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VIEWPOINT

Impact of Climate Change on Health and Performance

Aligning thermal physiology and biometeorological research for heat adaptation and resilience in a changing climate

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INTRODUCTION

At no other time in history has the importance of understanding and reducing the impacts of extreme heat on health been so vital. Climate change, an aging population, urban growth, and global sustainability challenges only bolster the need for interdisciplinary approaches that bring novel insights to extreme heat challenges for the betterment of public health. To understand environmental impacts more holistically on human heat stress and strain in a changing climate, ample opportunities for collaboration exist between biometeorologists and thermal physiologists. Although thermal physiologists work at the individual level, human biometeorologists, who study interactions between atmospheric processes and humans, apply various multiscalar techniques across climate science and epidemiology to understand exposures and impacts based on population-level characteristics. This Viewpoint underscores the importance of cross-disciplinary work and understanding across thermal physiology, biometeorology, and climate/atmospheric sciences in supporting real-world solutions to extreme heat challenges facing the globe—solutions that are applicable to cities, stakeholders, and people.

This Viewpoint approaches the problem of extreme heat challenges to human health from multiple angles, yet predominantly brings in critical insight from climate/meteorological perspectives across scales, data, and applications to heat and health. We provide an explainer for various types of biometeorological data, from weather and climate to unique urban or personal sensing systems, and how they can aid in creating enhanced impact of the work of thermal physiologists. We note limitations in spatiotemporal scales and assumptions of common data techniques, and further summarize impactful examples of interdisciplinary, synergistic endeavors that have advanced knowledge of human adaptive capacity to the heat. Finally, we call on more physiologists and biometeorologists to partner, particularly those focusing on urban-to-global climate change, to advance heat-health solutions that protect the most at-risk populations to better drive decision-making and heat resilience efforts.

HEAT: A LONG-STANDING, WIDESPREAD, INCREASINGLY SERIOUS GLOBAL CHALLENGE

According to the Intergovernmental Panel on Climate Change (IPCC), the globe has seen an increase in excessively warm days and nights since 1950, and it is "virtually certain" (99%–100% probability) that this increase, both in frequency and magnitude, will continue throughout the century. Statements of such certainty are rare and indicate robust evidence and high agreement of climate studies on global temperatures. The robust certainty underscores the importance of improving the knowledge of causal heat exposure pathways to support evidence-based decisions to protect health and support adaptation. Climate change attribution studies already show exacerbation of recent heat events due to climate change (1, 2), causing higher heat-related deaths (3). Attribution studies also support impact-based decision-making, adaptation, and policy moving forward (4, 5).

Deadly and record-breaking heat waves have affected nearly every continent in 2023, but the presence of heat waves and their impacts on human health and society at large are not new. A glance back at prominent heatwaves highlights widespread loss of life: the European heatwaves of 2003 [70,000 lives lost (6)] and 2022 [60,000 lives lost (7)], the India nationwide heatwave of 2015 [2,500 people perishing (8)], and the North American heatwaves and droughts of 1995 [700 victims (9)] and 2021 [1,400 victims (1, 10)]. These numbers do not account for the substantial heat-related morbidity associated with these events. New methods and measurements have arisen to help better quantify heat exposures in space and time, enhancing our ability to connect heat to human health. However, human-level factors (e.g., exposure, age) are rarely examined in conjunction with weather and climate data in a spatiotemporally appropriate way, whether under contemporary or projected climates. Such incongruence can limit confidence in selecting effective real-world interventions to reduce health impacts (11), yet scientists are also striving to answer such significant questions within their knowledge domains and under existing data constraints.

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What meteorological and climate data and methods exist to support thermal physiologists in their heat and health research? Where can thermal physiology align with biometeorology and bioclimatology to support meaningful heat adaptation research efforts? And what are the current limitations in each discipline to prioritize as future research foci to advance public health protection during extreme heat events? Here, we seek to engage physiologists on the diversity in environmental data (climate and weather) available or that can be collected across space and time for these interdisciplinary research applications.

A PRIMER FOR APPLIED PHYSIOLOGISTS: BIOMETEOROLOGICAL AND BIOCLIMATOLOGICAL OBSERVATIONS AND DATASETS FOR HEAT STRESS QUANTIFICATION

Numerous weather and climate datasets are available to quantify where and when dangerous environmental conditions exist, as measured at the individual level by thermophysiological studies, thus expanding the application of such studies. These datasets include data collected at different spatial and temporal scales, which creates varying modes of usefulness for applying thermophysiological insights. Most datasets, whether observation- or model-based, include at least three of the environmental variables that affect human thermal balance: air temperature, humidity, and wind speed; solar radiation measurements are often not part of such observational datasets. Solar radiation levels at the earth's surface, a critical component of the human energy balance, can be modeled or obtained from databases such as the National Solar Radiation Database (12). Here, we provide an overview of various weather and climate datasets and how they can be applied in a heat-health study, which is also summarized in Table 1.

Weather Station Observations

Observations have been regularly taken at thousands of ground-based weather stations over the past century, while some more primitive records go back multiple centuries (13). These data are archived and freely available on national and global scales through entities such as the National Centers for Environmental Information (NCEI), Hadley Center's Integrated Surface Dataset (HadISD), and the Global Historical Climatology Network (GHCN). Modern official observations are automated from the sensors, usually located at airports or other open spaces with minimal modification over time and recorded hourly. Typically, the placement of these stations should mean that these historical observations do not include urban heat island (UHI) effects (experienced by urban populations) on the station's ambient environment. However, recent studies have shown this not to be the case in all instances depending on station location. For example, the airport weather station in Phoenix, Arizona is within the urban area. This station shows intense increases in average mean daytime air temperature since 1950 and a decreased diurnal range (nighttime UHI), whereas a rural station shows a shallower air temperature increase and no significant change in the diurnal range (14). This phenomenon is called "urban-induced warming" and is important to account for when studying heat exposures to urban dwellers. State mesonets and urban micronets—networks of sensors to fill in gaps across states or even blocks across the cityscape—are becoming more popular, collecting similar data as airport observations (more likely to collect radiation) and at similar or finer time scales. Finally, researchers should use caution or avoid the use of crowd-sourced weather data from personal weather stations as quality assurance and control procedures cannot be ensured.

Gridded Data Products

Past weather data can also be represented on a spatially continuous grid for continuous spatiotemporal coverage. NASA's Daymet product ingests station observations and statistically interpolates between these data points to create a 1 km $\times$ 1 km grid of maximum and minimum temperatures, water vapor pressure, and shortwave radiation daily (15). Atmospheric reanalysis products combine the gridded structure of the models used in weather forecasting with ground-truth observations from weather station measurements to create a spatially continuous data set of atmospheric conditions in the past. A spatiotemporally continuous data set can be produced by rerunning a previous weather model and inputting observations at set times and locations to help tune the simulation toward the most correct solution. Some reanalysis products, such as the European Centre for Medium-Range Forecasting (ECMWF)'s 5th reanalysis (ERA5), have begun to output heat stress metrics such as wet-bulb temperature (T_w), wet bulb globe temperature (WBGT), and the Universal Thermal Climate Index (UTCI) as main results from the model run for immediate use (16).

Climate Models

Climate models are complex computer simulations that allow for coupling and interaction between all components of the climate system (land, atmosphere, ocean, ice, etc.) at various levels to predict how the given system evolves due to the transfer of energy and mass through the components. Projections of future climatic conditions are developed using future scenarios of socioeconomic production and associated greenhouse gas emissions. These scenarios, known as shared socioeconomic pathways (SSPs), impart differing amounts of radiative forcing (wherein higher forcing generally equates to higher global average temperatures) on the climate system based on the future trajectories of the world economic system (called a Representative Concentration Pathway, RCP). Together, a projected scenario is denoted by an "SSP-RCP." For example, SSP2-4.5 indicates a middle-of-the-road emissions scenario with 4.5 Wm^{-2} higher radiative forcing by 2100 compared to preindustrial levels, which may be likely considering existing net-zero commitments (17). The latest Coupled Model Intercomparison Project (CMIP), which provides the climate model output for IPCC reports, includes over 100 climate models, each running the different SSP-RCP scenarios to provide a range of future climates.

Overall, these hundreds of scenarios project possible future average climate warming by end-of-century, ranging from 1.0°C in the SSP1-1.9 scenario to as high as 5.7°C in the SSP5-

Table 1. *Descriptions of environmental data sources that can be used in studies linking biometeorology and thermal physiology*

Data Type	Description	Examples	Spatial Scale	Temporal Scale
Weather station observations	Automated measures of temperature, humidity, and wind (sometimes solar radiation)	Airport weather observations, US state mesonets, city-scale urban micronets	Point-scale measurements which may or may not be representative of weather conditions further away from measurement station	Standard observations are taken at least once an hour, but some systems may produce more frequent observations in their datasets
Gridded products				
Interpolated observations	Statistical interpolation of unevenly spaced weather observations to provide a continuous grid of weather data. Temperature is always included while other variables are dependent on product used.	NASA Daymet; NOAA nClimGrid; Hadley Center HadCRUT	Varies between products (e.g., Daymet—1 km; HadCRUT—5°)	Typically daily (maximum, minimum, average) or monthly (average)
Atmospheric reanalysis	The post hoc re-run of a numerical weather prediction model where observations of the observed weather are included at set temporal intervals to create a spatially continuous, better ground-truth version of the weather that occurred.	European Center for Medium-Range Weather Forecasting's 5th Reanalysis (ERA5); NASA's Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2); NCEP Climate Forecast System Version 2 (CFS v2)	10 s to 100 s of kilometers	Hourly, daily, or monthly
Climate model data	Historical and future projections of climate based on interactions between coupled Earth systems and predictions of future socioeconomic and greenhouse gas emission pathways	Composition of coupled model intercomparison project (CMIP) models used by the Intergovernmental Panel on Climate Change (IPCC)—e.g., Community Earth System Model (CESM; National Center for Atmospheric Research, USA), Canadian Earth System Model (CanESM; Canada), Max Planck Institute-Earth System Model (MPI-ESM; Germany)	10 s to 100 s of kilometers	3- or 6-hourly, daily, monthly
Personal exposure data	Measurements of the ambient environment at the location of an individual user, usually air temperature and humidity	Example sensors might include Kestrel Drops, iButtons, and Hobo dataloggers. Care should be taken to determine how to properly take indoor vs. outdoor measurements to avoid poor data quality	Point-based measurement either in one location (e.g., in home) or sometimes on a person (exposed to air)	User- and sensor-dictated, though resolution of an archived dataset will depend on the sensor's data storage capabilities

8.5 scenario (13). Understanding these potential pathways is essential to allow physiologists to interpret the possible futures that exist when it comes to heat exposures and necessary heat adaptation strategies. For example, without adaptation and following a high-emissions pathway, the IPCC reports that equatorial locations (e.g., Amazonia, Indonesia, Central Africa) will see 365 days/year by end-of-century with conditions that may cause heat mortality (13).

Climate models are not 100% accurate as uncertainty stems from the scenario used, natural variability of the climate, and internal model structure, but they have proven to perform well at reproducing the trajectory of the mean state of global temperature increases over the past few decades. They are gridded products, much like those described earlier, with trade-offs between spatial and temporal resolution due to compute time and data storage restrictions. Temporally, most climate model projections publicly available for research provide multihourly (e.g., 3- or 6-h data), daily, or monthly data out to at least 2100 at spatial scales of tens of kilometers [i.e., $\sim 1^\circ \times 1.25^\circ$ ($\sim 100 \times 100$ km^2) atmosphere/land grid]. Model outputs can be updated to finer spatial scales via a process known as downscaling based on user needs.

SYNERGISTIC ENDEAVORS ADVANCING KNOWLEDGE OF HEAT ADAPTATION

The wealth of climate and weather data spanning the past, present, and future can provide context to the empirically derived, individual-level connections between a person and their environment to support heat and health research. "Heat exposure pathways" are affected by climate region (e.g., humid vs. dry climates), environmental contexts (e.g., indoor, outdoor, building type, vegetation), population diversity and vulnerability (e.g., age, physiologic susceptibilities), and adaptive capacity (including behavior change and technology use) (18). Yet little is known regarding personal exposures and city-to-person-level adaptation strategies to modulate heat stress to avoid dangerous health consequences (19). Climate change, together with urban-induced warming, amplifies overheating in cities, increasing indoor energy demands (20). Outdoor climate and weather data are essential to inform indoor heat exposures and energy use during heatwaves using building energy models (21, 22). Yet ecologically valid data concerning heat exposures across built and environmental contexts alongside behavior, health impacts, and perception are virtually absent from the literature, as are studies and data (both climate and health) on the heat burden in low- and middle-income countries (LMICs), even though they are most affected by heat and have a lower capacity to adapt (23).

Numerous studies in the last two decades have called for more research on personal and household level heat exposures and impacts to fill a critical gap in our understanding of indoor heat exposure and vulnerability (24–27). Heat exposure can be measured at a personal level through the use of low-cost, small-scale sensors or mobile phone technology and at a household level with low-cost sensors (28); however, current data collection methods (such as quantifying thermal conditions with appropriate instrumentation) are inconsistent and do not account for the three dimensions of exposure (intensity, duration, and frequency) along with physiological outcomes; most research has focused on heat intensity (18, 29). Importantly, researchers are exploring new ways to conduct remote environmental and personal data collection to evaluate the ecological validity of controlled laboratory measurements (30)––such studies are excellent opportunities for collaboration in the biometeorology and physiological communities. Future research bridging climate sciences and thermophysiology can transform traditional personal heat exposure methods to seamlessly integrate many physiological, behavioral, and environmental variables of interest. Such work can also inform heat chamber studies using real-world situations and adaptive strategies to inform advanced monitoring protocols.

New information around adaptive capacity and behavior in the heat (together resulting in 'heat resilience') can and should support cities, governments, communities, and people in heat safety and protection. Yet how can we ensure that actionable information is translated to those it can benefit most? Heat vulnerability research has long-asked such questions, with a push to make heat and health research more relevant for policy- and city-level actions through heat metrics for evaluation (31).

Understanding the Limits of Human Tolerance to Extreme Heat

Due to anthropogenic climate change, current environmental conditions are increasingly challenging the limits of human tolerance to the heat in some parts of the world. Various physiology-based metrics have been applied to project future heat stress. For the past decade, the singular psychometric T_w threshold of 35°C, introduced by Sherwood and Huber (32), has been the conventional method for assessing the adaptability limits of humans exposed to extreme heat with climate change. This conservative limit is based on simple biophysical principles under which dry and evaporative heat transfer are not possible. Unable to dissipate heat, it is assumed the body reaches a core temperature at or higher than that associated with the onset of heat stroke after 6 h. The authors showed that this limit would be surpassed by end-of-century on regular timescales under 6°C of global mean surface temperature (GMST) rise. This work has been oft-cited in the media to describe the dangers of extreme heat associated with climate change but has also been cited in the literature to determine the future habitability of regions of South Asia (33) and current regional exceedance of this threshold (34). However, as noted by Huber (35), this limit was always understood to be an upper limit for fully hydrated, perfectly sweating (and thus healthy) people in the shade with no human agency to seek cooling. Indeed, the real-world limits are likely lower, as shown by Vanos et al. (36), who introduced modeled physiological survival limits using the T_w, whereby the 35°C T_w overestimates risk by 13.1°C under dry conditions for older populations [vs. being nearly equal (0.9°C lower) for humid conditions in healthy young populations]. Continued progression of such research provides ample opportunity for themophysiologists to engage with climate scientists to perform in chamber settings at a T_w of 35°C based on different combinations of temperature and humidity, with or without solar radiation, and varying winds over the time scales of climate model output (e.g., 3- or 6-h) for different types of people (36).

Empirical testing of the 35°C T_w limit did not occur until (37) published on critical wet-bulb limits across a range of extreme heat conditions in a population of young, healthy, yet unacclimated subjects in Central Pennsylvania, USA. The authors found that those subjects, doing minimal work, began to experience uncompensable heat stress at $T_w \sim$ 30.6°C in warm, humid conditions with a linear decrease in critical T_w with increasing temperature and decreasing relative humidity, indicating the critical role the interaction of temperature and humidity play in physiological heat strain (11). The onset of cardiovascular drift occurred in less severe environments in the same population (38). These new limits (37) have been used in larger biometeorological studies looking at past threshold exceedance, especially in South Asia (39, 40), as well as an update to future threshold exceedance, adaptive possibilities, and regional habitability (41, 42). Thermal physiology and climate research can align in this space and model the impacts of adaptation strategies, such as behavior (43) and personal cooling strategies (44), at exposures near the limit of human heat tolerance.

Public Health Guidance on Fan Usage

Most of the populated world is still decades from prolonged exposures to levels of heat exceeding human tolerance, yet heat still causes illness and death at alarming rates across the globe today. Although air conditioning (AC) can be a great equalizer in heat safety, it can be cost-prohibitive to install and its use is unsustainable (19). Electric fans can provide a cheaper alternative to cooling during extreme heat events. World Health Organization (WHO) guidelines advocated for fan use for cooling for air temperatures up to 35°C, after which the WHO argued that fan use would increase dry heat gain and be rendered ineffective and even harmful. Morris et al. (45) used biophysical modeling based on previous empirical research to show that fans could safely be used at temperatures ranging from 37°C to 39°C depending on age and medication taken. Using this new physiologically based data and past weather observations, they found that fan usage would be safe for all groups of people for a majority of extreme heat days from 2007 to 2019. Parsons et al. (46) then used these updated fan use thresholds in a United States-wide study, finding that areas with high social vulnerability (i.e., those who would be less likely to afford the costs associated with air conditioning and thus more dependent on electric fan use), as defined by the US Centers for Disease Control, are already experiencing conditions deemed unsafe for using fans as a cooling mechanism during heatwaves. This study provides another data point indicating that a public health crisis is already in progress in some of the most at-risk communities in the United States (46).

CALL TO ACTION TO PHYSIOLOGISTS

What can be done to further the collaboration between thermal physiologists and biometeorologists? Current computing power and data storage limits mean that large-scale weather and climate databases will not reach the spatial or temporal resolution of individuals going about their daily routines. Although evolving personal and household heat exposure methods and data are gaining traction, results that will guide public health recommendations and implementation will focus more on population-level characteristics, which are more applicable to the scales at which weather and climate data can provide adequate exposure assessments.

More data from diverse populations will help better understand how climatic and physiological variability may work in tandem to enhance acclimatization and adaptation to environmental conditions. Although we currently have critical environmental limits to heat tolerance for young, healthy, unacclimated people in a specific region (e.g., Ref. 37), studying diverse populations globally and across the lifespan is essential. Much of the thermal physiology data that biometeorologists attempt to apply to a global population is underpinned by data collected from predominantly white men in high-income countries. The National Institutes of Health has made strides in ensuring sexual diversity in funded studies, but more work is needed. Is the male US military recruit, which is used as the model for measuring heat stress with the WBGT, representative of the woman fetching water from the stream in South Asia who is more chronically exposed to moist heat stress? Likely not. More thermophysiological studies are needed to understand such nuances so that climate projections using the WBGT are not only applied to one type of person. Global climate change-induced impacts will disproportionately affect those living in LMICs where there is a lack of physiological and epidemiological data. It is imperative to work with those who live in these places to gather insight and show how physiological variability (or, perhaps, lack thereof) may play a role in adapting or thriving in a changing climate.

CONCLUSIONS AND FUTURE OPPORTUNITIES

Thermal physiologists and biometeorologists represent two disciplines among many that are working at the intersections of climate change and human health and whose work can be co-beneficial in supporting evidence-based public health interventions during extreme heat events. Thermal physiologists can describe direct impacts on the human body undergoing heat stress and strain. At the same time, biometeorologists can use these data to quantify periods of environmental exposure across weather and climate time scales for more generalized public health guidance. Although scale incongruence will continue to be a limitation for the foreseeable future, there are still ample opportunities for fruitful collaboration between the fields. However, knowledge transfer and cross-disciplinary training are needed to form fully fledged answers to these research questions. We call on thermal physiologists and biometeorologists to ask new questions, get curious, and foster cross-disciplinary ties together and with others to advance heat-health solutions––solutions that protect the most at-risk populations and can better drive decision-making and heat resilience. In the face of an aging and urbanizing global population within a changing climate, we argue that enhanced use-inspired research among physiologists, climate scientists, biometeorologists, and the most relevant end-users (e.g., public health agencies and governments) is a necessity to shift the needle in health protection from extreme heat.

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AUTHOR CONTRIBUTIONS

D.J.V. and J.K.V. drafted manuscript; edited and revised manuscript; approved final version of manuscript.

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