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Supporting sustainability initiatives through biometeorology education and training

Michael J. Allen [1] · Jennifer Vanos [2,3] · David M. Hondula [4] · Daniel J. Vecellio [5] · David Knight [6] · Hamed Mehdipoor [7] · Rebekah Lucas [8] · Chris Fuhrmann [9] · Hanna Lokys [10] · Angela Lees [11] · Sheila Tavares Nascimento [12] · Andrew C. W. Leung [13] · David R. Perkins IV [14]

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Abstract The International Society of Biometeorology (ISB) has covered significant breadth and depth addressing fundamental and applied societal and environmental challenges in the last 60 years. Biometeorology is an interdisciplinary science connecting living organisms to their environment, but there is very little understanding of the existence and placement of this discipline within formal educational systems and institutions. It is thus difficult to project the ability of members of the biometeorological community—especially the biometeorologists of the future—to help solve global challenges. In this paper, we ask: At present, how we are training people to understand and think about biometeorology? We also ask: What are the current tools and opportunities in which biometeorologists might address future challenges? Finally, we connect these two questions by asking: What type of new training and skill development is needed to better educate "biometeorologists of the future" to more effectively address the future challenges? To answer these questions, we provide quantitative and qualitative evidence from an educationally focused workshop attended by new professionals in biometeorology. We identify four common themes (thermal comfort and exposures, agricultural productivity, air quality, and urbanization) that biometeorologists are currently studying and that we expect to be important in the future based on their alignment with the United Nations Sustainable Development Goals. Review of recent literature within each of these thematic areas highlights a wide array of skill sets and perspectives that biometeorologists are already using. Current and new professionals within the ISB have noted highly varying and largely improvised educational pathways into the field. While variability and improvisation may be assets in promoting flexibility, adaptation, and interdisciplinarity, the lack of formal

✉ Michael J. Allen
mallen@odu.edu

[1] Department of Political Science and Geography, Old Dominion University, 7035 Batten Arts and Letters, Norfolk, VA, USA

[2] Climate, Atmospheric Science, and Physical Oceanography Department Scripps Institution of Oceanography, UC San Diego, San Diego, USA

[3] Department of Family Medicine and Public Health, School of Medicine, UC San Diego, San Diego, USA

[4] School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ, USA

[5] Climate Science Lab, Department of Geography, Texas A&M University, Texas, College Station, TX, USA

[6] Department of Engineering Education, Virginia Tech, Blacksburg, Virginia, USA

[7] Department of Geo-Information Processing, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands

[8] School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham, Birmingham, UK

[9] Department of Geosciences, Mississippi State University, Mississippi State, MS, USA

[10] Climatology Group, Institute of Landscape Ecology, University of Münster, Münster, Germany

[11] School of Agriculture and Food Sciences, Animal Science Group, The University of Queensland, Gatton, QLD, Australia

[12] Agronomy and Veterinary Medicine, University of Brasília, Brasília, DF, Brazil

[13] Climate Laboratory, Department of Physical & Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Canada

[14] Center for Climate Change Communication, George Mason University, Fairfax, VA, USA

training in biometeorology raises concerns about the extent to which continuing generations of scholars will identify and engage with the community of scholarship that the ISB has developed over its 60-year history.

Keywords Biometeorology · Interdisciplinary · Education · Sustainable Development Goals

Introduction

As the International Society of Biometeorology (ISB) moves into its seventh decade, there is opportunity to reflect on how current educational pathways prepare scholars for a career in the discipline. Biometeorology, as described by S. W. Tromp, is an *interdisciplinary collaboration of physicists, biologists, physicians, meteorologists, and other scientists and the development of meteorology in relation to man, animals, and plants* (Tout 1987; Tromp 1980) and interfaces with many of the challenges and goals identified for the next century. Within biometeorology, the most common type of collaboration is interdisciplinary which refers to the holistic analysis, synthesis, and interaction between disciplines (Choi and Pak 2006). While in certain instances researchers may work in their separate disciplines and come together or transcend traditional boundaries, other types of collaboration are far less frequent compared to interdisciplinary. The integrative approach that underpins most biometeorological research is championed by the United Nations in its description of the Sustainable Development Goals (SDGs), which feature *deep interconnections and many cross-cutting elements across the new goals and targets* that aim to end poverty and hunger, improve health and education, make cities more sustainable, combat anthropogenic climate change, and protect oceans and forests (Table 1; United Nations 2015). Biometeorologists study interconnections between the physical, natural, and social systems (Sheridan and Allen 2017), with weather, climate, and the atmosphere as a common, foundational base.

Given that biometeorology is a discipline that seems well-positioned to help society achieve the SDGs, it is important to understand how biometeorologists are presently educating and training people to understand and think about the discipline and consider the ways in which they might address future challenges.

In July 2016, members of the Students and New Professionals (SNP) group of the ISB gathered at the group's second international workshop entitled *Enhancing the Teaching and Learning of Biometeorology in Higher Education*. The purpose of the workshop was to provide a forum for students and new professionals to reflect on the current state of biometeorological education and propose new pathways for training. This manuscript describes the outcomes of the workshop and subsequent literature review and synthesizing discussions among the SNP membership. The manuscript addresses three separate questions. First, what is the current state of biometeorological education and training? In this discussion, we consider both educational programs and more informal training opportunities. Second, what are the tools and perspectives that biometeorologists are likely to use to address future challenges? We evaluate how these tools have changed and consider the emerging techniques that may aid in our understanding of biometeorological themes. Finally, we connect these two questions by asking: What type of training and skill development are needed to prepare the "biometeorologists of the future" to effectively address forthcoming challenges? We reference the SDGs throughout the manuscript as a means of identifying plausible connections between current and future biometeorology training and education and significant global goals concerning health, well-being, equity, and the environment.

Current biometeorology education

Biometeorological research bridges across multiple disciplines and draws on the dominant themes of plant, animal, and human well-being (Sheridan and Allen 2017). This was no more apparent than in the foreword of the first special issue of "*New Insights into Biometeorology*" in the *International Journal of Biometeorology*, which noted published papers from five different "fields" of which some could have been separated into even more specialized sub-fields (Gosling et al. 2014). Although biometeorology sits at the intersection of modern curricula that remain focused on foundational disciplines (e.g., ecology, meteorology, physiology), today's students largely continue to study discipline-specific content and learn how to develop and address discipline-specific questions (Ebi et al. 2009). This approach (and the underlying institutional forces that support it) has led to tremendous advances in understanding how the world works, but is not necessarily well-suited to the *accelerating complexity that marks contemporary life* (Crow 2010). Learning how to apply knowledge across disciplinary boundaries is a clear requirement for addressing global challenges such as those that motivate the SDGs.

Are academic curricula organized to support the integrative approach demanded by the SDGs? The neighboring discipline of environmental science provides an interesting case for illustration. Like biometeorology, environmental science is an interdisciplinary science, one that acknowledges its role as a critical contributor to the emerging field of sustainability studies and widely identified as a crucial means for academic researchers to effectively address complex, worldly problems (Tarrant and Thiele 2016).

Interestingly, existing undergraduate degree programs in interdisciplinary areas like environmental sciences display stark differences in how students obtain credit for degree completion (Knight et al. 2013). Degree programs requiring a

Table 1 Examples of biometeorology activities that support United Nations Sustainable Development Goals

Thermal comfort and exposures

- Goal 1. End poverty in all its forms everywhere: identify opportunities to reduce costs associated with heating and cooling, assist in technology development
- Goal 3. Ensure healthy lives and promote well-being for all at all ages: measure health impacts of hot and cold environments, evaluate interventions to reduce adverse health events
- Goal 4. Ensure inclusive and quality education for all and promote lifelong learning: research concerning thermal conditions and learning outcomes
- Goal 8. Promote inclusive and sustainable economic growth, employment and decent work for all: evaluate links between thermal comfort and preferences and economic activity in different sectors
- Goal 9. Build resilient infrastructure, promote sustainable industrialization and foster innovation: identify optimal locations for deployment of infrastructure that mitigate thermal extremes, contribute to improvements in design strategies
- Goal 11. Make cities inclusive, safe, resilient, and sustainable: reduce adverse impacts of urbanization on thermal environments (e.g., heating, radiation load, wind flows)
- Goal 13. Take urgent action to combat climate change and its impacts: evaluate temporal trends in heat and cold-related weather impacts to inform policy, identify intervention strategies most effective for protecting public

Agricultural productivity

- Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture: identify variants that provide better nutrition (e.g., golden rice) or uses water more efficiently
- Goal 12. Ensure sustainable consumption and production patterns: support scientific and technological capacity of developing countries to develop more sustainable consumption and production patterns
- Goal 13. Take urgent action to combat climate change and its impacts: reduce environmental impacts of agricultural production
- Goal 14. Conserve and sustainably use the oceans, seas and marine resources: research the role of aquaculture and marine ecosystems and identify best management strategies
- Goal 15. Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss: improve productivity on existing land and promote more efficient use of natural resources

Air quality

- Goal 3. Ensure healthy lives and promote well-being for all at all ages: measure indoor and outdoor air quality and develop community-level intervention methods to improve air quality
- Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all: support scientific and technological endeavors to provide modern energy for all
- Goal 11. Make cities inclusive, safe, resilient and sustainable: integrate air quality standards into management and planning strategies
- Goal 13. Take urgent action to combat climate change and its impacts: communicate the benefits of improved air quality and reduced GHG emissions
- Goal 16. Promote just, peaceful, and inclusive societies: evaluate the social justice aspect of poor air quality and consider those most vulnerable

Urbanization

- Goal 2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture: promote locally sourced agriculture in urban environments
- Goal 6. Ensure access to water and sanitation for all. Expand international cooperation and capacity building in developing countries to address water and sanitation issues
- Goal 7. Ensure access to affordable, reliable, sustainable, and modern energy for all: enhance clean energy research and investment in energy infrastructure and technology
- Goal 11. Make cities inclusive, safe, resilient, and sustainable: incorporate community-based solutions to address concerns such as water resources, transportation, and urban heat island
- Goal 13. Take urgent action to combat climate change and its impacts: support technological innovation while reducing resource and energy consumption
- Goal 15. Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss: integrate biodiversity in urban design and planning
- Goal 16. Promote just, peaceful, and inclusive societies: broaden and strengthen community participation in urban design and planning

smaller number of total classes (e.g., five to ten classes) tend to outsource those requirements to other academic departments while programs who place a larger focus (i.e., more courses required for full degree) on an interdisciplinary degree tend to nurture this knowledge within their own department. There is no comprehensive assessment of the utilization of different types of credit and course models for biometeorology, however, nor any evaluation of the manner in which different models support interdisciplinary learning or preparation to address global needs like the SDGs.

To gain perspectives from young scholars on the current state and potential for future development of biometeorology in education, the ISB SNP group held an international workshop from July 28 to August 1, 2016 at Old Dominion

University. The purpose of this workshop was to explore the use of biometeorological concepts in interdisciplinary teaching and learning in higher education and discuss how to effectively integrate biometeorological concepts, learning modules, and pedagogical techniques into undergraduate and graduate courses and curricula (Perkins et al. 2017).

At the workshop, biometeorology and a general "state of the field" were juxtaposed with the methodological nuances implemented within the differing biometeorology sub-fields. A wide array of current and potential teaching examples was presented from broad viewpoints (international, sub-disciplines, career levels) to catalyze discussion, which led to a formalized assessment of what biometeorology training entails and specific workshop outcomes (e.g., website development for sharing of ideas and resources, class modules and laboratories, technology).

Workshop assessment instruments included an external evaluation and anonymous prework survey (6 weeks prior) and post-workshop survey (2 weeks after) of the participants (Knight 2016). Evaluation was also performed with observational field notes. The surveys and evaluation illuminated professional experiences, new ideas, and opportunities related to teaching and learning in biometeorology. The surveys also highlighted roadblocks and concerns that arose in terms of implementing newer pedagogical approaches (e.g., service learning, experiential learning) and biometeorology teaching modules. Thus, even with changes in personal teaching pedagogies and future outlooks resulting from the workshop, specific and well-founded obstacles emerged as to why there is a non-systemic approach to educating and training young biometeorologists even though the importance of interdisciplinary perspectives is ever-increasing. Four general findings emerged: (1) training in biometeorology falls within a vast array of courses, (2) unclear and haphazard pathways exist for students seeking a future in biometeorology, (3) technology is critical to future success, and (4) structural constraints within academia are widely present. These findings are each discussed further below.

1. Many new scholars that participate in biometeorology research are also involved in teaching courses within related disciplines; however, one of the challenges for the field of biometeorology is the wide array of classes in which biometeorology topics currently reside. Such courses include but are not limited to geography, atmospheric science, climatology, cartography, hazards, environmental sciences, climate change, engineering, biophysical environment, animal biometeorology, animal behavior and welfare, precision agriculture, and environmental physiology. Although these courses being taught by new scholars in the ISB are broad, topics or concepts that emerged across the classes included health (human and animal), well-being, adaptation, agriculture/food systems, air pollution, and urban systems. Thus, the classes being taught outside of biometeorology play a key role in addressing modern and future worldwide sustainability challenges, all of which fall within the purview of the SDGs (United Nations 2015). Historical perspectives have noted that the nurturing and the advancement of the field of biometeorology has been a challenge due to the numerous areas covered (Sargent 1963) and because cross-disciplinary sciences were seen as a "particularly arduous job, for its [biometeorology] literature is widely scattered among some 50,000 scientific and technical publications" (Conrad 1957). Today, communication advancements have created vast opportunities for worldwide studies and the sharing of literature and data. Therefore, opportunities exist to tackle the increasingly complex challenges, such as the SDGs, that require more diverse training and teams of scientists to find long-lasting and effective solutions. Developing these skills would be a natural byproduct of more formalized educational curricula designed around biometeorology.
2. The pathways by which scholars have come to identify themselves as biometeorologists are incredibly varied, and it is unclear what pathways currently exist that would systematically support the development of future generations of biometeorologists. While teams of researchers (groups or labs) exist for research purposes at many universities worldwide, students often would not enter said research until after their undergraduate degree and thus may lack the planning or forethought to complete the necessary training across disciplines. Within a survey of workshop attendees, the new scholars stated that their pathway towards biometeorology often occurred through mentorship or by chance and/or that individual drive after being exposed to biometeorology late in their education was required to string together courses and/or expose themselves to research (Knight 2016). Rather than a systematic or formal pathway, training is often viewed as ad hoc and individually driven, with encouragement from mentors during graduate school. This situation may not be surprising, as courses that focus on biometeorology are seldom found at the undergraduate or graduate level (Knight 2016).
3. A third perspective continually emphasized by young professionals is the ever-increasing need for technological savviness applied to real-world problems. There is a recognition that the skills and tools (especially concerning hardware and software technologies) required and utilized to be an effective biometeorologist are evolving (Mehdipoor et al. 2017). It was evident from the workshop discussions that a curriculum in biometeorology must account for rapid advancements in technology (Knight 2016). With technological innovation, more elaborate data collection and analysis have become possible.

Common examples of the ever-increasing use of technologies in biometeorology included remote sensing, personal sensors, and unmanned aerial vehicles. Workshop participants recognized the need for exposure to the applications of these technologies in formal educational and training settings. Although the workshop participants use novel technologies in their research, use of this technology in the classroom settings was minimal due to issues such as lack of funding, lack of time to develop assignments/modules, lack of support from supervisors, low emphasis put on teaching effectiveness, managing timeliness of lectures, formal/traditional lecture-style teaching not lending itself to hands-on technologies, and lack of space (Knight 2016). These roadblocks constrain opportunities for the deeper, higher-order knowledge gain that is facilitated by active experiential learning (Reohl et al. 2013; Kolb 2014).

4. Finally, many participants recognize the structural constraints within institutions that hinder the development of new, clear, and adaptive pathways to undergraduate training specific to biometeorology. Forging new pathways can be time-consuming, and current promotion and tenure guidelines often do not incentivize interaction across disciplinary boundaries. Furthermore, a large variation is found between institutions and countries in terms of what topics and learning outcomes can be added or changed within a current class (Knight 2016). However, new techniques in instructional technology do provide the capability of increased knowledge-sharing and participation across disciplines (Jacob 2015). Although participants perceived a low likelihood in developing a biometeorology degree, near-term helpful actions may include creating "minors" or "areas of emphasis" within a degree program that already contains necessary courses or including lectures specific to biometeorology. Another opportunity to expose students to biometeorology would be the inclusion of a certificate program within the curriculum. Stone et al. (2009) details the creation of seven certificate programs at the University of Colorado at Denver, including two with biometeorological underpinnings: environmental science and sustainability. However, due to the expansive atmospheric knowledge needed for most biometeorological applications, consideration must be given as to whether the requirements for such a program would be able to include the breadth of those courses in addition to the interdisciplinary knowledge which must be gained. Stewart (2010) advocates for these interdisciplinary certificates in some form or fashion, but specifically for sustainability, noting that flexibility and collaboration between disciplines is the way to solve future problems. By exposing students to the notion of biometeorology earlier than graduate school, the visibility of the discipline could provide a path to obtain necessary education and training.

To illustrate the first three emerging themes above, we next examine a suite of contemporary topics identified by workshop participants in which biometeorologists may play an important role in addressing sustainability goals.

Biometeorology and twenty-first century opportunities

During workshop discussions, participants identified several cross-cutting and overlapping themes within biometeorology. These themes include thermal comfort and exposures, agricultural productivity, air quality, and urbanization (Table 1). These topic areas do not represent an exhaustive list of all critically important topics in the coming century nor are they topics that are addressed by biometeorologists alone but instead are representative of the types of study areas that biometeorologists are well-positioned to contribute to and may be helpful in the future. Within each of the four themes, we present (1) past and recent research, (2) address how each relates to UN SDGs, (3) provide a description of tools, methods, and perspectives that are essential in solving twenty-first century challenges. We also highlight some of the skills and opportunities that could be useful in the future.

Thermal comfort and exposure

The issues of thermal comfort and thermal inequality relate to several of the SDGs recently put forth by the United Nations, including "good health and well-being" and "sustainable cities and communities" (Table 1).

The role of the thermal environment as a determinant of the health and productivity of organisms, including people, is one of the more enduring areas of interest for biometeorologists. Plants, animals, and humans may be expected to experience increasing thermal heat stress under projected climate change as temperature continues to rise. Given that air temperature alone is seldom the reason for heat or cold stress, numerous thermal comfort models have been developed over the past century to account for a combination of meteorological and behavioral variables on the human energy balances (*See* reviews by Epstein and Moran 2006; de Frietas and Grigorieva 2015). Human biometeorology specifically has relied upon human thermal comfort models, beginning with Fanger's indoor predicted mean vote model (Fanger 1970), advancing to more complex, dynamic, multidimensional outdoor models of human heat balance over time and space (de Frietas and Grigorieva 2009, 2015; Coccolo et al. 2016; Jendritzky et al. 2012). Thermal comfort models have also been applied to understand the influences of urban landscape ecology (Connors et al. 2013), to assess associations between landscape characteristics and human outcomes (Harlan et al. 2006) and to relay holistic weather information for tourism (Matzarakis et al. 2014).

These human thermal comfort models and related direct or empirical indices have been developed to design satisfactory and safe environments for occupational, sporting, and residential settings. It is important to recognize that these models and indices have been designed in and for (at least initially) developed country settings and active working populations (Lucas et al. 2014; Epstein and Moran 2006). Subsequently, the applicability of these models' norms for alternative populations is debatable. Thermal inequality represents the disproportionately greater temperature-related health burden found among specific sociodemographic groups. Epidemiological research investigating health impacts from climatic events has identified various vulnerable populations, such as the elderly, individuals with chronic diseases, and people who are socially isolated or are experiencing financial constraints (Astrom et al. 2011; Gronlund 2014). Cardiovascular impairments associated with aging and chronic diseases are chiefly responsible for increased susceptibility to heat waves on account of physiological heat loss mechanisms increasing demand on the cardiovascular system (Kenney et al. 2014). Social factors such as constraints on energy use for air conditioning and social isolation also impact risk of adverse heat-related outcomes (Uejio et al. 2011). Although much of the heat-related health outcome research has been completed in urban areas and in developed nations, a significant heat-health burden also exists in rural areas and in the developing world. For example, Kovach et al. (2015) found that rates of heat-related illness, as identified using records of emergency department visits, across NC were higher in rural areas compared to urban areas. There is also disproportionately greater risk of heat-related health outcomes among working populations in tropical developing countries, where health and safety regulations may not be as tightly regulated, a large and informal work sector exists, and daily temperatures are increasing (Lucas et al. 2014; Kjellstrom et al. 2009). Recent evidence is also emerging regarding the thermal inequality for migrant workers, particularly in manual labor jobs including construction and agriculture (Crowe et al. 2010; Mirabelli et al. 2010; Gares and Montz 2014).

Most strategies for reducing heat-related health outcomes assume some level of homogeneity in heat exposure. In this case, an implicit methodological assumption is made that individuals living or working in the same city, neighborhood, or community experience the same environmental conditions. This type of assumption is necessitated by the availability of exposure data, as well as data on population characteristics and other environmental and socioeconomic factors (Kuras et al. 2015). Moreover, most individuals move across a range of thermal conditions throughout the day, and the prevalence of climate-controlled buildings has likely increased the divergence between weather station observations and personal heat exposure (Bernhard et al. 2015). Small-scale variations in land cover, as well as other atmospheric variables such as humidity, solar radiation, and wind speed, also contribute to potential exposure misclassification (Bernhard et al. 2015). As a result, efforts aimed at mitigating heat-health outcomes based on population-level, fixed-point datasets might target locations and populations that are different from those where exposure to extreme heat is greatest (Höppe 1997; Hondula et al. 2015). Therefore, further analysis of heat exposure at the scale of the individual is needed and such analysis is becoming increasingly possible through a wide range of methodological techniques (Kuras et al. 2017). New techniques and the adaptation of techniques from other fields, such as crowd sourcing of social media data (Jung and Uejio 2017), transportation simulation modeling (Karner et al. 2015), or mobile weather units serve as potential avenues of research (Rajkovich and Larsen 2016).

As biometeorologists continue to contribute to discussions regarding the reduction of outdoor thermal stress and health risks, indoor environments command the attention of this research community as well. The indoor environment has long been recognized as an important area of study for the biometeorology community (Höppe and Martinac 1998), because people on average spend upwards of 90% of their time indoors (Institute of Medicine 2011), with important research completed on the vulnerable elderly sub-group. Indoor exposure (to heat, cold, or air pollutants) is thus a non-trivial component of the cumulative exposure of many individuals. Furthermore, if projections of increasingly frequent and intense heat waves come to bear (Meehl and Tebaldi 2004), the indoor environment may increasingly become a place of refuge for urban dwellers, particularly in places that are projected to experience extreme heat and humidity at levels unsafe for spending time outside at given times (Mazdiyasni et al. 2017). Given that the global population is aging and chronic disease rates continue to rise, further research examining practical and cost-effective interventions and warning systems is needed (Huang et al. 2013).

Finally, debate continues regarding the role of air conditioning as an effective adaptation measure for reducing rates of heat-related mortality (Bobb et al. 2014; Kysely and Plavcová 2012). Related consequences involve the anthropogenic heating created from air conditioning units (Salamanca et al. 2014), issues of brownouts or blackouts that cause cascading failures across public health systems (Klinger et al. 2014), and a lack of human natural acclimatization to higher temperatures due to tropical air penetrating into sub-arctic regions (Leung and Gough 2016). Building a more comprehensive understanding of the social and physical determinants of indoor and outdoor thermal conditions (including physical and social factors) and shaping policy and programmatic efforts to alleviate circumstances of dangerous indoor heat and cold is a significant opportunity for biometeorologists and collaborators from engineering and social science disciplines in the coming decades.

Agricultural productivity

Global agricultural production has doubled since the 1970s in conjunction with population. This growth is associated with a 25% increase in worldwide greenhouse gas (GHG) emissions (Bennetzen et al. 2016), yet based on 2005 to 2007 production levels, an estimated 60% increase in agricultural output is needed to fulfill the dietary requirements of the increasing global population (FAO 2013). In addition to population and agricultural growth, society is faced with the impacts of climatic change and other environmental changes such as deforestation. It is also important to consider the socioeconomic impact of agricultural production, particularly in developing countries, as regional variability in future temperature and precipitation patterns may impact food security, economic development, and global geopolitics (IPCC 2014; Silanikove and Koluman-Darcan 2015; Wheeer and Von Braun 2013). Moving forward, numerous challenges exist with respect to agricultural production and consumption—intertwining economics, climatology, and environmental management. These issues fall directly within the realms of ongoing research in plant and animal biometeorology and connect to several of the SDGs proposed by the United Nations, especially "zero hunger" and good health and well-being (Table 1).

Crops

Climate variability and the uncertainties that coincide with climate change are expected to play a significant role in crop production in the future. Crops accumulate biomass through photosynthesis, and rising temperatures can modify the crop growing season (Allen and Sheridan 2016) which may reduce biomass accumulation and impact crop yield in certain regions of the world (Zhang et al. 2017). These increased temperatures along with changes in precipitation will also modify where and when crops are grown. From 1964 to 2007, Lesk et al. (2016) estimated losses of up to 10% in global cereal production due to droughts and extreme temperatures. While increased probability for drought and/or high-precipitation events is among the projected changes in climate for some regions (Lesk et al. 2016; Teixeira et al. 2013), there are opportunities to expand agricultural production in areas projected to receive higher amounts of annual precipitation (Laurance et al. 2014). And while these impacts may be regional, the interconnected nature of our food system is important to highlight. Water resources, declining soil quality, and increased GHG emissions are related factors to cost, quality, and quantity of crop production (Tipathi et al. 2014).

In developing more sustainable agricultural production, there are several key adaptive strategies which can be adopted. Developing and implementing best management practices can lessen runoff pollution and the need for additional management costs. In addition to improving communication and collaboration with local stakeholders and communities, the refinement of regional crop models that understand the complex processes and interactions (water cycle, soil type, and climate-related indicators) associated with crop production enhances application and adaptive capacity of farmers (Elliott et al. 2015; Nelson et al. 2014). Improving data collection and resolution in time and space is also a key challenge in understanding agriculture productivity and thus managing or planning for the future. Remote sensing has provided valuable measurements into agronomic management over the past few decades, and multispectral and hyperspectral imagery is inseparable part of twenty-first century crop modeling (Gitelson 2016). These data collecting techniques can better detect crop yield, drought, and crop yield prediction. Regional adaptation in agronomic management (Liu et al. 2013) and cultivar renewal (Wang et al. 2012) is also necessary to improve crop production in a sustainable manner.

Citizen scientists collecting agricultural observations are more ubiquitous and qualified than ever (Mehdipoor et al. 2015). These timely, low-cost observations can calibrate and validate the current crop productivity models at different spatial and temporal scales (Beza et al. 2017). However, citizen scientists' observations are largely sparse throughout the world without the possibility of replication and with important differences in collection protocols (Schwartz et al. 2013). Thus, training and educating are necessities in this area to allow for efficient and reliable data collection, a goal that falls under the SDG of "quality education."

Animal

Livestock production plays a key role in the provision of food, accounting for 70% of agricultural land use worldwide (Gaughan and Cawdell-Smith 2015). Silanikove and Koluman-Darcan (2015) described the negative impacts of extreme temperatures on livestock production, namely: decreased feed intake and growth; decrease of the quality of meat, milk, and eggs; occurrence of reproductive problems; and increased susceptibility to infections and diseases. These climate-related impacts can result in a financial burden to both livestock producers and consumers (Gaughan and Cawdell-Smith 2015; Sejian et al. 2015).

An animal's genotype is a major factor contributing to heat tolerance. The identification of heat tolerant livestock species is not a new concept, and many breeds are already known for this thermal tolerance characteristic, i.e., Brahman and other *Bos indicus* cattle breeds (Brown-Brandl et al. 2006). Genetic selection and modification create an opportunity to improve the thermotolerance of many species. For production species, Rhoads et al. (2013) suggested that as genetic improvement programs continue to place emphasis on the economically significant traits (i.e., growth and production, feed conversion, carcass quality, reproductive efficiency), the thermotolerance of these animals decreased. However, in many cases, heat tolerance comes at a cost of growth and reproduction when compared with non-heat tolerant counterparts (Gaughan et al. 2010). The use of intensive systems for animal husbandry—for which the main objectives are to reduce land use and to provide a controlled microclimate for optimal performance conditions—has been associated with the occurrence of some sanitary and ecological problems as well as a loss of genetic diversity. Moreover, consumers continue to demand improved animal welfare standards in production systems (Napolitano et al. 2013); thus a solution is needed to provide sustainable, safe, and optimal reproduction while maintaining food quantity.

Animal thermal comfort models are a common biometeorological method for managing animals within hot climatic conditions and commonly used in the agricultural sector (Hahn 1999; Mader 2003; Gaughan et al. 2008; Mader et al. 2010). As within human models, a challenge is present in identifying methods of incorporating meteorological and physiological variables into a single thermal comfort index. This challenge is further confounded by developing a model that is applicable for numerous species (and genotypes) across varied environmental conditions worldwide (Mader et al. 2010; DaSilva and Maia 2013). The development and use of these models also require an understanding of thermal exchanges between the animal and their thermal environment (Parsons et al. 2001) and thus require appropriate technologies and sample size. However, such studies are increasingly important with rising temperatures and the imminent increase of animal production in tropical areas; thus, it is more crucial than ever to study thermal exchanges and the resulting impacts on the animal health and production (Nascimento 2015).

These above challenges crossing animal and plant biometeorology must be reconciled with the need to increase global food production from both livestock and crops. Therefore, continued investigation of the science of seasonal plant and animal activities and how seasonal and interannual variations in climate influence these activities will become increasingly important as climate change progresses. For example, plant or animal diseases and pests may change their range with changing climates (Silanikove and Koluman-Darcan 2015). Pest species may adapt and survive in warmer environmental conditions and their control may depend on the increasing use of pesticides and herbicides. Additionally, water concerns exist with respect to agricultural productivity (Nath et al. 2017; Howitt et al. 2014; Vargas et al. 2017).

It is important to note that the potential effects of climate change are difficult to quantify as it relates to agricultural production as the impacts will vary across both time and space (Gaughan and Cawdell-Smith 2015). Some regions will experience additional precipitation which may offer opportunity to increase production. Thus, future research directions must encompass the potential of a wide range of "futures," allow for mitigation of GHGs with increased production, and prepare for the challenges facing agricultural production with respect to future demands for global food production from both livestock and crops. Moving forward, collaboration among researchers spanning biometeorological sub-disciplines (microclimatology, thermal comfort, phenology, etc.) and related areas of water resource management and animal physiology is essential in addressing the SDGs noted in Table 1. In addition to reducing GHG emissions, new techniques will be needed to increase agricultural yields all the while improving water and land use conservation and providing greater support across sectors to ensure a more equitably and safe distribution of food.

Air quality

To address the human health, ecological, and policy implications of atmospheric pollution, teams of scientists that understand its multifaceted nature—the physical, biological, meteorological, chemical, and social processes—are necessary. Air quality relates to multiple UN SDGs, in particular good health and well-being and "climate action," and the effects of air pollution on plants, animals, and humans have been a prominent focus in the study of biometeorology (Table 1). As noted by former ISB President Frederick Sargent, *air of many urban aggregations contains sufficient levels of manmade biologically active chemicals to damage the health of plants and animals as well as man himself* (Sargent 1963). With air pollution recognized as the number one burden of disease worldwide (Cohen et al. 2005; Brauer et al. 2012; Cohen et al. 2017), collaborative potential with respect to air quality issues have expanded. Although prominent steps have been taken to lower the air pollution levels in most developed countries, levels remain elevated in highly populated countries such as India and China (Health Effects Institute 2017), and population growth remains a challenge to mitigate pollution levels—both indoor and outdoor—worldwide.

While there are numerous regulations or guidelines for outdoor ambient air quality, such as in the United States (EPA 1990), the European Union (EU 1996), or Australia (AU 2015), Steinemann et al. (2017) highlight the fact that there are no consistent regulations concerning indoor air quality, where people spend 90% their time. Even with improvements in indoor air quality in many developed countries, indoor air pollution is still responsible for approximately 4.3 million deaths per year, predominantly in developing countries (WHO 2016). The sources of indoor air pollution vary largely and range from indoor biomass burning, smoking, building materials and furnishing, air conditioning, and infiltration of ambient air pollution, resulting in the presence of air pollutants such as particulate matter (PM), nitrogen dioxide, carbon monoxide, formaldehyde, volatile organic compounds, and biological agents (Gold 1992).

The large difference in pollution patterns between low- and high-income countries is a significant challenge in current indoor air quality research. In low-income countries, the lack of adequate energy sources affects approximately three billion people and leads to indoor biomass burning resulting in high-PM concentrations and other combustion exhausts (WHO 2005). In the latter, indoor air pollution results less often not only in mortality but also in cardiovascular and respiratory diseases, as well as reduced productivity (Tham 2016).

Research interest in indoor air quality in developed countries increased further with the introduction of low-energy or green buildings. Recent studies emphasize how reduced energy consumption in buildings may promote sustainability but not necessarily indoor air quality (Tong et al. 2016; Steinemann et al. 2017). In particular, after renovation and building of new “green” houses, increased levels of volatile organic compounds and formaldehyde were found (Kauneliene et al. 2016; Coombs et al. 2016). Tong et al. (2016) focused on the influence of outdoor and indoor AQ when passively ventilating the buildings. They found the indoor particle concentration to decline exponentially with the distance from a road. The main objective for future research will be to develop a consistent system of measurement of indoor AQ (e.g., low-cost air quality sensors) in both developing and developed countries for protection of health and well-being. New technologies will play a large role in the accurate and finely scaled measurements in indoor-outdoor air quality studies for source recognition and to reduce exposure classification (Mehdipoor et al. 2017).

Past research in outdoor air quality—a well-studied area over the last few decades in the epidemiological literature (see review by Schwartz 1994)—has examined specific air pollutants in a direct association manner (Goldberg et al. 2013), utilized air pollutants as confounders or effect modifiers in studying heat or cold mortality (Baccini et al. 2008; Ma et al. 2011; Basu 2009), and assessed interactive effects (with temperature and/or other pollutants) at various time lags (Breitner et al. 2014). Further, the use of biometeorological indices in connection to several pollutants is advancing our ability to understand combined influences of the combined thermal environment and air pollution on health (Lokys et al. 2017; Jacobs et al. 2014). Further, many have studied the effects of biogenic and/or aeroallergens on urban subpopulations (Makra et al. 2015; Hebbern and Cakmak 2015; De Gouw et al. 2015), with growing concerns of elevated levels of aeroallergens and thus respiratory illness and allergies with climate change (Beggs and Bambrick 2006).

With the spatial and temporal variability of air pollution, the impact cannot adequately be assessed from just one point in time or space (Kwan 2012). Therefore, opportunities that connect finer scale information via models or sensors to health outcomes and indoor/outdoor exposures. These data can augment current measurement and methods surrounding air pollution epidemiology and citizen science (McKercher et al. 2017; Özkaynak et al. 2013), and from new technologies, opportunities arise for novel discoveries concerning both outdoor and indoor urban air quality. Advocates of social justice for low income or children are also interested in air pollution research to reduce air quality-related vulnerabilities and inequalities in exposure (Mitchell and Dorling 2003; Jerrett et al. 2001; Vanos 2015). A biometeorologist of the future studying air quality and human health will also require knowledge of sensor technologies, physiology, spatial modeling, and citizen science. Within biometeorology, researchers in public health, architectural design, energy, environmental toxicology, and chemistry are well-positioned to come together, acknowledging connections with meteorology, agriculture, economy, and climate change, for solving new challenges into the coming century.

Urbanization

Currently, 54% of the world’s population lives in urban areas, and this share is expected to increase to 66% by 2050 (United Nations 2014). Rapid urbanization combined with projected climate change will impact our social, economic, and health systems both now and in the future (Grimmond et al. 2010) and is intricately connected to thermal environments, air quality, and agriculture needs for growing urban populations. This rapid change will also shape society’s ability to achieve many of the UN SDGs, notably sustainable cities and communities and “clean water and sanitation” (Table 1).

Over the scale of metropolitan regions, the impacts of urbanization on climate can equal or exceed those associated with global-scale climate change (Georgescu et al. 2014). Within cities, atmospheric variables such as temperature, radiation, wind, and humidity change rapidly over small spaces due to complex urban design (Brown and Gillespie 1995). The migration of individuals towards urban environment may have negative consequences to their personal well-beings. For example, aboriginal Canadians became more susceptible to weather-related health effects after moving from remote communities to urban areas (Tam et al. 2013). However, design of the urban landscape can help to ameliorate the combined effects of weather and the built environment on humans. The inclusion of large green spaces has been shown to have the effect of lowering urban temperatures (Brown et al. 2015). Some epidemiological research suggests an association between proximity to urban green and blue (water) and lower incidence of certain adverse health outcomes (Burkart et al. 2016).

Coastal communities, urban and rural alike, are faced with infrastructure challenges and water quality concerns. Programs such as the Chesapeake Bay Landscape Professional Certification Program provide training for conservation-based landscaping and residential scale stewardship (Chesapeake Bay Landscape Professional Certification 2017). By leveraging green infrastructure, flood risk can be reduced and water quality improved. Collaborations such as Dutch Dialogues combine the expertise of architects, engineers, marine scientists, and policy-makers to mitigate the impacts of sea level rise on highly vulnerable communities (Dutch Dialogues Virginia 2016). After Hurricane Hazel in 1954, there was broad public support for Toronto to create a centralized regional conservation agency that oversees and manages the watershed, flood risk, environmental monitoring, and housing development within its regulated area. Consequently, the impact of major floods was reduced (Nirupama et al. 2014). These initiatives draw on the interdisciplinary nature of ongoing research in biometeorology.

Urbanization in developing countries presents further challenges for solving problems due to the need for refined adaptation needs based on local conditions and capacity, yet a lack of physical, environmental, and health data exists and the adaptive capacity in developing countries is lower. For example, the spatial synoptic classification, which is a powerful tool in biometeorology, cannot be used without a critical look on actual weather data in the tropics (Dixon et al. 2016), yet often data are not available for the system to be applied. This underlines the need for implementation of regular, quality controlled measurements of biometeorological variables so that solutions affecting the most vulnerable populations can be refined. Even though researchers try to address this problem with an increasing number of biometeorological studies in these regions (Eludoyin et al. 2014, Ndetto and Matzarakis 2015), the challenges still provide additional opportunities to the research community.

Biometeorology has long played a significant role in understanding biophysical processes within urban areas (Nastos et al. 2013). Biometeorologists within architecture, engineering, design, and public policy provide expertise and recognition of the synergy across their disciplines. Such perspectives are advantageous in addressing future urban issues whether it be related to the urban heat island, water and food resources, urban development and design, or economic growth.

Synthesis and conclusions

Across the four themes we have examined in this commentary, it is clear that the tools needed to be an effective biometeorologist in the modern era are diverse and evolving. Common data types and methodological approaches across the four themes include new data science techniques, low-cost sensor technology, GIScience, physiological modeling (of people, plants, and animals), and remote sensing. Some themes also alluded to citizen science and the social science fields of anthropology, economics, psychology, and sociology as becoming an increasingly important part of the biometeorological research landscape. Research in all themes seems increasingly dependent on cross-disciplinary collaboration, systems-level thinking, and the ability to adopt international or global perspectives. We have also identified many connections between predominant themes of biometeorology research and the UN SDGs, which suggests that continuing improvements to biometeorology training and education could enhance the likelihood of making progress towards those goals in the future.

Our experiences suggest that the wide array of tools that will likely be demanded of future biometeorologists are not housed within the institutional programs (e.g., degree tracks) that students are expected to follow in higher education. An immediate need is to more rigorously document the different formal training models that currently exist for developing animal, human, and plant biometeorologists. Complementary enrichment opportunities such as study abroad/exchange programs, and/or participation in workshops specifically tailored to interdisciplinary research, have and will likely continue to serve as important parts of a comprehensive educational experience for an aspiring biometeorologist. The fact that these types of educational and training experiences tend to fall outside of the traditional degree programs that biometeorologists will emerge from—at least in the relatively near future—places the responsibility upon academic advisors and mentors to help trainees become aware of and pursue opportunities that they are not guaranteed to encounter in their academic track. Networking between trainees can also help broaden awareness of and access to complimentary educational opportunities.

In our discussions, we have come to realize that biometeorological researchers, especially new professionals, may not be the best-positioned to advocate and dedicate time for changes in educational infrastructure that might facilitate improved training models for biometeorologists moving forward. A key factor contributing to this lack of time is the current incentive structure for young researchers, requirements for promotion and tenure do not incorporate exploring and building new educational models or programs. Inclusion of researchers who study the processes of higher education in the discussions of the ISB would potentially create a better alignment of incentive structures and perspectives to achieve the types of changes that the society's membership deems important. Such collaboration might also be attractive to higher educational researchers interesting in interdisciplinary teaching and learning and the role of certain teaching styles such as project-based, experiential, and service learning that seem to interface well with biometeorology.

In summary, the membership of the SNP sees an opportunity for a collision of biometeorology-framed research and education with the grand sustainability challenges of the twenty-first century. The educational foundations that have served the society well through its first 60 years, however, are not necessarily going to serve the next generations of scholars as well as they have the previous ones. We advocate for a more explicit integration of biometeorological education into post-secondary curricula in a manner that not only allows young scholars' access to foundational concepts such as physiology and meteorology but also requires across today's disciplinary boundaries. We see this approach as essential because the global challenges we face must be dealt with in an interdisciplinary manner. As Allen and Akpinar-Elci (2016) note, o*ur disciplines must serve as lenses by which we view and interpret the world rather than barriers to progress*. Our twenty-first century challenges are connected, and our strength as a society—international in scale, collaborative across disciplines, and integrative with methodological approaches—makes biometeorologists well-positioned to help solve the complex sustainability challenges of the coming century.

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