. *Each bar* on the figure represents the percentage for one publication year relative to the total for that year

Energy and Buildings). International interest in urban biometeorology is evident as well from our review, with more than 40 different countries represented as study sites (Table 1). Studies have been published in *IJB* from all six inhabited continents as well as all six of the World Health Organization regions, although higher-income countries are much more represented than lower-income ones. Of the 30 countries that were the setting of two or more articles we reviewed, five (Argentina, Mexico, Brazil, Iran, Cuba) are classified as upper middle-income economies by the World Bank, one is considered a lower middle-income economy (Pakistan), and the rest are considered high-income economies. The only low-income economy country that was the setting of any article we reviewed was Tanzania (Ndetto and Matzarakis 2017).

We assigned each urban biometeorology article to one or more of the following five themes: measuring urban climate, theoretical foundations and models, human thermal comfort, human morbidity and mortality, and ecological impacts. Predominant topics and methodological approaches within each of these themes are reviewed below.

Measuring urban climate

At least 20 articles appeared in *IJB* during the study period in which a significant contribution was made to the understanding of how urban morphology affects various weather and/or climate variables within an urban area. The majority of these papers featured micrometeorological in situ measurements made by the researchers themselves over relatively short periods of time (less than 5 years); others took advantage of existing daily instrumental climate records to characterize urban to rural differences over various time scales.

Many of the studies we reviewed within this theme documented spatial variations in urban climate with a focus on heat-related comfort and/or distress for humans. For example, Barradas (1991) measured air temperature and relative humidity in Mexico City and documented that the adverse thermal comfort impact of slightly higher moisture levels in parks was more than offset by lower temperatures, resulting in a net effect of improved human comfort. Using similar methods, Unger (1999) determined that the warmer urban center of Szeged, Hungary, produced twice as many pleasant "beer garden" evenings than the surrounding rural area. Yahia and Johansson (2013) found that Old Damascus, with its deep canyons and shade, was cooler and more comfortable than modern Damascus with far less shade. Other studies for Goteborg, Sweden (Svensson et al. 2003); Tel Aviv, Israel (Saaroni and Ziv 2003); Colombo, Sri Lanka (Johansson and Emmanuel 2006); and Bologna, Italy (Sajani et al. 2008) showed that central built-up urban areas result in an increase in human discomfort during the summer season.

Other studies featured data collected within and outside of cities to quantify the urban effect on climate and its impact on phenological responses of plants. For example, Roetzer et al. (2000) examined the flowering dates of various trees for ten cities in Europe, and in nearly all species studied, the flowering occurred earlier within the city compared to corresponding rural areas. Indeed, Defila and Clot (2001) showed that trees are flowering earlier within the urban "warmth" island of Geneva, Switzerland, when compared to a more rural town of Liestal. Earlier flowering dates within cities were also detected in Rennes, France (Mimet et al. 2009), and Kerman and Shiraz, Iran (Fitchett et al. 2014), and an earlier start to the growing season was found within seven Chinese cities as compared to adjacent rural areas (Liang et al. 2016).

While most studies we reviewed focused on spatial patterns, others used a time series approach to identify urban signals in weather and climate data. Jáuregui et al. (1997) noted that the nocturnal heat island of Mexico City has increased by 10 °C as the city has grown since the 1920s, resulting from the replacement of a large lacustrine system with built infrastructure that has also led to increased precipitation intensity. Cueto et al. (2010) examined summer maximum temperatures in Mexicali, Mexico, and found a general increase since the mid-1980s resulting in more deadly heat

Table 1 Countries that have been the setting of urban biometeorology articles published in *IJB* between 1974 and 2017, organized by World Bank income groups. The numbers in parentheses indicate the number of times that each country was a study setting for a published article; some studies included more than one country as a study setting. Studies with study sites spanning many countries (e.g., continental- to global-scale studies) were excluded from these counts

World Bank income group	Countries (number of articles)	Total number of study sites
High income	USA (22), Spain (21), Germany (11), Korea (10), Greece (10), Sweden (9), Portugal (9), Japan (9), Canada (8), UK (8), Australia (7), France (5), Hong Kong (4), Israel (4), Hungary (4), Taiwan (4), Poland (3), Brazil (3), Iran (3), Italy (3), Czech Republic (2), Netherlands (2), Cuba (2), Croatia (2), Switzerland (1), Singapore (1), Barbados (1), Trinidad and Tobago (1), Austria (1), Denmark (1)	171
Upper middle income	China (21), Argentina (6), Mexico (5), St. Lucia (1), Malaysia (1), Turkey (1)	35
Lower middle income	Pakistan (2), Ukraine (1), Syria (1), Bangladesh (1), Sri Lanka (1), Vietnam (1)	7
Low income	Tanzania (1)	1

waves. In a study of heat waves and human mortality, Tan et al. (2010) used data from 11 stations throughout Shanghai to show how different parts of the city altered climate over the past 25 years. With a focus on improving heat warnings, Martin et al. (2015) used satellite-derived warm season land surface temperatures in and around Montreal, Canada, from 1984 to 2011 and found that the strength of the heat island was related to solar radiation observed 24 to 48 h prior to the satellite overpass.

Theoretical foundations and models

Assessment of meteorological impacts on the well-being of living organisms in cities necessitates attention to three processes: local urban modifications to weather and climate, exposures of organisms to these modified climates (stress), and physiological responses to these exposures (strain). Understanding how those processes interact and building models of those processes and their interactions have been topics of emphasis in the urban biometeorological literature, with a greater focus to date on humans (for whom cities are primarily designed) rather than other organisms.

A recent pair of *IJB* reviews identifies 165 human thermal climate indices designed to represent the state of the thermal environment for individuals, including models of human biometeorological stress and strain (de Freitas and Grigorieva 2015, 2017). Ten of the 26 "energy balance stress indices" published in the English language literature during our review period appear in *IJB*, indicating the journal's key role in theoretical developments concerning atmospheric exchanges with the body. For example, the Universal Thermal Climate Index (UTCI), developed by 45 scientists from 23 countries, is intended to standardize results in biometeorological research, enhancing comparability (Jendritzky et al. 2012). It includes state-of-the-art heat budget, thermoregulation, and clothing models (Fiala et al. 2012; Havenith et al. 2012). The perceived temperature (PT) index represents the body's heat budget in a computationally efficient manner, rendering it suitable for applications that require high spatiotemporal resolution (Staiger et al. 2012).

Energy balance stress indices such as UTCI and PT typically incorporate the full spectrum of body-atmosphere energy exchanges, including shortwave and longwave radiation, convection of sensible and latent heat from the skin, respiratory exchanges, and internal energy flow and storage (Höppe 1999; Jendritzky et al. 2012). Body-atmosphere energy exchanges depend on the following atmospheric variables locally: air temperature, vapor pressure, wind speed relative to the body, and the mean radiant temperature (MRT) (or incoming all-direction radiation fluxes). Urban areas affect all of these variables, and radiation and wind can be particularly variable at the street scale (Herrmann and Matzarakis 2012).

Studies of urban effects on air temperature are well represented in *IJB* and other journals (Stewart and Oke 2012). The 3-D radiation environment is a dominant factor in thermal stress during clear summer days with weak winds, and its modulation by buildings, paved surfaces, trees, and other urban features has been approached by two recent models published in *IJB*: SOLWEIG 1.0 (Lindberg et al. 2008) and RayMan (Matzarakis et al. 2007, 2010). Both models require few inputs, and they make different approximations to predict mean radiant temperature. The initial publications of these two models already combine for 350 citations, indicating a demand for models that capture urban effects on atmospheric heat exchanges with the body.

Urban effects on wind and humidity received comparatively less attention in *IJB* during the review period. Wind flow at pedestrian level in urban environments, in particular, is highly variable spatially and temporally, and it can be an important factor in the body's energy budget, modifying clothing insulation for example (Blazejczyk et al. 2012).

Human thermal comfort

Models and metrics presented in the previous sections have been applied by urban biometeorologists to understand the impact of weather on human thermal comfort—the perceived and therefore subjective satisfaction with thermal environmental conditions (ASHRAE 2004). Outdoor environments were the setting of 47 of the 50 articles we reviewed within this theme, and the majority of the outdoor articles focused on heat stress. Only one study referred to indoor thermal comfort, and two recent studies combined indoor and outdoor environments. Few studies compared thermal conditions across cities or climatic zones.

Nearly half of the thermal comfort articles we reviewed used physiologically equivalent temperature to describe thermal comfort, followed by UTCI (5) and MRT (4). Other indices used in thermal comfort studies include predicted mean vote, index of thermal stress, and standard effective temperature, as well as temperature- and humidity-based indices (temperature-humidity index, wet-bulb globe temperature). Thermal comfort assessments were often enhanced with collection of air temperature, humidity, wind speed, globe or mean radiant temperature, and/or solar radiation observations and were typically conducted during the summer months or across multiple seasons.

Of the 50 papers in this theme, 24 investigated thermal conditions without linking the results to people's experiences. Ten of these 24 analyzed weather station data or performed meteorological measurements (e.g., Unger 1999), while 11 modeled thermal comfort in various urban conditions (e.g., Johansson and Emmanuel 2006). Three studies employed geographical information systems in order to analyze the spatial distribution of thermal comfort across cities or states (e.g., Matzarakis et al. 1999).

A combination of surveys and measurements was used in 26 studies to investigate subjective thermal perception and compare it to microclimate conditions (e.g., Thorsson et al. 2004). Structured interviews or questionnaires have been used to collect non-atmospheric variables relevant for thermal comfort, such as personal characteristics, thermal sensation, perceived comfort, influence of culture, environmental attitude, esthetics, and psychological aspects. Most survey studies used random or convenience sampling within urban areas, revealing various thermal comfort ranges in cities around the world due to varying climatic and cultural conditions (e.g., Yahia and Johansson 2013; Yang et al. 2013). Fewer studies focused on specific populations of interest (e.g., beach tourists by Rutty and Scott 2015; Ndetto and Matzarakis 2017).

Thermal comfort observations have generally been place-based, monitoring thermal conditions at various locations throughout cities. Several studies have examined how changes in thermal comfort affect patterns of human behavior such as street use (Zeng and Dong 2015), zoo visitations (Hewer and Gough 2016), and park use (Thorsson et al. 2004), the latter considering the time of exposure and clothing modification. Two recent studies employed people-based monitoring of environmental variables to investigate diurnal variability in heat exposure (Kuras et al. 2015) and human-physiological response (Nakayoshi et al. 2015). Most recently, the role of trees and shade as determinants of outdoor thermal comfort in hot environments has been among the most popular topics of study (e.g., Johansson and Emmanuel 2006; Antoniadis et al. 2016; Song and Jeong 2016; Middel et al. 2016). While most of the studies focused on thermal comfort of city inhabitants, the importance of thermal comfort for tourism development has been emphasized in several papers (e.g., Hartz et al. 2006; Pantavou and Lykoudis 2016; Roshan et al. 2016).

Human morbidity and mortality

Nearly one third of the articles published in *IJB* to date relevant to urban biometeorology are based on analysis of the association between atmospheric variables and human mortality and morbidity. This pool of articles is dominated by studies relating high temperatures and human mortality; the keywords temperature, heat, and mortality are each present in roughly half of the reviewed articles. China, the USA, Korea, Japan, and Australia were the most common study settings, whereas South America, Africa, and tropical regions more generally were highly underrepresented in this set of articles.

The exposure variable most frequently examined was air temperature (or combined temperature-humidity indices, such as apparent temperature), and studies of the effect of high temperature outnumbered those of low temperature by a factor of 5. Air pollution was the next most common exposure variable, which was often investigated as a modifier and/or confounder of temperature effects on health. Synoptic weather types, indicators of temperature variability, humidity, and radiation (primarily shortwave) were each examined in several studies, sometimes in combination with temperature and/or air pollution. Common health outcomes examined include all-cause mortality, mortality and morbidity from specific causes including cardiovascular and respiratory ailments, and emergency calls and ambulance dispatches for subsets of health ailments, especially symptoms related to heat exposure. Only a few studies we reviewed related weather and climate to morbidity due to vector-borne and infectious diseases (e.g., hepatitis, dysentery, diarrheal diseases, dengue fever).

"Climate change" was one of the most common terms in titles and keywords within this theme, appearing in 17 articles. However, more than half of these 17 did not directly address time-varying impacts of weather and climate on health. Ten of the articles examined historical associations between meteorological variables and health outcomes, based on the premise that understanding these associations would be useful to anticipate future consequences (e.g., Tong et al. 2010). One paper was written to describe different approaches for estimating heat exposure in urban areas (Schaeffer et al. 2016). Only six manuscripts explicitly considered temporal change in health outcomes. Of these six, five involved projections of future temperature-related mortality or morbidity (Ostro et al.

2012; Martin et al. 2012; Maloney and Forbes 2011; Gosling et al. 2009; Dessai 2003), whereas only one involved historical trends in heat-related mortality (Davis et al. 2003). Although projections of future health impacts related to climate change are rapidly growing in number in the literature, no such studies have been published in *IJB* since 2012. Furthermore, although all five of the projection-oriented studies were set in cities, none explicitly considered urban effects on climate.

Ecological impacts

People are not the only organism influenced by weather and climates in cities. The urban climate causes a number of ecological impacts, from increasing aerobiological irritants (Skjøth et al. 2009) to shifting phenology of urban bird reproduction (Glądalski et al. 2016). We identified 56 articles with a focus on the impacts of the urban climate on different types and components of ecosystems, many of which focused on urban vegetation. Developed European countries were the most commonly studied locations, whereas other western countries such as the USA were underrepresented. Major themes include the implications for ecological change on human health outcomes, shifts in urban phenology, and interactions between the urban climate and vegetation.

Within the *IJB* urban-ecological literature, many articles have been oriented toward human health. Human aerobiological irritants such as airborne pollen, fungal, and bacterial spores are of particular focus. Twenty-four studies published in *IJB* have explored the association between pollen variability across time and/or space and urban climate parameters. Overall, pollen levels in cities are considered to be an increasing health risk, partially due to the pollen season growing longer and rising pollen counts (Schmidt 2016). *IJB* authors have found that ornamental trees are especially responsible for the increase in pollen counts, causing suburban areas to have higher pollen counts than either high-density or ex-urban areas (Ríos et al. 2016), and that people reported higher amounts of allergies around parks and urban green space (Skjøth et al. 2008). Shifts in urban climate parameters (especially temperature) that elevate pollen counts in cities (Peternel et al. 2004) can also influence the seasonal patterns of vegetation.

Cities are hypothesized to influence plant phenology by reducing the diurnal temperature range, which is also tied to growth and developmental stages of vegetation (Mimet et al. 2009). Phenology shifts caused by the urban climate are another main focus of *IJB* research, and many *IJB* studies involve analysis of simultaneous, co-located observations of phenological response and meteorology (see "Measuring urban climate" section). As described above, most studies reported that phenological events such as flowering happen earlier in cities, such as Roetzer et al. (2000) who determined that pre-spring phenophases came about 4 days sooner for urban areas, but cite that phenological events are still highly variable in nature. However, articles we reviewed showed mixed results for the significance and direction of the relationship between the urban climate and phenology. Globally, the start of the growing season has been coming earlier in the year, but this trend is not necessarily associated with urbanization (Jochner et al. 2012). We identified only one study on avian reproductive time, which found that cities buffered the effects of a colder than average spring on laying clutches (Glądalski et al. 2016).

A smaller number of articles focused on photosynthesis rates within the city, which can be reduced by factors such as the urban canyon effect (Kjelgren and Clark 1992). Urban vegetation is important because shade produced by the tree canopy can improve thermal comfort (Yoshimura et al. 2010; Fukuoka 1997), but development and maintenance of a dense urban tree canopy can pose challenges related to water resources, necessitating consideration of tradeoffs. Thorough examination of interplay between water, vegetation, and human and ecosystem health in cities can reveal surprising guidance for policymakers—for example, Ruddell and Dixon (2014) suggested that drought-resistant approaches to landscape management may bring adverse impacts to community and ecosystem health.

Situating *IJB* in the urban biometeorological literature

A search for all articles published over the period 1974–2017 that included one of the three keywords "urban," "city," or "cities," along with the keyword "biometeorology," yielded 53 results. The fact that this number of articles is smaller than the number of articles we extracted from *IJB* alone is likely indicative of two factors. First, few authors publishing in *IJB* use "biometeorology" as a keyword for their articles, given its redundancy with the publication title. Second, it may be the case that very few authors publishing outside of *IJB* on topics related to urban biometeorology identify their work as "biometeorology." Of the 53 articles we identified, 21 (39.6%) were published in *IJB*, and no other publication accounted for more than four articles. Journals that have published more than one article on urban biometeorology (based on our search criteria) since 1974 are *Meteorologische Zeitschrift*, *Advances in Meteorology*, *American Journal of Epidemiology*, *Environmental Health*, *Experientia*, and *International Journal of Climatology.*

We next searched for articles published in any journal that included any of the five most frequently used keywords among the *IJB* articles matched into each of the five themes identified above. For example, the most common keywords among *IJB* articles in the measuring urban climate theme were as follows: urban, thermal, temperature, climate, and heat. Across the five different themes covered in this review article, we found that *IJB* was well represented among the most relevant articles within each theme. In terms of total article counts within the samples of 500 articles we examined, *IJB* accounted for the fifth most publications related to measuring urban climate, the second most publications related to theoretical foundations and models, the third most publications in thermal comfort, the most publications in human morbidity and mortality, and the second most publications in ecological impacts. The journals with the ten highest number of publications within each theme appear in Table 2. The theme for which *IJB* accounted for the highest fraction of the subsample of articles we examined was ecological impacts (12.4%), and the theme with the lowest fraction was measuring urban climate (3.8%).

When examining citation counts within each of the thematically relevant samples of 500 articles, we found that *IJB* had at least one article among the 25 most highly cited in each theme. *IJB* was especially well represented among the most highly cited articles in the themes of theoretical foundations and models (six papers within the top 25) and thermal comfort (five). Conversely, *IJB* accounted for only one of the 25 most highly cited articles within the human morbidity and mortality theme, despite the fact that the journal accounted for the highest number of total articles within this theme.

Discussion

Urban biometeorological research published in *IJB* since 1974 has spanned a wide range of topical areas, methodological approaches, and geographic settings. Urban biometeorologists have contributed knowledge regarding how the built environment impacts weather and climate with both observational and modeling approaches, but have more so tended to focus on understanding how weather and climate in cities influences people and ecosystems. The more highly cited urban biometeorology articles we reviewed fall in this latter category, including all six articles we reviewed that have been cited more than 100 times according to Web of Science. Of these six, two focused on modeling human-atmosphere energy exchanges in physiologically relevant terms (Matzarakis et al. 1999, 2007), one focused on human thermal comfort (Thorsson et al. 2004), two focused on heat-related mortality (Tan et al. 2010; Smoyer et al. 2000), and one focused on phenology (Defila and Clot 2001). These six articles alone have accounted for nearly 23% of all urban biometeorology citations in *IJB*.

Comparative approaches between urbanized and non-urbanized locations, or different locations within urbanized areas, were more evident in the articles we reviewed that focused on ecosystems or human thermal comfort rather than human morbidity and mortality. There is thus a need and opportunity for the *IJB* community to expand knowledge of the biometeorology *of* cities from a human morbidity and mortality perspective, not only measuring associations between weather or climate variables and human health outcomes in cities but also more specifically and intentionally measuring the extent to which those associations are modified by environmental variability associated with urban form. This knowledge is especially critical at a time when cities are taking actions to mitigate adverse impacts of local-scale climate effects with only a minimal understanding of the full spectrum of direct and indirect causal relationships (Sailor et al. 2016). More comprehensive knowledge of associations between urban climate and human morbidity and mortality is also warranted given that the impacts of urbanization and global-scale radiative forcing may have climate effects of similar order of magnitude in cities (e.g., Grimmond 2007; Georgescu et al. 2014). More broadly, given the demand for more knowledge of the links between climate change and human health (Portier et al. 2013), we were surprised by the relatively small number of human health-oriented studies that explicitly considered temporal variability in exposures or outcomes.

Other needs and opportunities we identified in our review span both methodological and topical considerations. Similar to other fields of research inquiry, urban biometeorological research needs to expand its geographic focus to be more inclusive of low- and lower middle-income countries. In fact, one could reasonably argue that these locations are those in most need of urban biometeorological research, given the extent to which urbanization and climate change are anticipated to pose challenges for urban populations in developing countries (McCarthy et al. 2010; Sherwood and Huber 2010; Ndetto and Matzarakis 2017). At the same time, continued attention is needed to high-density urban areas in humid and dry tropical and subtropical climates where risks of thermal discomfort and heat stress are already high and will continue to grow (Cheng et al. 2012; Hartz et al. 2013; Yang et al. 2013; Lin et al. 2015; Middel et al. 2016, 2017; Ndetto and Matzarakis 2017). Related to measuring and modeling the urban climate, opportunities exist for development and integration of high fidelity, computationally efficient models of microscale urban variation of mean radiant temperature and wind to yield predictive 2-D urban mapping of urban microclimates and resulting exposures. Continuing improvements in computational and data resources and access (including open source resources) will accelerate this line of research (e.g., Bechtel et al. 2015; Middel et al. 2017). Collaboration between urban climate modelers and those with biometeorological expertise will be important to ensure that input and output variables and data sets have relevance to human and ecological systems. Furthermore, this line of work could be increasingly aligned with or driven by input from human geographers, political and social scientists, and urban planners, so that it can be appropriately contextualized within and

Table 2 Peer-reviewed scientific journals ranked by the number of articles published over the period 1974–2017 within five themes of urban biometeorological research. The number of articles published in the most frequently identified journal as well as the *International Journal of Biometeorology* is shown in parenthesis. Ties in keyword or journal frequency are indicated with a slash

Theme	Measuring urban climate	Theoretical foundations and models	Thermal comfort	Human morbidity and mortality	Ecological impacts
Keywords	Urban, thermal, temperature, climate, heat	Thermal, temperature, urban, comfort, equivalent	Thermal, comfort, urban, temperature, climate	Heat, mortality, temperature, climate, weather	Pollen, climate, urban, aerobiology, airborne/meteorological
Rank 1	*Building and Environment* (50)	*Building and Environment* (128)	*Building and Environment* (139)	International Journal of Biometeorology (59)	*Aerobiologia* (108)
2	*International Journal of Climatology*	International Journal of Biometeorology (59)	*Energy and Buildings*	*Science of the Total Environment*	International Journal of Biometeorology (62)
3	*Energy and Buildings*	*Energy and Buildings*	International Journal of Biometeorology (44)	*Environmental Research*	*Annals of Agricultural and Environmental Medicine*
4	*Sustainable Cities and Society*	*Landscape and Urban Planning*	*Landscape and Urban Planning*	*Environmental Health Perspectives*	*Science of the Total Environment*
5	International Journal of Biometeorology (19)	*Architectural Science Review*	*Indoor and Built Environment*	*International Journal of Environmental Research and Public Health*	*Grana*
6	*Landscape and Urban Planning*	*Indoor and Built Environment*	*Architectural Science Review*	*Climate Research*	*Atmospheric Environment*
7	*Remote Sensing of Environment*	*Sustainable Cities and Society*	*Sustainable Cities and Society*	*International Journal of Climatology*	*Journal of Investigational Allergology and Clinical Immunology*
8	*Atmospheric Environment*	*Building Research and Information*	*Urban Forestry and Urban Greening*	*Environmental Health*	*Allergy*
9	*Environmental Research Letters*	*European Journal of Applied Physiology*	*Solar Energy*	*American Journal of Epidemiology*	*Environmental Monitoring and Assessment*
10	*Urban Forestry and Urban Greening*	*Urban Forestry and Urban Greening*	*Building Research and Information/International Journal of Climatology*	*Environment International*	*International Archives of Allergy and Immunology*

inform long-term decision-making related to the well-being of people and ecosystems in cities (Eakin et al. 2017).

Next, while there is a relatively strong thread of biometeorological research focused on animals outside of urban areas, there were almost no animal-oriented studies in our review (with the exception of birds). This is likely the case because much of the animal biometeorological literature is geared toward farming and livestock (which does not typically occur in cities) (e.g., Seo 2015), and those studying how animal behavior within cities is related to weather or climate may identify more closely with the field of urban ecology (e.g., Ackley et al. 2015). More dialog between scholars who identify as urban ecologists and urban biometeorologists could yield fruitful advances within both communities. Finally, we observed a paucity of urban biometeorological studies in *IJB* related to indoor environments. Given that—at least in developed countries—many individuals spend a high portion of their total time indoors (e.g., Schweizer et al. 2007), a substantial share of individuals' total exposure to meteorological factors is essentially unaccounted for by biometeorologists thus far. Work published in *IJB* related to indoor environments to date highlights challenges in anticipating indoor conditions based on outdoor weather (e.g., Nguyen and Dockery 2016) and the potential for indoor environments to contribute to human heat stress (e.g., Walikewitz et al. 2015). Although indoor environments in cities may not immediately come to mind in the realm of urban weather and climate, we suggest that the spirit of biometeorology—understanding the totality of the impacts of weather and climate on the well-being of all living creatures—necessitates advancing this understanding beyond the walls that separate indoor from outdoor environs.

Conclusions

Scholars contributing to *IJB* are increasingly focusing on urban areas in biometeorological research; today, roughly one in every four articles published in the journal is oriented toward urban biometeorology. We identified five major themes in urban biometeorological articles published in *IJB:* measurement of urban climates and comparisons across time and space, modeling of thermal environments and energy exchanges within cities for assessing physiological stresses and strains, assessment of human thermal comfort, analysis of patterns in human morbidity and mortality, and the study of ecological system responses to urban effects on local weather and climate. Across these five themes, *IJB* authors have thus far concentrated most of their effort on higher-income countries. Furthermore, heat and its implications for human health and well-being have been the dominant topic of study within urban biometeorological literature in *IJB* to date.

Our review highlighted the interdisciplinary nature of urban biometeorological research and, specifically, its connections to the fields of meteorology, environmental health, building science, and urban planning. It also highlighted that *IJB* and its contributing authors are playing a significant role in the broader academic discussion about cities and their impacts on the well-being of people and other organisms. Within the general themes of interest to authors contributing to *IJB*, the journal is among the most well represented in terms of total article counts and highly cited articles. Furthermore, the themes of the urban biometeorological articles that have been most highly cited are quite diverse. Contributors to *IJB* are advancing our understanding of the impact of weather and climate in cities on multiple fronts and from several different methodological perspectives.

As biometeorologists continue to direct an increasingly large share of their attention toward urban areas, we encourage continued diversification of the topics and geographical settings of study. More research focused on low- and middle-income countries, indoor environments, and urban wildlife, as well as an increase in the number comparative and synthesis-oriented studies, may be especially fruitful. As cities around the world become the home for more and more of the world's population, more comprehensive knowledge of the many causal pathways that impact all of their inhabitants can help the future be one of greater human and ecological well-being and productivity. *IJB* and its contributing authors are well positioned to shape how such an urbanized future will unfold.

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