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Dynamic Environment, Adaptive Comfort, and Cognitive Performance

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ABSTRACT

Since the invention of airconditioning over 100 years ago a central research challenge has been to define the indoor environmental temperatures best suited for occupants. The first scientific approach to this question was framed in terms of *optimising occupant thermal comfort*, commonly expressed as a U-function, symmetrical around a single optimum temperature for any given combination of the remaining comfort parameters (ISO, 2005). The inescapable conclusion drawn from such logic in the minds of risk-averse design engineers is that the only strategy able to reliably deliver occupant comfort is HVAC applied to sealed-façade architecture.

A rigorous scientific rebuttal of the "single temperature optimum" model of comfort came 30 years after PMV/PPD was first floated (e.g. de Dear and Brager, 1998; 2001). Known as the *adaptive comfort model*, a clear implication is that passive design solutions are capable of delivering comfortable internal environments across a broad swathe of climate zones, throughout most if not all of the year. But recently the "single temperature optimum" model has resurfaced, this time with its justification shifting away from the thermal comfort requirements of occupants towards their cognitive performance.

Beyond the building science domain, in disciplines such as psychology and ergonomics, the prevailing wisdom regarding temperature effects on cognitive performance is an *extended-U* rather than an inverted U function. The gist of the model is that cognitive performance is relatively stable throughout the moderate temperature range, but it rapidly deteriorates at the boundaries of thermal acceptability where stress drains the performers' attentional resources. The *extended-U* model has garnered broad acceptance across a range of disciplines with the notable exception of HVAC engineering and indoor air sciences. But the weight of research evidence tends to support the extended- rather than inverted-U model. In this paper the arguments regarding thermal effects on cognitive performance are critically evaluated.

KEYWORDS

Cognitive performance, arousal theory, temperature optimum, adaptive model.

INTRODUCTION

The effect of the thermal environment on performance and productivity has been a focus of interest among indoor environmental researchers for nearly a century, but most of that work has been conducted in relative isolation from the cognate disciplines of human performance evaluation. In his wide-ranging survey of the indoor environmental research domain Corsi (2015) observed that "… *indoor air scientists all too often work in narrow trenches, interacting primarily with those they have interacted with for years, content to dig more deeply into that of which they already have significant knowledge, and unaware of the* *connections that their work may have to those who dig in other trenches*." This insularity is clearly evident in cognitive performance research theme.

The range of indoor temperatures deemed acceptable has a strong bearing on building energy requirements because it constrains the geographic scope as well as the seasonal duration when *passive* designs are able to achieve acceptable indoor environments. Secondly, the design temperature range indoors directly impacts energy required by active systems (HVAC) to achieve them. Up until about the end of the last century the range of indoor design temperatures was mostly couched in terms of thermal comfort. Simple comfort models suggested that a range of ±1.5K around an invariant optimum temperature could ensure 90% occupant thermal acceptability (Fanger, 1970; ISO, 2005). However, more recent adaptive thermal comfort models have challenged these narrow temperature prescriptions with strong empirical evidence that indoor comfort temperatures are dependent on outdoor climatic conditions (e.g. de Dear and Brager, 1998, 2001). The adaptive comfort approach encourages warmer indoor temperatures in warmer climate zones and seasons, and *vice versa* in cooler climates and seasons. In response to this debunking of the comfort arguments HVAC peak bodies such as REHVA and ASHRAE have shifted their justifications for tight indoor temperature control away from occupant comfort towards occupant productivity (ASHRAE, 2013). Since these HVAC peak bodies exert a strong influence on air conditioning practices, HVAC-related energy and greenhouse gas emissions well beyond their European and North American jurisdictions, it behooves us to critically review the scientific evidence put forward in support of temperature effects on cognitive performance.

In this review we examine a broad collection of papers, all specifically examining the effects of thermal environment on cognitive performance, but from a variety of disciplinary perspectives *beyond* the indoor environmental sciences.

LITERATURE REVIEW

Moderate indoor thermal environments are far from hyper- and hypo-thermic scenarios because they pose no threat to health and safety. Nevertheless they are still capable of exerting adverse impacts on building occupants' cognitive performance, although the literature remains conflicted on the significance of these impacts. Two distinct theoretical perspectives have emerged. The first posits a dose-response relationship between the indoor thermal environment and cognitive performance, with *any* deviation from thermal optimum leading to a decrement in performance and productivity. The second position asserts that, depending on the thermal intensity of exposure, type of cognitive activity, and other attenuating factors, externally imposed cognitive demands can be absorbed by the buffering capacity or "cognitive reserve" of the subject, with little or no deleterious effect appearing until those adaptive resources are depleted.

The inverted-U model

Arousal theory (e.g. Duffy, 1962) has been ubiquitous in the stress literature. Alternatively known as the *Yerkes-Dodson law,* it postulates an *inverted-U relationship*. Performance of a particular task improves as arousal increases until reaching an optimal level for the task in question. Beyond this optimum, performance starts to decline when the arousal level continues to rise, and likewise with reductions below the optimal level of arousal. In regards to the effects of thermal environment on cognitive performance, the same inverted-U relationship has been assumed, substituting arousal level with the intensity of the environmental thermal load (e.g. Griffith and Boyce, 1971).

In the indoor environmental science domain, arousal theory and the associated inverted-U relationship, has held sway for several decades, judging by the number of citations it has received. Arithmetic relationships have been proposed by different researchers to quantify the performance decrement in percentage terms as room temperature (or thermal sensation) deviates from the single optimum. These functions have then been widely applied to cost-benefit analyses that trade off the costs of lost performance from the building's workforce against the costs of variations in building and building services design, retrofits, and operational facilities management practices. Seppänen and Fisk (2006) along with Seppänen et al. (2006) have emerged as the most influential studies in the indoor environmental science literature. Their meta-analysis collated 24 previously published studies, then fitted an inverted-U relationship to the summary data. The resulting model shows performance increasing as temperatures increased towards 21.6 °C, then decreasing in temperatures beyond 22 ºC. The same inverted-U relationship is mirrored in the *American Society of Heating, Refrigerating, and Air-Conditioning Engineers' Handbook of Fundamentals* (2013), but instead of room temperature, as in Seppänen et al. (2006), the *ASHRAE Handbook* shows the x-axis as room temperature relative to the optimal comfort temperature T_c for the group. Despite the large variance in data points in the meta-analysis, *ASHRAE's Handbook of Fundamentals* graph shows a smooth parabolic curve for performance, peaking at the optimum comfort temperature (corresponding to "*neutral*" thermal sensation), and then tapering off as soon as room temperature deviates from neutrality (Figure 1).

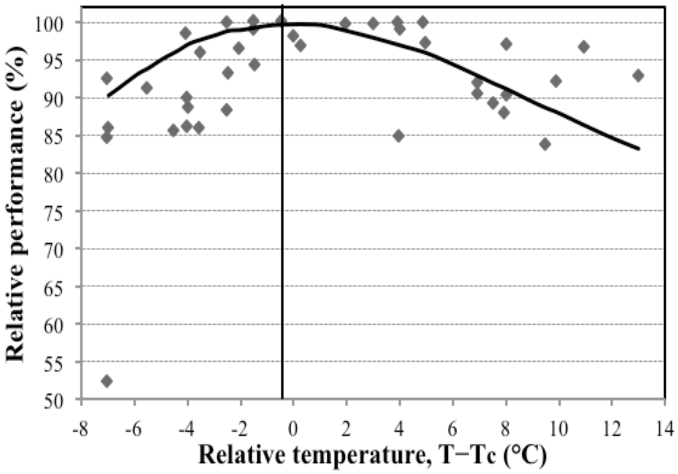

Figure 1 Relative performance of office work vs. deviation from optimal comfort temperature T_C (adapted from *ASHRAE Handbook of Fundamentals*, 2013).

The extended-U model

The extended-U model, initially proposed by Hancock and Warm (1989) and also known as the *Maximal Adaptability Model* contends that human performance remains relatively stable across a broad range, but rapidly deteriorates at the boundaries of thermal acceptability (Figure 2). Thermal stress exerts its adverse impacts on performance by consuming and ultimately depleting the performers' attentional resources (e.g. Kahneman, 1973). The normative zone falls in the middle of the continuum of input stress intensity, and it is here that zero compensatory effort is required of the participant in order for them to maintain optimal performance. The comfort zone encompasses broader conditions than the normative zone, but cognitive adjustments are easily accomplished within the comfort zone in order to maintain a near-optimum level of performance. However, when the environmental stress exceeds the comfort zone, attentional resources begin to be depleted. At first, equivalent or even improved performance can still be achieved by psychological adaptive behaviours such as attentional focus. Because of the central role played by psychological adaptability this region is referred to as the psychological zone of maximal adaptability in Figure 2. When the stress level continues to increase, human performance deteriorates as attentional resources begin to be depleted, indicated by the dashed line at the boundary of the psychological zone of maximal adaptability.

The extended-U model has garnered broad acceptance and currency across a range of disciplines with the notable exception of HVAC engineering and the cognate indoor environmental sciences. It has been confirmed by several authoritative literature reviews on this topic, none of which were published in the HVAC engineering and building science outlets. For example, Ramsey (1995) performed a meta-analysis on 160 individual performance studies and concluded that mental or simple tasks would most likely undergo negligible performance loss in hot environments, and may even be enhanced, at least for exposures under two hours. For perceptual motor tasks other than mental tasks, performance decrements were discernible only beyond 30°C WBGT (approximately 32°C air temperature at 50% RH).

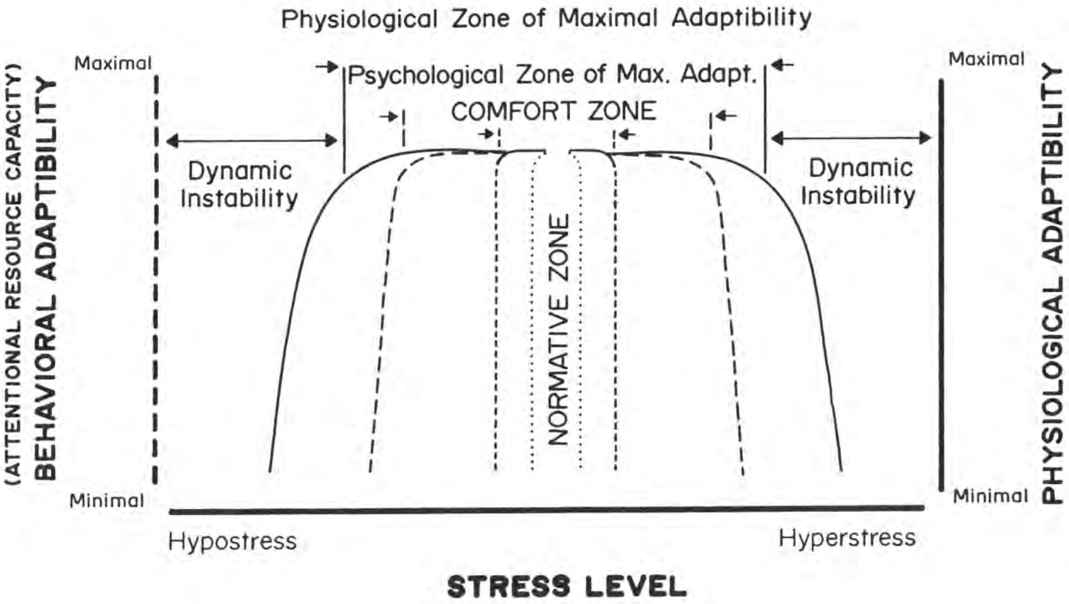

Figure 2 Extended-U model linking stress and performance (Hancock and Warm, 1989)

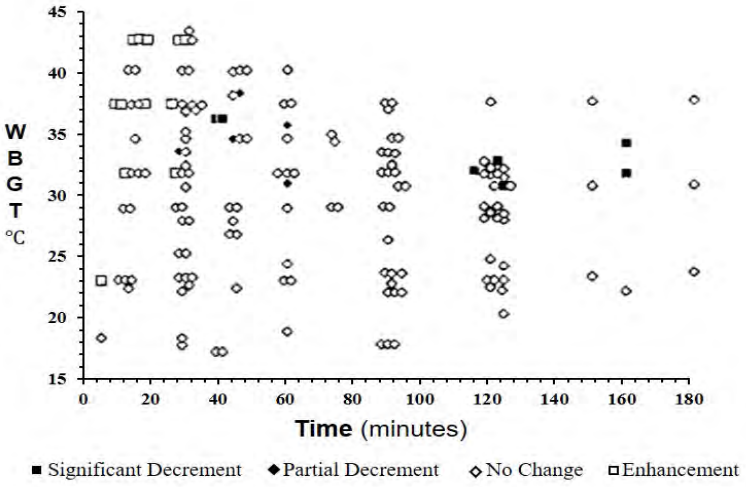

Figure 3 Mental or simple task performance under thermal stress (after Ramsay, 1995)

Another definitive meta-analysis by Pilcher et al. (2002) extracted 515 effects sizes from 22 original studies, and could find no effect of temperature on mental performance in the air temperatures ranging from 23-28.8ºC at 50% RH. This meta-analysis provides some of the strongest confirmation of the extended-U model. In Hancock et al.'s (2007) meta-analysis of 49 separate studies providing 528 effect sizes, the original studies were classified into four effective temperature ranges: below 25.7°C, 25.7°C–29.4°C, 29.4°C–35.2°C, and above 35.2°C. It was found that, "*… with the exception of the lowest temperature range, it is clear that the effect size variation sequentially increases across the three remaining categories. This gives rise to the proposition that performance is relatively stable over much of the temperature range but exhibits radical variation at the highest extreme* " (p.862) and this observation represents a core feature of the extended-U theory of stress and performance.

CONCLUSIONS

Notwithstanding its overly simplistic concept and methodological flaws throughout its empirical bases, the inverted-U relationship has held sway in the indoor environment research literature on thermal environmental influences on cognitive performance and productivity. Moreover, it has permeated engineering practice, as reflected in design guidelines and handbooks published by HVAC peak bodies. The dose-response inverted-U model has been uncritically implemented across broad swathes of the world's commercial building sector. Enhancements in HVAC equipment and control technology over recent decades have facilitated ever-tighter tolerances on indoor temperatures around a speciously defined performance optimum. Scientifically illiterate tenants and their facility managers have begun specifying overly stringent temperature clauses in their commercial office space lease agreements under the mistaken belief that they will maximise productivity from their human resources. However, this multidisciplinary review conducted in this paper finds the evidence for the single-temperature optimum dose-response relationship between indoor environment and occupant performance less compelling, which calls into question the crude cost/benefit of productivity decrements prevalent in the indoor environmental and HVAC engineering domains. Much stronger evidence in support of an extended-U relationship exists in literature published *outside* the usual for building science and indoor air fora.

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Green Infrastructure and Urban Sustainability: Recent Advances and Future Challenges

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ABSTRACT

Although the majority of urban green infrastructure (GI) programs in the United States, and elsewhere, are being driven by stormwater management challenges arising as a result of the impervious nature of modern cities, GI is also believed to provide other benefits that enhance urban sustainability. This paper discusses the role that GI systems might play in urban climate adaptation strategies for cities like New York City, where increases in both temperature and precipitation are projected over the coming decades. Examples of work conducted by the author and colleagues in New York City to quantify the performance of urban GI are first presented. This work includes monitoring efforts to understand how extensive green roofs retain rainfall, reduce surface temperatures and sequester carbon. Next, a discussion of the advantages that a distributed, or neighborhood level, GI system might bring to a climate adaptation strategy is provided. The paper then concludes with an outline of some of the future work that is needed to fully realize the potential of urban GI systems to address future climate change impacts.

Keywords: Green infrastructure, distributed infrastructure, urban sustainability, stormwater management, climate adaptation

1. INTRODUCTION

The term *green infrastructure* (GI) was coined in 1994 as part of a greenway planning report that advocated for land conservation through a system of greenways, or *green infrastructure*, that were as well-planned and financed as traditional built infrastructure [1]. Since then, the term has been used by planners, designers, scientists, and engineers alike to describe networks of green space, including *natural areas* such as waterways and woodlands, and *built areas* such as parks and community gardens - all of which are widely considered to provide an array of services to humans and the environment [2], [3]. More recently, green infrastructure has gained attention as a means of improving urban stormwater management. This focus has given rise to a class of *engineered green infrastructure*, whose primary design purpose is to reduce urban stormwater runoff and pollution. Examples of *engineered green infrastructure* (GI) include green roofs, porous pavement, rain-gardens and rain cisterns. It is these green infrastructure types that are those most closely associated with GI programs to promote sustainable buildings, neighborhoods and cities. Examples of US cities where large investments in engineered GI are currently underway include Philadelphia ($2.4 billion), New York City ($1.5 billion), Chicago ($50 million), and Cleveland ($42 million) [4]–[6].

Although the majority of urban GI programs in the US, and elsewhere, are being driven by stormwater management challenges arising as a result of the impervious nature of modern cities, GI is also believed to provide other benefits that advance urban sustainability. By increasing vegetation and perviousness within city boundaries, it claimed that GI can help cool urban environments, thus reducing urban heat island impacts [7], trap harmful air-borne particulates [8], sequester greenhouse gases [9], increase and/or restore urban biodiversity [10], improve public health and well-being [11], [12] and even create so-called "green collar jobs" [13], [14]. Thus, many GI programs are promoted not only on the basis of their stormwater management goals, but also on the basis of these claimed co-benefits.

The goal of this paper is to examine some of the advantages and hurdles associated with green infrastructure programs for urban sustainability. The paper will do so by using climate adaptation as an example urban sustainability challenge. In order to focus the paper, New York City (NYC) will be used as a case study. Nonetheless, many of the discussions and conclusions reached in the paper are also relevant to other urban settings, as well as other sustainability challenges.

2. CLIMATE CHANGE IMPACTS

Current climate change projections involve significant uncertainty, not least because scenarios for future green-house gas emissions are unknown. For high emissions scenarios (RCP8.5), mean global temperature rise is projected to be about 4ºC (~ 8ºF) over the course of the 21st Century, Figure 1, while mean global sea-level rise is projected to be about 2.5 meters (~ 8 feet), Figure 2. Local sea-level and temperature rises are projected to be above or below the mean global levels shown in Figures 1 and 2, depending upon the region under consideration.

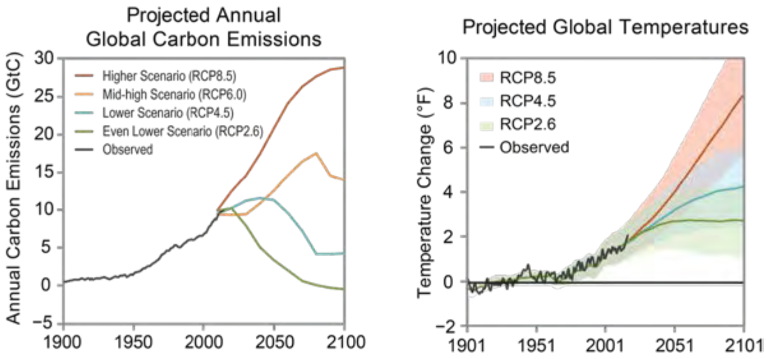

Figure 1. Past and projected changes in global mean temperature rise under different emissions scenarios, from [15].

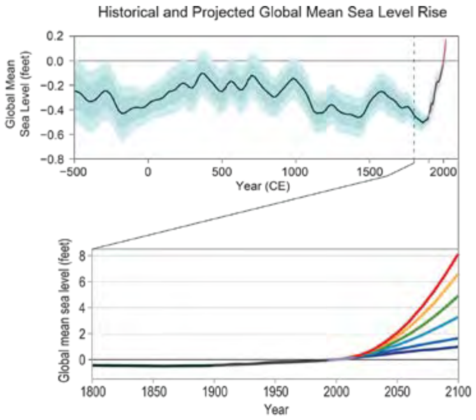

Figure 2. Past and projected changes in global mean sea level rise under different emissions scenarios, from [15].

Nonetheless, despite uncertainties in the projected magnitude of climate change effects, there are general trends that climate scientists and others agree upon. These include a raise in sea-levels; an increase in temperatures; changes in the patterns and amount of precipitation; a decline in snow-cover, permafrost and sea-ice; acidification of the oceans; an increase in the frequency, density and duration of extreme events, and a change in eco-system characteristics. These effects will negatively impact water resources, infrastructure, food supplies and eco-systems, as well as human health and well-being. Given the rapid pace of urbanization, adaptation to climate change impacts is especially important for the world's cities, which are expected to house 66% of the world's population by 2050 [16].

2.1 New York City Temperature and Precipitation Changes

In New York City, historic trends over the past 110 years indicate an increase in both the average temperature and annual precipitation, as recorded at the Central Park Meteorological Station [17]. From a baseline of the year 2000, projected climate change scenarios for a mid-range of emissions scenarios indicate temperature rises of up to 3^{o}C and precipitation increases of up to 11% by the 2050s [18]. These increases will only intensify the present day challenges New York City faces with respect to its stormwater management issues [19] and mitigation of the urban heat island effect [20].

3. NEW YORK CITY GREEN INFRASTRUCUTRE PLAN

In 2010, New York City (NYC) released the NYC Green Infrastructure Plan, which is a multi-decade, multi-billion-dollar plan to improve water quality in the City via the introduction of engineered interventions such as green roofs, right-of-way bioswales, green streets and urban street-trees into NYC's impervious landscape [19], Figure 3. By increasing the amount of vegetation in the City, the NYC Green Infrastructure plan aims to allow precipitation to be soaked up locally, thereby reducing contamination of local water bodies and also incidents of rain induced flooding.

(a) **(b)**

Figure 3. a) Green roof on a Columbia University building, and b) Right-of-way bioswale in the Bronx, New York City. Image (a) courtesy of Stuart Gaffin, Columbia University. Image (b) courtesy of Nandan Shetty, Columbia University.

3.1 Green Infrastructure Performance Monitoring in New York City

Over the past decade, the author and her colleagues have been researching the performance of green infrastructure in NYC from the vantage point of multiple sustainability metrics [21]–[32], including those relevant to climate adaptation. In the following paragraphs, some example findings are provided for the performance of a common building level GI intervention, namely green roofs.

The two major green roof categories include extensive green roofs, whose substrates are typically 15 cm thick or less and feature short rooting, drought resistant plants such as *sedum*, and intensive green roofs, whose substrates are greater than 15 cm thick and may be sowed with deeper rooting plants including shrubs and trees. Due to their lower cost, reduced maintenance requirements, and lighter weight per unit area, extensive green roofs are more frequently adopted than their intensive counterpart [27]. For this reason, the majority of green roof studies engaging the author and her colleagues involve extensive green roofs. Figure 4 provides the location of three of these extensive green roofs, each of which encompasses a popular construction type. W118 is a Xero Flor America XF301+2FL *vegetated mat system* with a substrate depth of 32 mm, ConEd is a GreenGrid-G2 *modular tray system* with a substrate depth of 100mm, while USPS is a Tecta Green *built-in-place system* with a substrate depth of 100mm. All three roofs are planted with *sedum* species. Monitoring of green roof performance began in 2009 and has been almost continuous since then. Further information on the characteristics of each green roof, monitoring equipment and set-up can be found in [21].

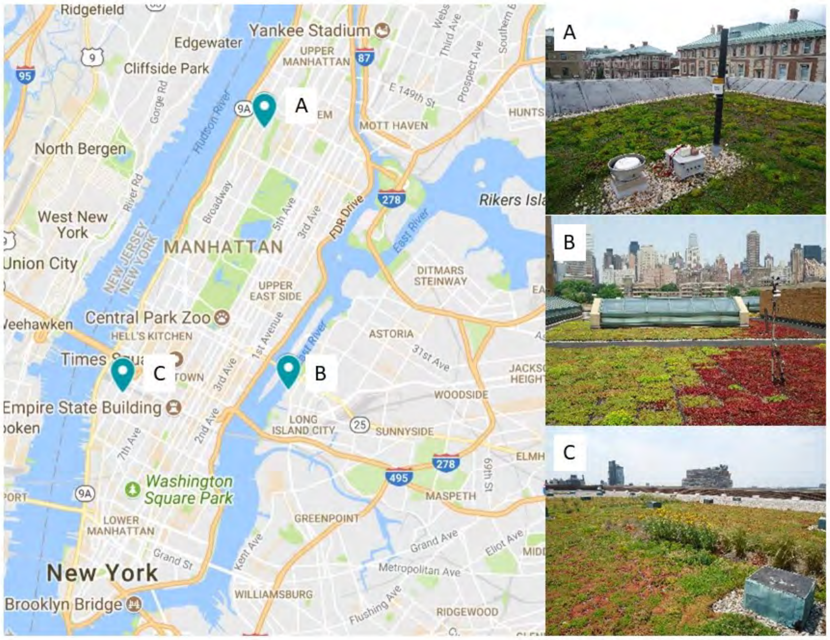

Figure 4. Locations and rooftop views of the W118 (A), ConEd (B) and USPS (C) green roofs, respectively. Map data retrieved from Google Maps (Google Chrome 2018).

Figure 5 summarizes stormwater retention values by storm size category for the three extensive green roof types. As would be expected, green roof rainfall retention reduces with increasing storm depth. Nonetheless, even for largest of storms (50mm +), rainfall retention is

30% or more of incident rainfall. In general, the thinner W118 green roof under-performs with respect to rainfall retention in comparison to the thicker ConEd and USPS systems. Since July 2011, the date when vegetation on all three roofs was considered fully established, the observed annual retention of the W118, ConEd and USPS green roofs has been 45.9%, 50.7% and 56.5%, respectively.

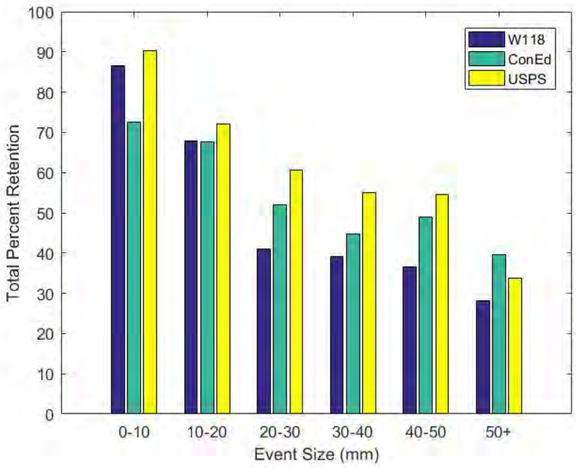

Figure 5. Green roof stormwater retention performance for the W118, ConEd and USPS *sedum* green roofs for different storm event categories.

Green roofs achieve air temperature reductions by transforming adsorbed sunlight into water vapor through evapotranspiration (ET), also termed latent heat loss. White or "cool" roofs, which achieve a high reflection of sunlight, are an alternative to green roofs for air temperature reduction. Temperature data collected over a period of a year from the ConEd green roof and nearby white and black roof treatments, show that white roof and green roof temperatures are actually fairly close, except during summer wet periods when the efficiency of latent heat loss lowers the green roof temperatures significantly below that of the white roof [33]. An illustration of the surface temperature differences that are possible between black, white and green roof areas are shown in Figure 6. It is the observation of large, surface temperatures differences like those shown in Figure 6 (e.g., a different of 46ºC between the black and green roof surfaces) that has spurred interest in the use of vegetated GI to moderate extreme heat in urban spaces.

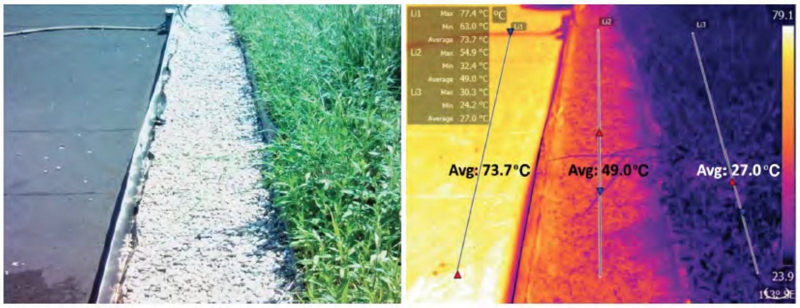

Figure 6. Standard (left) and Infra-red (right) photographs of an NYC based rooftop comprising black, white and green surfaces. Image courtesy of Stuart Gaffin, Columbia University.

Figure 7 provides measurements of diurnal surface-atmospheric CO_2 fluxes for the W118 green roof taken during the month of April. The data show the green roof to be a source of CO_2 during night-time hours (0 – 5am, and 9pm to midnight) and a sink during daylight hours. Overall, the calculated net ecosystem exchange (NEE) of CO_2 for the measurements shown in Figure 7 is -116.5 g CO_2 m^{-2} $month^{-1}$, or -31.8 g C m^{-2} $month^{-1}$. This value is very similar to values reported for an extensive sedum green roof located in Berlin, Germany during the Spring growing season [34]. The authors of [34] report an annual, cumulative NEE of -313 g CO_2 m^{-2} $year^{-1}$, equivalent to -85 g C m^{-2} $year^{-1}$, for the green roof that they studied. For comparison [35] estimate a NEE value of -7.33 kg C m^{-2} $year^{-1}$ associated with carbon storage and sequestration of the NYC urban tree cover, where area refers to the canopy area, which was obtained from aerial photographs taken during a leaf-on state.

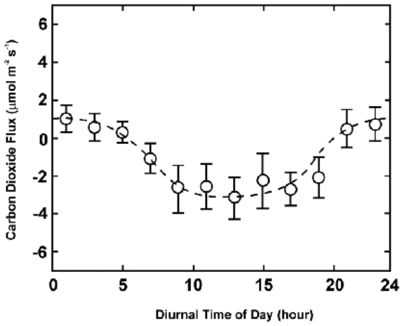

Figure 7. Measured values of CO_2 surface-atmospheric exchange during the Spring growing season for W118.

3.2 Green Infrastructure and Climate Adaptation

Like many other municipal green infrastructure plans, the NYC Green Infrastructure Plan is targeting the construction of thousands of GI interventions, located on both public and private property, to achieve the City's stormwater management goals. The plan is therefore relying on a distributed, or neighborhood scale, infrastructure approach to realize a city-wide objective.

Unlike centralized infrastructure approaches, which usually comprise a smaller number of large investments, distributed infrastructure approaches can be incorporated into urban fabrics at a range of densities and scales. These approaches can thus evolve as performative systems over space and time as needed. Given current uncertainty in climate change projections (see Figures 1 and 2), strategies for climate change adaptation need to be able to change as projections improve over time and/ or impacts are better quantified. Given the flexibility with which a distributed infrastructure system can evolve, the use of distributed infrastructure as part of an urban climate adaptation strategy has many advantages.

Although the NYC Green Infrastructure Plan was not developed as a climate adaptation strategy for NYC, the Plan's promotion of green infrastructure could help mitigate the projected effects of increased precipitation and temperatures in the City, as well as augment local carbon sequestration (refer to Figures 5, 6 and 7). Thus the Plan, inadvertently, encourages a climate adaptation strategy that relies on a distributed infrastructure approach in the face of ill-quantified climate impacts.

4. CHALLENGES AND FUTURE NEEDS

As discussed above, distributed GI appears to have promise as a strategy for climate change adaptation in urban environments. Nonetheless, as discussed below, there are still hurdles that need to be overcome in order to fully realize the actual potential of this promise.

Despite significant progress in documenting the performance of an individual GI intervention, an understanding of how thousands of GI interventions perform as a system of interventions remains lacking. Developing this understanding is essential to advancing system level optimization of multi-component GI schemes for climate adaptation, or other urban sustainability goals. Modeling approaches might be one way to make the necessary progress. However, even in the well-studied area of stormwater management, process-based predictive models have had limited success in forecasting the behavior of an individual GI installation [23], let alone a multi-component GI system. One reason for this, is poor parameterization of evapotranspiration processes for engineered GI. An alternative to systems level modeling is systems level monitoring. This approach has the advantage of providing direct, possibly real-time, information on neighborhood or city-wide GI performance. Furthermore, with enough data collection, it might be possible to create data driven models to inform future system design, optimization and operation strategies. Nonetheless, advancement of this approach will require the development of appropriate sensor networks as well as accompanying data-management and support systems: In other words, a "smart-cities' type approach to urban GI programs.

Improved understanding of the role of engineered GI in mitigating urban heat island effects is also needed. While it is true that large patches of greenery, such as NYC's Central Park, have measureable effects on air temperatures within the park boundary, the cooling effects exerted by smaller areas, such as the green roofs or right-of-way bio-swales shown in Figure 3, are less clear. Thus, more research is needed to define the scale and spatial patterns of urban vegetation required to significantly lower air temperatures in dense urban environments like NYC.

Different from larger-scale climate adaptation strategies, such as the installation of massive underground stormwater storage tanks, distributed GI systems are not only comprised of many more elements, they are also more likely to interface with urban social systems and communities. This can add complex facets of public acceptance and stewardship to the equation of GI performance, which are not always accounted for in GI design, siting and maintenance. Public acceptance and stewardship lessons learned to date from NYC's Green Infrastructure program indicate the importance of greater public dialogue regarding infrastructure placement in the public right-of-way (e.g. Figure 3b). In general, public acceptance of right-of-way GI in NYC has been mixed, with many residents not embracing this vegetative intervention due to concerns about loss of parking, accumulation of trash in the GI, dislike of GI plant palettes – especially native grasses, and general dis-satisfaction about perceived lack of public consultation prior to implementation. In some instances, right-of-way GI has been vandalized in ways that actually compromise its physical performance. Survey work by the author and colleagues indicate that the public places more value on the cultural, social and aesthetic services provided by GI, than the environmental services. Thus, GI designs that account for public value systems, might have better long-term performance and stewardship outcomes than present-day designs.

Currently, efforts to design GI to maximize performance beyond stormwater management remain limited. For example, [34] note that carbon uptake by the sedum green roof they monitored in Berlin, Germany declined when substrate moisture content fell below 0.05 m^3m^{-3}, while [33] observed that high substrate moisture contents were linked to lower green roof temperatures. Yet, the active management of substrate moisture content to enable optimal rainfall capture, carbon uptake and the lowering of surface temperatures is neither a design nor operational feature of most extensive green roofs. Going forward, more attention needs to be paid to the design and operation of GI interventions that maximize as many sustainability benefits as possible.

Finally, questions still remain as to how to define "acceptable" performance for a distributed GI system, whether for the purpose of climate adaptation or not. For example, with respect to performance redundancy, questions remain as to what is an acceptable factor of safety for a distributed system? And should a factor of safety be applied to each individual component of a GI system (i.e, each component has a built-in factor of safety) or the entire system itself (i.e., the system has redundant components)? In addition, there are questions regarding system resiliency. For example, are distributed systems more resilient because they are comprised of very, many components (so if several components fail the overall system performance is not compromised) or are they less resilient because it is hard to manage and secure a system of very many components? Furthermore, with respect to funding, what is the model for financing distributed GI systems that are installed on private land to perform public good? These, and other, questions will need answers if distributed GI systems are to become viable elements of urban climate adaptation strategies.

5. CONCLUSIONS

Distributed, or neighborhood level, systems of green infrastructure can contribute to urban sustainability goals in multiple ways. This paper discussed climate adaptation as one such example. Because GI can be incorporated into urban fabrics at a range of densities and scales, the performance of GI systems can evolve over space and time as needed. Given current uncertainty in climate change projections and impacts, the flexibility of an adaptation strategy whose performance can continually evolve has many advantages. Nevertheless, there are a number of challenges that need to be overcome to advance the use of GI for climate adaptation.

Despite the fact that significant progress has been made in documenting the performance capacity of individual GI interventions, an understanding of how thousands of GI interventions perform as a system remains lacking. Developing this understanding is essential to designing multi-component GI interventions for climate adaptation, or other urban sustainability goals. In addition, better understanding of the scale and patterns of urban vegetation required to mitigate urban heat island effects is needed, as are new designs for GI that optimize different performance attributes and improve public acceptability and stewardship outcomes for GI sited in the public-right-of way. Finally, fundamental questions regarding what defines acceptable performance for a distributed GI system still need to be addressed.

ACKNOWLEDGEMENTS

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Humans and Nature in the Loop: Integrating occupants & natural conditioning into advanced controls for high performance buildings

Vivian Loftness[1], Azizan Aziz[1], Volker Hartkopf[1], Khee Poh Lam[1], Bertrand Lasternas[1]
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ABSTRACT

Post Occupancy Evaluation plus Measurements (POE+M) has revealed that thermal, visual, acoustic and even air quality standards derived through controlled experimentation alone does not ensure comfort or health in buildings. Introducing human input into environmental standards and into user centric controls is critically needed for a sustainable future. For over a decade, CMU's Center for Building Performance & Diagnostics has been gathering POE+M data from over 1500 workstations around the world and testing the benefits on innovative environmental control systems. The separation of ambient and task conditioning, the provision of task controls, the introduction of occupant voting and bio-signal inputs into ambient and task set-points, offers major gains in comfort, task performance, energy savings, as well as health and wellness.

KEYWORDS

Humans in the Loop, Internet of Things, Task and Ambient Conditioning, Bio-signals, POE

INTRODUCTION

Addressing the seriousness of climate change and resiliency necessitates breaking out of the control impoverished, reflective, sealed commercial buildings of today. These buildings are often driven by first least cost, treat humans as a liability by hiding sensors and controllers, and treat nature as a liability by blocking natural solar heating and sealing out natural ventilation and cooling. These buildings are not intelligent and not resilient. Next generation buildings will embrace the Internet of Things (IoT) to make every point of service – every air diffuser, light fixture, heating or cooling unit, window, shade and plug point - a point of sensing, control and intelligent feedback (figure 1). Sensor and control rich environments will engage humans and nature as assets for ensuring indoor environmental quality, organizational flexibility, individual health and productivity, as well as ecological sustainability.

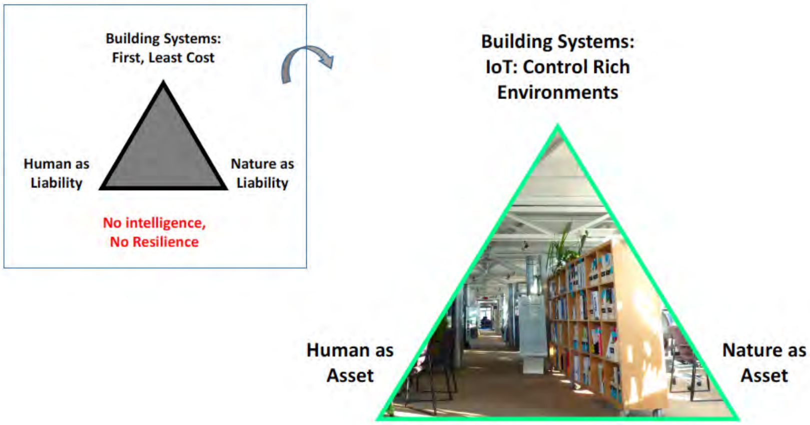


figure 1. Next generation buildings will be IoT control rich, treating humans and nature as assets

Post Occupancy Evaluation plus Measurement (POE+M) in 70 Federal Facilities

Over the past 20 years, The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University and the U.S. General Services Administration (GSA) launched a nation-wide effort to complete post occupancy evaluations in federal facilities before and after the investments to improve the quality of the federal workplace. A National Environmental Assessment Toolkit (NEAT) was developed that critically merged user satisfaction surveys (long term and right now surveys) with physical measurements of environmental conditions and expert walkthroughs and interviews to capture the technical attributes of the building systems that supplied the thermal, air quality, lighting, acoustic and spatial performance (Loftness 2009, Aziz 2012, Choi 2012). Armed with national and international IEQ standards & thresholds, teams of Carnegie Mellon faculty and graduate students surveyed, measured and recorded conditions in over 1600 Workstations in 70 GSA buildings to build the NEAT data base, completing studies with recommendations, and leading to numerous Masters and PhD dissertations. The term POE+M was coined to emphasize the importance of simultaneously recording user satisfaction at given environmental conditions and given physical configurations of the building systems.

CMU POE+M = User Satisfaction (COPE) + Environmental Conditions (NEAT) +
Technical Attributes of Building Systems (TABS)

For example, comparing field measured air temperatures with "right now" satisfaction Reveals: that US buildings are unacceptably and unnecessarily cold in summer (figure 2); that highest user satisfaction with air quality is achieved at CO2 thresholds of 600 ppm ($p<0.05$) not the 1000 ppm presently used; that the highest satisfaction with lighting quality is achieved at less than 250 lux, given the computer intensive tasks in the office today. POE+M data bases offer a wealth of environmental learning and innovation (CBPD 2013), and should be the basis of both educational and professional commitments to field studies.

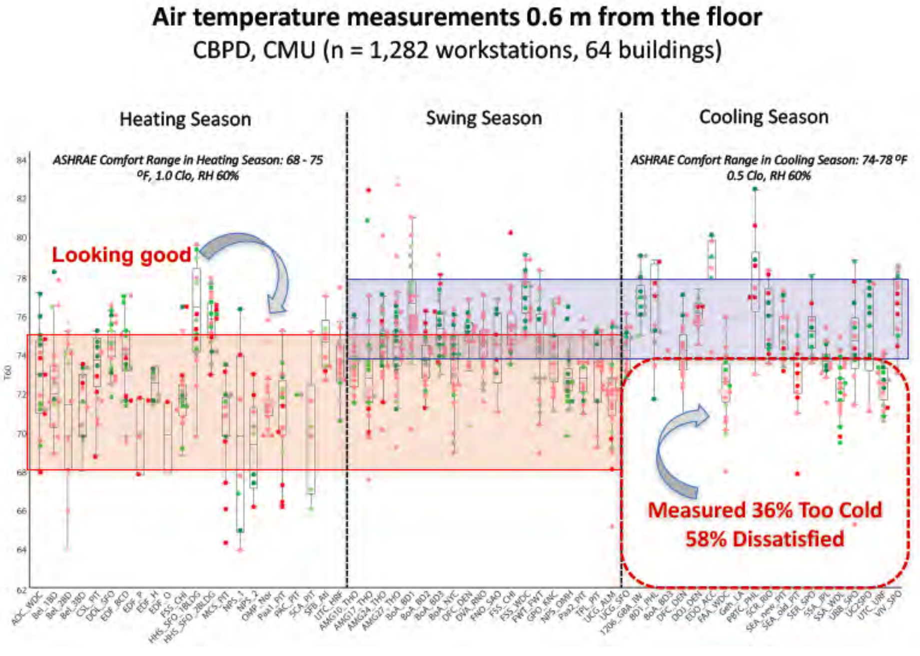
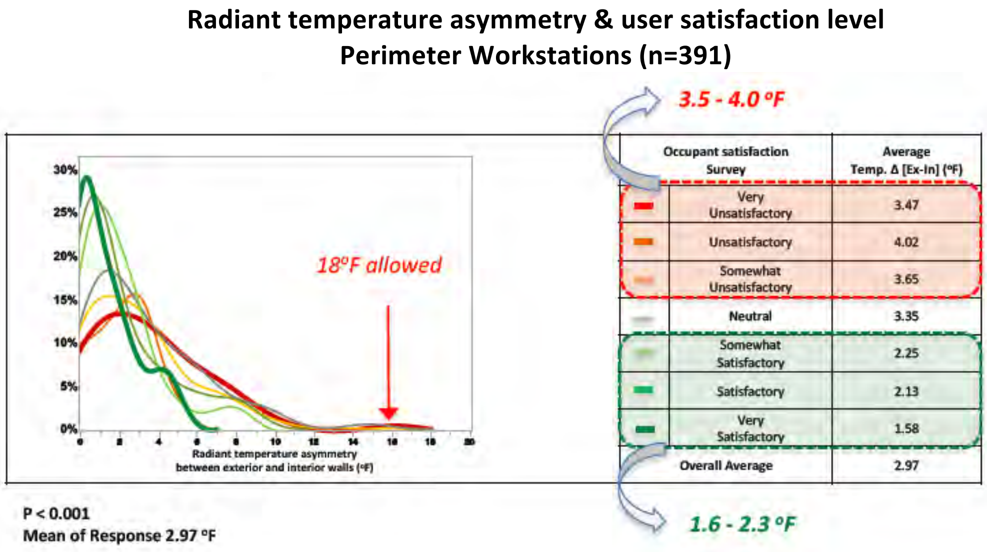


figure 2. Comparing field measured air temperatures with "right now" satisfaction reveals that US buildings are unacceptably and unnecessarily cold in summer.

"Are Humans Good IEQ Sensors? Using occupants as sensors for thresholds that matter."

With measurements in 1600 workstations in 64 buildings in the POE+M database, the 2014 CMU Dissertation of Jihyun Park used a rich array of statistical methods to definitely answer the research question 'Are Humans Good IEQ Sensors". The thermal, air quality, lighting and acoustic findings are both critical to building operation and future design, and statistically significant (Park 2015). The dissertation identified five building environmental conditions (NEAT) or physical conditions (TABS) significantly impacted thermal satisfaction: Air temperature at 0.6 m from the floor; Radiant temperature asymmetry with façade; Size of Zone; Window Quality; and Level of Temperature Control. These findings challenge existing design and engineering practices as well as existing comfort standards. For example, in 391 perimeter workstations, satisfaction with thermal conditions (-1 to +1) cannot be achieved unless horizontal radiant asymmetry is contained below 3.4oF (p<.001), not the 18oF presently in the code (see figure 3). The highest user satisfaction with thermal conditions in summer is achieved at 76.5oF (p<0.05), not the 72oF so prevalent as a year round set-point in the field, and occupants in spaces with hidden or locked thermostats will be 20-40 % less satisfied with air temperature in their work area (p<0.01). Beyond thermal satisfaction, the research continued to identify the building environmental (NEAT) or physical (TABS) conditions that significantly impacted satisfaction with air quality, lighting quality and acoustic quality.



Occupant satisfaction Survey		Average Temp. Δ [Ex-In] (°F)
🟥	Very Unsatisfactory	3.47
🟧	Unsatisfactory	4.02
🟧	Somewhat Unsatisfactory	3.65
▬	Neutral	3.35
🟩	Somewhat Satisfactory	2.25
🟩	Satisfactory	2.13
🟩	Very Satisfactory	1.58
Overall Average		2.97

figure 3. Comparing measured horizontal temperature asymmetry with "right now" satisfaction suggest ASHRAE standards need to reduce acceptable delta's from 18F to <5F (Park 2015).

The CMU Intelligent Workplace: A Living Laboratory of Systems Integration for Performance

The Intelligent Workplace is one of the most sensored and controllable workplaces worldwide, shifting from traditional settings with one control for every 20 occupants to 20 controls for every occupant. With the emergence of wireless sensors and controllers and the Internet of Things (IoT), the IW is a testbed for the engagement of occupants as both sensors and controllers for the improvement of environmental quality and energy conservation.

In addition to field POE+M studies, the faculty and graduates in the Center for Building Performance have been testing the performance of innovations in component and integrated systems in the Intelligent Workplace at CMU. In collaboration with Siemens Corporate Research, Siemens Building Technology and the U.S. Department of Energy (DOE), this living and lived in laboratory supported two years of research on “Advanced, Integrated Controls for 40% Energy Savings in Building Operations” (figure 4) (Siemens 2012). A combination of seasonal controlled experimentation and computer simulation revealed that up to 75% of the ventilation energy, 36% of the heating energy, 25% of the cooling energy, and 70% of the lighting energy could be saved in cool and temperate climates through learning, occupant and nature responsive controls.

For example, the 36% in heating energy savings from the 2010 Baseline of US commercial buildings with limited sensors, limited controllers and sloppy 7x24 operation could be cumulatively reduced:

- 7.7% through updated sensors, time of day operation, and no over/under start up times;
- 15.5% through night setback Δ5°F and weekend setback Δ2-7°F; and
- 36.1% through lower ambient settings & occupant controlled low watt task heating.

The 70% in lighting energy savings from the same 2010 baseline could be cumulatively reduced:

- 40% savings by daylighting when it met space requirements alone;
- 64% savings by adding occupant scene control to daylighting; and
- 71% total savings by Daylighting + Occupant Scene Control + Daylight Harvesting (possible through dimming controls).

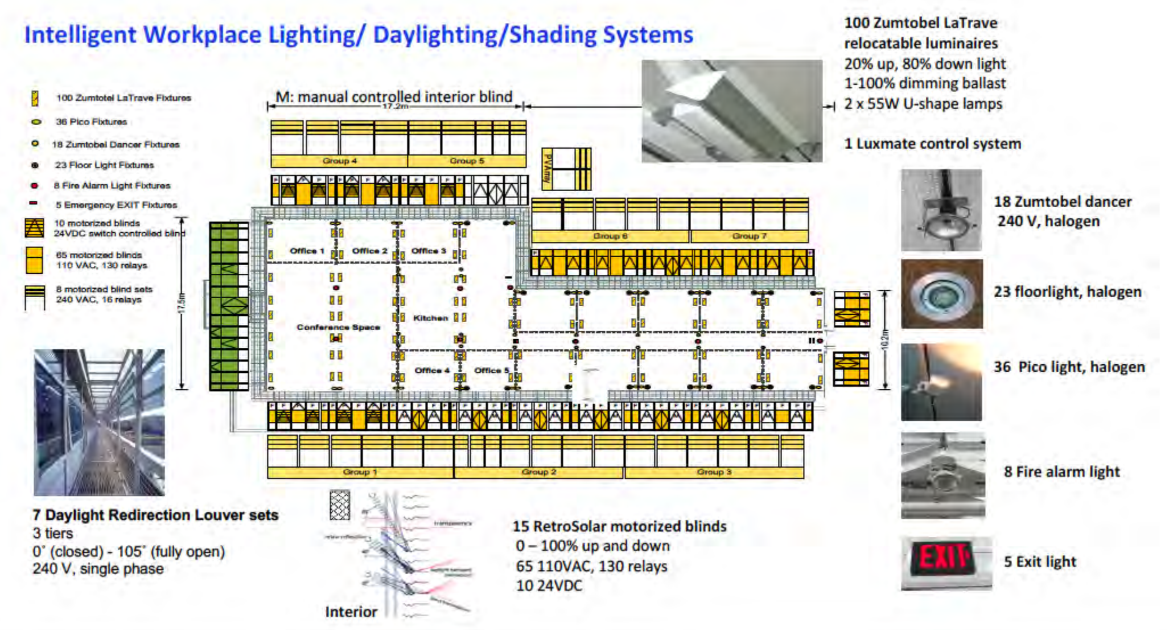


figure 4. The CMU Intelligent Workplace is a living and lived in laboratory for high performance building systems, the IoT, and human and nature responsive controls

The research also demonstrated that “control density is far more important than sensor density” and that the Internet of Things (IoT) offers a future where every node of service – every light fixture, air diffuser, heating or cooling coil, every plug – would support control optimization that integrates across environmental conditioning systems, and includes occupant & natural conditioning strategies. These advances are key to net zero energy, resiliency, as well as human health and performance.

CoBi: Bio-Sensing Building Mechanical System Controls for Sustainably Enhancing Individual Thermal Comfort

The CMU Intelligent Workplace has also been the testbed for numerous Master and PhD thesis projects including the path-breaking work on human bio-signals completed by Joonho Choi (Choi 2010, 2012). With IRB certified human subject testing of a host of bio-signals to control thermal conditions - skin temperatures from ten body locations, heart rate, heart rate variability, and sweat rate – the research identified the wrist as one of the most responsive body location relative to thermal sensation and comfort, given variations in seasons, BMI, MET and CLO conditions. When each individual's variation in wrist temperature is correlated to their thermal sensation votes and enabled to control air temperature, over 93% neutral sensation votes can be achieved, with 5.9 % energy savings for office cooling. This thesis helps to illustrate the importance of distributed controls for environmental systems and engaging occupants as sensors and controllers for energy savings and maximum user comfort, health and task performance.

Smart Phone Controls for the Internet of Things (IoT)

The potential of micro-zoning, of separating thermal and ventilation, of layering ambient and task conditioning, and of controlling every plug - is unlocked by the Internet of Things (IoT). Every node of service – every light fixture, air diffuser, heating or cooling coil, window, window shade, and even every plug – will support control optimization that integrates across environmental conditioning systems, and includes occupant and natural conditioning strategies. In 2010, the IW faculty began a long term collaboration with the students of Dr. Bernd Bruegge in the Institut for Informatik at the Technical University of Munich. Through this collaboration, the IW has been the laboratory for Bachelor, Masters and PhD thesis projects exploring the capabilities of smart phones to provide communication, expert feedback and consulting, and intuitive control (Peters 2012, 2016). These efforts have introduced wifi triangulation for IoT locations, gesture and voice control, innovative smart phone based occupancy sensors, environmental sensing, geo-fencing, smart plug data analytics and more (figure 5).

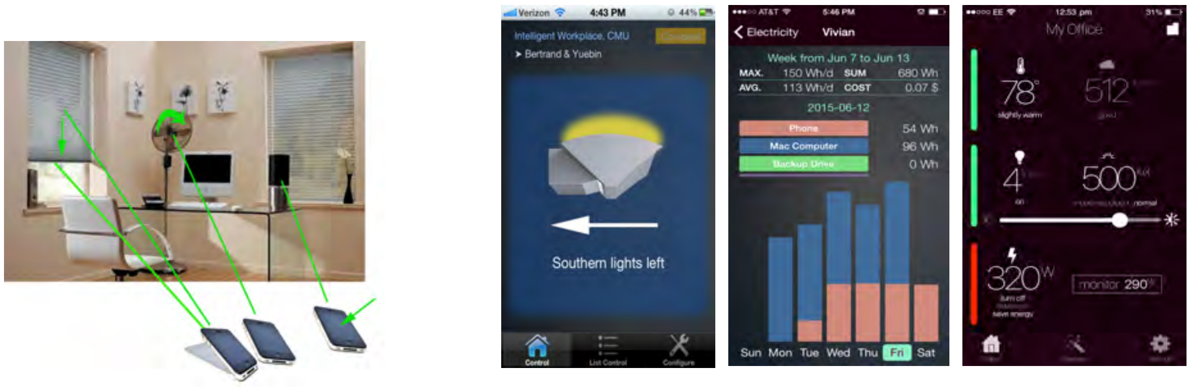


figure 5. Smart phones support intuitive gesture control of every fixture (left 2), provide energy use information (center) and readings of individual sensors and set points (right), (Peters, 2016)

Persistent Workplace Energy Savings and Awareness through Intelligent Dashboards

The importance of communication, feedback, expert consulting, and multiple levels of control are the basis of CMU's research into Intelligent Dashboards for Occupants (ID-O). The PhD thesis of *Ray Yun* explores the impact of nine critical interventions for behavioral change, structured in three sets: Instructional interventions – education, advice and self-monitoring; Motivational interventions – goal setting, comparison and engagement; and Supportive interventions – communication, control and reward (figure 6). With a focus on controlling plug loads, the fastest growing energy end use in commercial buildings, the nine-month controlled field experiment with 80 office workers at a leading green corporation in Pittsburgh revealed that occupant dashboards for controlling desktop technology, with ongoing energy communication and expert consulting generated by the occupants own data set, can generate up to 40% energy savings in plug loads (Yun, 2014).

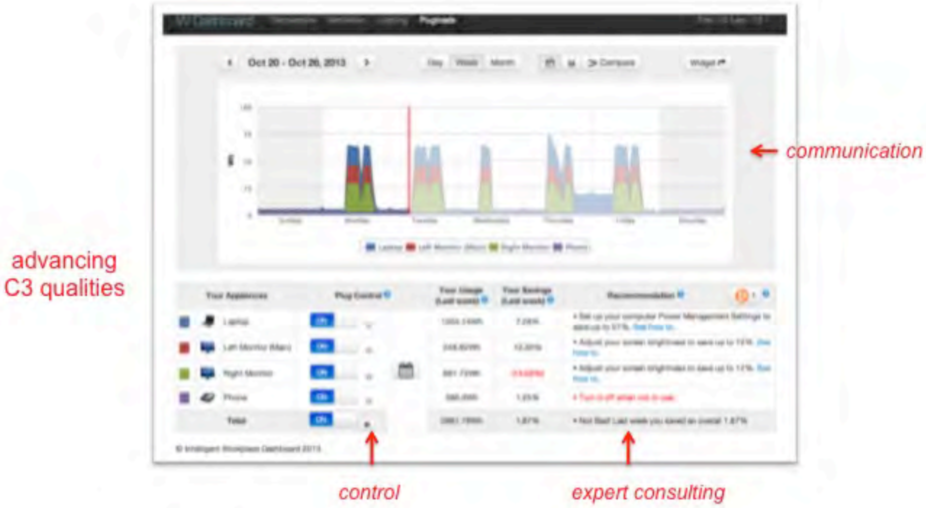


Figure 6 Desktop energy feedback and control dashboards for occupants yielded as much as 40% sustained savings from an already efficient workstation (Yun, 2014)

Occupant-oriented, mixed-mode, Energy+ predictive controls

In addition to engaging occupants directly, the power of occupancy and nature responsive building energy management (BEM) is also a critical development for the Internet of Things. The CBPD has been developing dynamic life-cycle building information models (DLC-BIM) into building energy models (BIM to BEM) focused on total building performance to ensure best practices in sustainable and green architecture. Jie Zhao completed a dissertation in 2015 demonstrating "Design-Build-Operate Energy Information Modeling for Occupant-Oriented Predictive Building Control", moving from controlled experimentation in the IW to a partnership with a newly awarded Living Building in Pittsburgh. This dissertation developed and demonstrated the concept of design-build-operate Energy Information Modeling infrastructure (DBO-EIM), which can be used at different stages of the building life-cycle to improve energy and thermal comfort performance (figure 7). Given the Pittsburgh weather context and current operation, the Occupant-oriented Mixed-mode EnergyPlus predictive control (OME+PC) system provided a 29.37% reduction in annual HVAC energy consumption. In addition, OME+PC enables building occupants to control their thermal environment through an internet-based dashboard, updating a design stage EnergyPlus model for use through the entire DBO-EIM process." (Zhao, 2015)

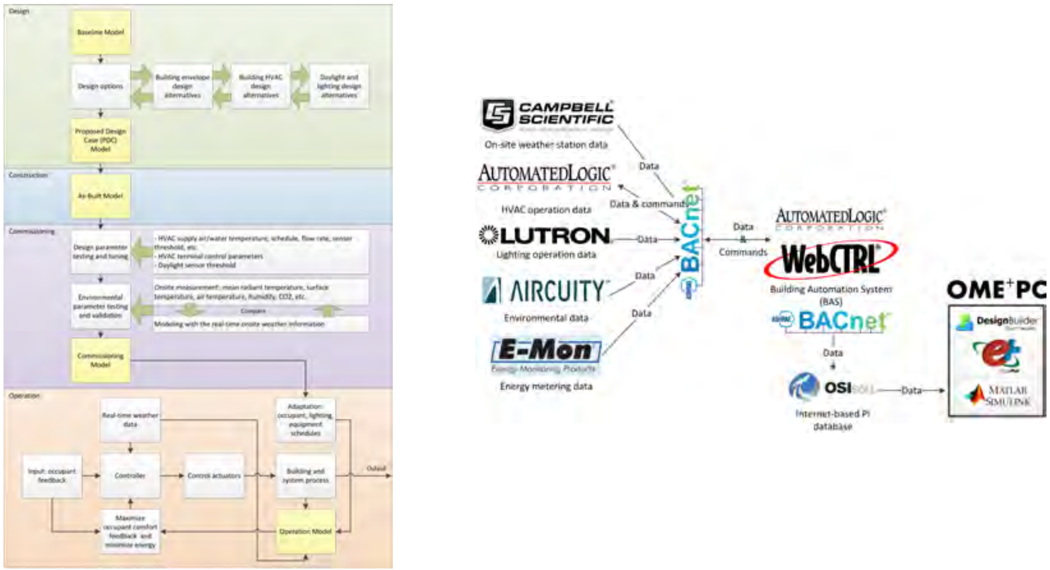


Figure 7 Design-build-operate Energy Information Modeling (DBO-EIM) infrastructure (left), and data collection and system integration architecture (Right) (Zhao, 2015)

Embracing Natural Conditioning

Erich Fromm used the term ‘biophilia’ to describe the psychological orientation of being attracted to all that is alive and vital. EO Wilson and Stephen Kellert, in their book ‘The Biophilia Hypothesis’ described biophilia as the links that human beings instinctively seek with other living systems (Kellert 1993). For those of us in the bricks and systems that define buildings, biophilia must include a passion for natural conditioning. Yet we know that advances in conditioning systems, sensors and controls are equally invaluable to our goals of intelligence, resiliency, health and productivity – especially in the warming and wildly fluctuating changes in our environment. Our future is in the marriage of the high tech and the low tech. First, we must pursue every possible hour of natural conditioning through environmental surfing for daylight, natural ventilation, night ventilation cooling, time lag cooling, passive solar heating, evaporative cooling and more. Then we must lightly introduce mechanical and electrical conditioning through mixed mode design. This demands no more heavy handed, pervasive overlighting or overcooling, and no more over-sealing, over-darkening our building facades. Instead, we must fully design for:

Mixed Mode: Daylight & Electric Light
Mixed Mode: Natural Cooling & Mechanical
Mixed Mode: Natural Ventilation & Mechanical
Mixed Mode: Outdoor & Indoor Work/Learn/Play/Heal

For each of these mixed mode solutions, the disciplines must collaborate from the earliest stages of design – to integrate structure, enclosure, mechanical, lighting, interiors and control systems that fully engage nature and the building occupants in a sustainable future.

CONCLUSION

Several decades of field and lab experiments at the Center for Building Performance and Diagnostics at Carnegie Mellon University have demonstrated that humans are good environmental sensors and humans are good environmental controllers, especially when given information, recommendations, and rewards. Occupants contribution to both energy savings and the highest level of individual satisfaction and delight is even greater when natural conditioning opportunities are introduced – daylighting, natural ventilation, night ventilation cooling, passive solar heating and more. Nature offers abundant, albeit variable, free energy sources for environmental conditioning. The future of intelligent buildings for resiliency, health and productivity depends on building systems that engage humans and nature to save energy and increase environmental quality.

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Multiphysics Modeling of Materials, Assemblies, Buildings and Cities

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ABSTRACT

There is growing evidence that heat waves are becoming more frequent under increased greenhouse forcing, associated with higher daytime temperatures and reduced night-time cooling, which might exceed the limits of thermoregulation of the human body and affect dramatically human health. Especially urban areas are affected, since these regions in addition experience an urban heat island (UHI) effect characterized by higher air temperatures compared to the surrounding rural environment. A necessary breakthrough is a shift away from a fragmented approach towards an integrated multiscale urban climate analysis. This type of research is a rather new domain of research and might be based on an all-physics understanding and modeling of the urban climate ranging from the scales of material and buildings, to the scales of a group of several buildings, street canyons, neighbourhoods, cities and urban regions, referred to as multiscale building physics. To adequately cover global and local urban heat island effect, regional and mesoscale climate analyses have to be downscaled to sub-kilometer resolution and linked with urban climate models at neighborhood and street canyon scales. Such a multiscale urban climate model allows to analyze the influence of urban and building parameters on thermal comfort and the building cooling demand. The importance of accounting for the local urban climate when quantifying the space cooling demands of buildings in an urban environment is demonstrated. The heat-moisture transport model for building materials allows the design of new building materials, which can help in the mitigation of local heat islands. With respect to evaporative cooling materials, we need to optimize their water retention and evaporative cooling by tailoring their pore structure. The understanding and information obtained from pore-scale investigations enables to understand macro-scale transport processes, and enabling us to explore the potential of new evaporative cooling materials at local urban scale.

KEYWORDS

IBPC 2018, building and urban physics, multiscale modelling, building energy demand, pore scale modelling

THE BROAD VIEW: URBAN CLIMATE AND CLIMATE CHANGE

There is growing evidence that heat waves are becoming more frequent under increased greenhouse forcing (e.g. Seneviratne et al. 2012, Hartmann et al. 2013, Schleussner et al. 2017). Climate simulations project an increase of the number and intensity of heatwaves and hot extremes in many regions in the world (Sillmann et al. 2013, Fischer et al. 2014) even for moderate scenarios of global warming of 1.5°C or 2°C (Seneviratne et al. 2016, Wartenburger et al. 2017, Dosio et al. 2018). In future, heat waves associated with higher daytime temperatures and reduced nighttime cooling might exceed the limits of thermoregulation of the human body and affect dramatically human health. Switzerland experienced important heat waves during the 2003 and 2015 summers, which were the two warmest summers over more than 150 years. For these summers, an excess mortality of 6.9% and 5.9% respectively was estimated corresponding to 975 and 804 extra deaths for these years, see Figure 1a (Vicedo-Cabrera et al. 2016).

Urban areas are especially affected, since these regions, in addition, experience an urban heat island (UHI) effect characterized by higher air temperatures compared to the surrounding rural environment (Oke 1987, Moonen et al 2012b). Urban heat islands in cities have been reported for more than 400 cities around the world (Santamouris and Kolokotas 2016). The magnitude of UHI is found to vary from place to place with urban heat island intensities up to 6 - 7°C (Santamouris and Kolokotsa, 2016). For Zurich, we found an urban heat island intensity of around 4.5 degrees during the heat wave of 2015 (see Figure 1b-c, Mussetti et al. 2016). Li and Bou-Zeid (2013) showed that the combined effect of UHI and heat waves is larger than the sum of the two individual effects.

The UHI leads not only to a reduction of urban thermal comfort, but also to an increase in building energy demand, especially in space cooling demand during warm periods. Due to local and global climate change and growth of world’s population and economic, the world global space cooling demand for buildings is expected to strongly increase in future. In 2010 the global cooling consumption of the residential sector represented 4.4 % of the total space conditioning of buildings. This number is expected to increase to 35 % in 2050 and 61% in 2100 (Santamouris 2016, Isaac and van Vuuren 2009). Not only the annual but also the peak cooling demands will strongly increase. This means that also the power capacity for cooling, and thus electricity, may have to be strongly increased to satisfy future peak energy needs (Sanatmouris 2016). Santamouris (2016) proposed three main actions to face the problem with the increase in cooling demands: (1) mitigation of the global and local climate change, (2) adaptation of the building sector and improvement of its energy performance and (3) improvement of mechanical air conditioning and alternative cooling technologies.

In addition to the global UHI effect, heat waves are accompanied with local hot spots in cities, called local heat islands (LHI), see Figure 1d (Allegrini and Carmeliet, 2016). Certain city quarters or zones between individual buildings may show much higher air temperatures compared to neighboring urban areas, due to lower wind speeds by wind sheltering leading to less removal of heat. On the other hand, at low wind speeds, higher urban surface temperatures due to solar radiation may lead to more buoyancy enhancing heat removal. As a result, the origin of LHIs is a complex phenomenon depending on a set of parameters such as lack of urban ventilation, lack of vegetation, densification and urban morphology.

The continuing spread of urban areas and the growing fraction of people living in cities direct nowadays a particular spotlight on urban climate and urban heat islands, and the corresponding effects on thermal comfort and heat stress during heat waves. As a result, many research teams worldwide aim at formulating adequate measures to adapt to and/or mitigate these threats, but most approaches remain fragmented focusing on specific scales or topics of the urban climate.

A necessary breakthrough is a shift away from a fragmented approach towards an integrated multiscale urban climate analysis. This type of urban climate research is a rather new domain of research and might be based on an all-physics understanding and modeling of the urban climate ranging from the scales of material and buildings, to the scales of a group of several buildings, street canyons, neighbourhoods, cities and urban regions. The final aim is to propose adequate urban adaptation measures for climate change (CC) at regional scale in view of different CC scenarios and to develop adequate UHI mitigation measures. Such an approach for urban heat island mitigation allows communities to identify spots of local heat islands, reduced urban comfort and increased health risks, to pinpoint the causes for the appearance of local urban heat islands, and to propose possible mitigation measures using high-resolution urban mapping techniques.

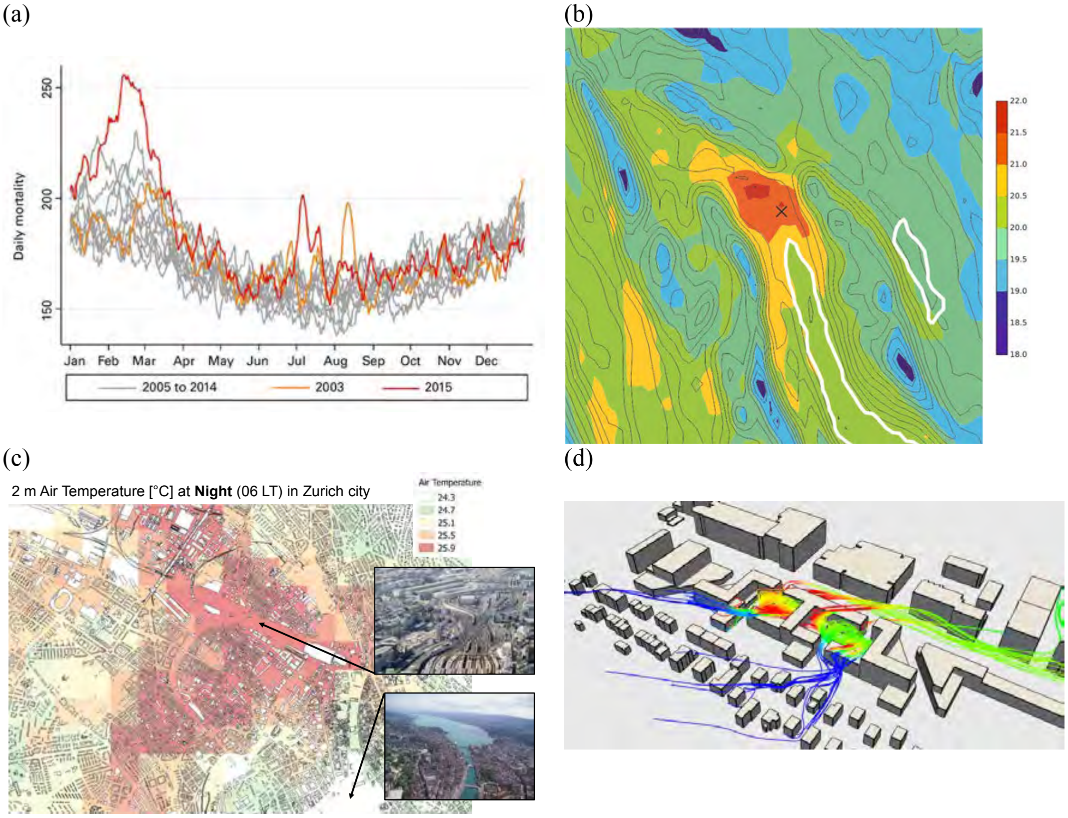

Figure 1. (a) All-cause daily mortality (number of deaths) in Switzerland in 2003, from 2005 to 2014 and in 2015. Two prominent mortality peaks in the summer months, July 2015 and August 2003. (b) Global heat island in Zurich during the heat wave of 2013: map of air temperatures at 2 m height at 12 pm averaged over 5 consecutive days. (c) Urban mapping of air temperatures at 2 m height at 6 am in city of Zürich showing higher air temperatures during the night. (d) Local climate at a neighborhood in Zurich determined with coupled Building Energy - CFD simulations. Selected streamlines where colours indicate local temperature increase due to new buildings (Allegrini and Carmeliet 2016).

WHY MULTISCALE BUILDING PHYSICS ? WHICH SCALES TO CONSIDER?

Traditional building physics focusses on the scales of materials towards building components and buildings systems, and finally whole buildings. The aim of building physics is assuring a correct indoor comfort with minimal building energy consumption, while guaranteeing a correct hygrothermal and acoustic performance, maintenance and durability. Urban physics focusses on physical processes from the scales of urban materials, to the scales of a group several buildings, street canyons, neighbourhoods and total cities. Urban physics can be seen as a complement to building physics, filling the missing link between studies at meteorological and climate scales and building physics. There is nowadays not only a high need of integrating urban and building physics, but also to develop a new discipline, called multiscale building physics. The challenge for multiscale building physics is not only to broaden its field over different scales from material to city scale, but also to link up with other fields. From one side urban climate scientists and planners generally consider only UHI mitigation measures to limit the negative impact of local heat islands. Climate model scientists on the other hand mainly focus on the effects of greenhouse gas mitigation to limit the climate change impact globally. A necessary breakthrough consists in the combination of regional climate modeling combining the effects of greenhouse gas forcing on larger scales with the assessment of UHI mitigation measures on smaller scales for local heat islands during heat waves, and the analysis of their interaction. Such a global approach allows the formulation of more general UHI mitigation measures integrating the use of materials, energy and water on different scales, which can be considered in climate change projections and climate change adaptation.

Scales in urban climate analysis

To adequately cover global and local urban heat island effects, regional and mesoscale climate analyses have to be downscaled to sub-kilometer resolution and linked with urban climate models at neighborhood and street canyon scales. The scales to be considered are represented in Figure 2. We start from global climate models and scale them down to the European (~25 km resolution) and further to the regional scale (entire Switzerland and a portion of central Europe at 1-2 km resolution) using a regional/mesoscale climate model. The regional climate model is further downscaled for selected cities to resolve small-scale thermal circulations and intra-urban variability at sub-kilometer resolution (~200 m). At the urban level, we consider city, neighborhood and street canyon scales.

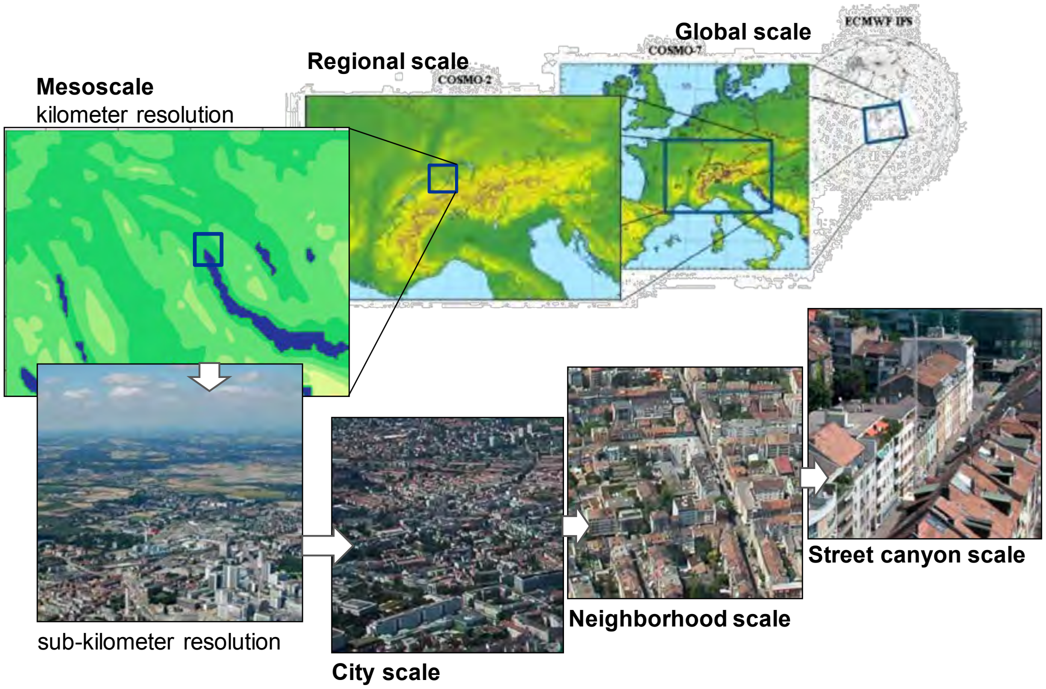

Figure 2. Different scales in urban climate modelling and multiscale building physics (photos from Christen 2005).

MULTISCALE MODELING?

Regional and urban climate interactions

Urban surfaces interact with mesoscale meteorology and climate in several different ways (Roth 2000; Masson 2006; Martilli 2007). Their roughness exerts enhanced drag on the flow and they alter the surface energy balance by trapping radiation, storing heat in urban materials, changing the ratio between sensible and latent heat fluxes, and releasing additional heat due to human activities. These interactions motivated the development of urban canopy parameterizations in atmospheric models enabling a better representation of the mesoscale forcing of urban weather and climate. These models describe the sub-grid scale effects of buildings and urban surfaces on the flow and on surface heat exchange in a parameterized fashion, for example by representing buildings within a grid cell as a statistical ensemble of street canyons of different orientations and dimensions and calculating radiative transfer (including multiple reflections between surfaces) and energy and water vapor exchange between atmosphere and building and street surfaces in each canyon separately.

As an example, the urban heat island effect in Zurich was simulated with the climate version of COSMO in order to capture the local atmospheric circulation influenced by the orography and the presence of Lake Zurich, see Figures 1b-c (Mussetti et al. 2016). The model has currently been extended with the representation of street trees and a detailed representation of short- and long-wave radiation in the street canyons by ray tracing.

From urban to building scale: building-resolved analysis

At city scale, a CFD based urban climate model is used which, in contrast to mesoscale models, also resolves the physical phenomena at street canyon scale. These models take into account accurately the building and street geometry, where buildings are geometrically resolved in computational fluid dynamics (CFD) (figure 3a). They also take into account the used urban materials, particular weather conditions (wind, sunshine, rain, temperature, relative humidity), shadowing, as well as the local urban water cycle.

The influence of higher scales such as the global urban heat island are modeled via appropriate boundary conditions (wind velocity and orientation, surface temperatures) from simulations at sub-kilometer resolution using a nesting approach (Vonlanthen et al. 2017). In order to solve the mismatch between different scales and physics involved in the two models, we apply a blending layer. Transpirative cooling and shadowing effects from trees as well as the evaporative cooling effects of water bodies or absorbed water (by rain or spraying) can be considered. Figure 3b gives an example of the air temperatures at 3 m height in downtown Zurich during a heat wave day.

These models at city scale are further downscaled to neighborhood and street canyon scales for selected parts of a city. At this scale, an all-physics model is used considering solar and longwave radiation, three-dimensional turbulent wind flow and buoyancy, temperature and relative humidity in the air domain and heat and moisture transport in the porous domains of urban surfaces (see Figure 3c, Kubilay et al. 2016). The surface temperatures are determined by a thermal balance of solar and longwave radiation, convective heat transport at surfaces, heat conduction and storage of heat in the building materials and soil, and evaporative cooling effects. The urban climate model is extended with vegetation using a porous media approach with sink and source terms for moisture and heat to model the transpiration and the related transpirative cooling effect. The vegetation model includes moisture transport within the soil/roots, tree, stem, branches and leaves, allowing the consideration of the complete water cycle at street canyon scale between air, soil and tree. A multiphase Eulerian model for wind driven rain has been developed and validated in order to accurately determine the wetting of the building surfaces and soil, see Figure 3d (Kubilay et al. 2013). The wind driven rain model is able to predict the rain load and wetting of all urban surfaces including roofs, facades, pavements, streets, soils and other surfaces. The porous heat-moisture transport model allows the determination of the heat and moisture transport and storage in these materials. When evaporation occurs, evaporative cooling is considered.

The urban climate model is further integrated with an urban water cycle model including rain and drainage systems at city scale in order to explore the potential of using urban water resources locally for UHI mitigation, especially during heat waves. This enables the assessment of when stormwater can be used to reduce the local heat island effects via evaporative cooling. A thorough analysis on stormwater availability and storage potential in cities can then be performed. This provides answers to questions such as: Is the stormwater volume sufficient and available when required to mitigate urban heat island effects? How does dedicated stormwater storage solutions compare with other existing urban water infrastructure in terms of city infrastructure retrofitting possibilities and costs?

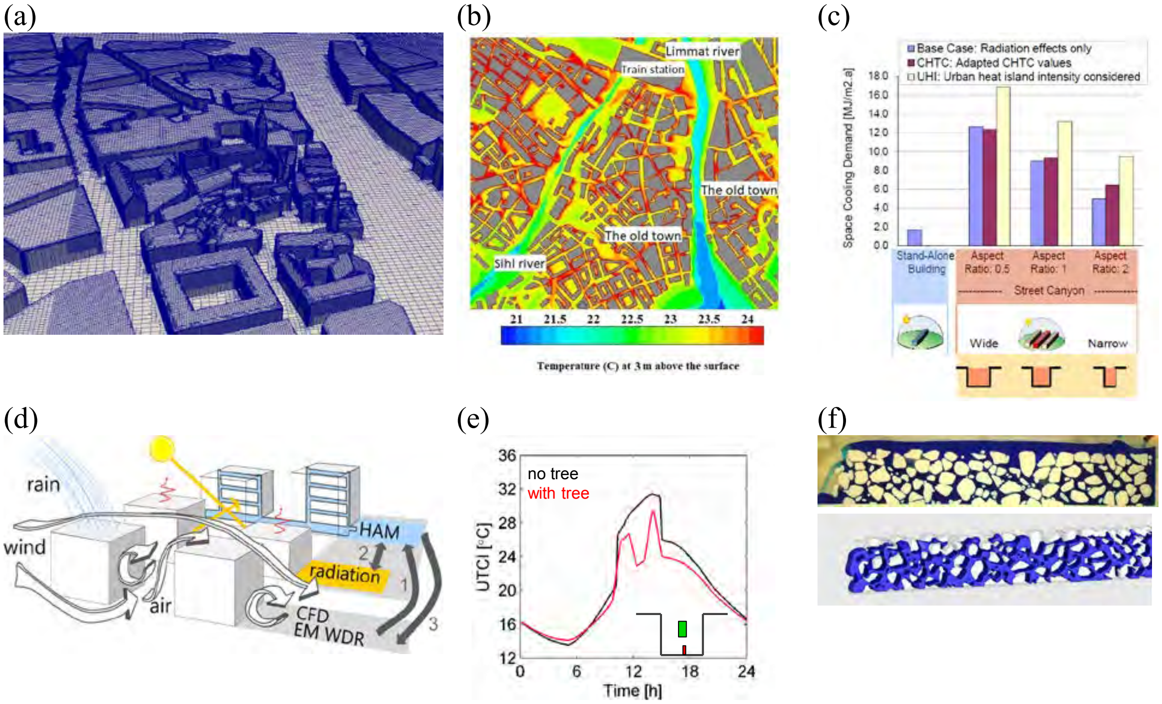

Figure 3. (a) CFD mesh for the old city of Zurich. The area of interest is represented with more geometric details (roofs), while the surrounding neighborhood is represented by simplified building blocks. (b) Air temperature at 3 m height in downtown Zurich during heat wave day June 23 2015 at 2 pm. (c) Annual space cooling demands for different building configurations and using different modelling approaches (Allegrini 2012). (d)All-physics approach of local urban climate model. The momentum, heat and moisture transport in the air domain is solved using computational fluid dynamics (CFD). Wind driven rain is modelled using an Eulerian Multiphase method. Results from the CFD simulation are exchanged with a model for heat and moisture transport (HAM) in urban materials like facades, roofs, pavements and soils. A radiation model solves for the solar radiation, shadowing and thermal radiation between the different surfaces and the environment. (e) Universal Thermal Climate Index (UTCI) for a person (red box) standing below a tree (green box) showing the positive effect of a tree mainly through shadowing on the thermal comfort.). (f) top Liquid distribution in micro-fluid device representing porous asphalt during drainage. bottom: PM-LBM simulation of drainage in porous asphalt (Son et al. 2016).

The urban climate model allows to analyze the influence of urban parameters on thermal comfort by determining the variables at a certain location in the street canyon, such as air temperature, air speed, radiant temperature and relative humidity. These variables are used to determine thermal comfort/heat stress using a common thermal comfort indicator, such as the UTCI (Universal Thermal Climate Index, Bröde et al., 2018). As an example we show the influence of a tree on the UTCI for a person (red box) standing below a tree (green box), showing the positive effect of a tree mainly through shadowing on the thermal comfort.

COUPLING URBAN CLIMATE AND BUILDING ENERGY

It is clear that space cooling demands of buildings in urban environments exposed to climate change and heat waves will increase in future due to hotter urban climates.

To propose new building designs and/or building energy systems and to adapt existing buildings to future urban climates, the impact of the local urban climate on the space cooling demands of buildings has to be better understood. At the moment, no full scale studies where models for the different scales of the urban climate are coupled to accurately simulate the local urban climate for building energy simulations taking into account all interactions between the scales, exist. There is a strong need for a better understanding and quantification of the impact of local urban climate, its modification due to climate change as well as possible urban mitigation measures on the cooling demand of buildings in cities. Such knowledge will allow proposing new solutions to improve the energy performance of buildings taking into account their local urban climate.

Most of the building energy simulation models, which are used to predict energy demands of buildings, were originally developed for stand-alone buildings (Hensen 2011). For buildings in urban environments, the space cooling demand is strongly influenced by the local urban climate (Figure 3e) and can be quite different to buildings in rural areas (Allegrini et al. 2012a). The short and longwave radiation exchange between buildings in dense urban areas has a strong impact on the building performance (Allegrini et al. 2012a, Allegrini et al. 2016). The shortwave radiation entering the street canons is entrapped between the buildings due to multiple reflections between the buildings. Additionally sunlit surfaces exchange hot and radiate longwave radiation with non-sunlit surfaces and heat them up. These increased surface temperatures have a direct impact on the energy performance of the buildings and on the local air temperatures. Another important impact is the increased local air temperatures due to the urban heat island effect. The lowest impact comes from the convective heat transfer coefficients. This study showed clearly the importance of accounting for the local urban climate when quantifying the space cooling demands of buildings in an urban environment.

DOWN TO MATERIAL SCALE

The multiscale urban climate model can be used to understand the impact of different urban parameters on the local heat island effect and to propose adequate mitigation measures. Especially one can study the impact of (1) radiation properties of building surfaces (albedo value), (2) the heat-moisture transport and capacity properties of building materials, (3) the presence of vegetation such as green roofs and facades, (4) the role of impervious versus porous substrates (different pavements and sublayers, different soils, cover ratio), (5) the presence of urban shadowing devices, (6) the role of active evaporative cooling by water spraying during heat waves of collected urban water.

The heat-moisture transport model allows the design of new building materials, which can help in the mitigation of local heat islands. With respect to evaporative cooling materials, we need to optimize their water retention tailoring their pore structure. This requires the use of pore-scale simulation of two-phase flow in porous media and an upscaling using pore-network models for the determination of the macroscopic fluid transport properties

As an example, we recently showed that hydrophobic macro-porous materials, such as porous asphalt with pore sizes ranging from micron to millimeter size, can retain water in their pore structure for long time after wetting by rain or artificial wetting (spraying), as such opening potentials for new evaporative cooling materials (Lal 2016). To study the two-phase flow in such complex materials, we developed a pseudopotential multiphase lattice Boltzmann model (PM-LBM). The use of LBM was motivated by the need for the explicit tracking of the liquid-vapor interface during gravity-driven drainage in macro-porous asphalt as well as the drying process. The PM-LBM was validated with micro-fluidic measurements, where liquid distributions were monitored by high speed camera on quasi-2D transparent micro-fluidic devices, where the porous structure was printed by additive manufacturing (Figure 3e-f) (Son 2016). To predict the unsaturated permeability of building materials, pore-network modeling was used (Carmeliet et al. 1999, 2004, Vandersteen et al. 2003). The understanding and information obtained from pore-scale investigations enables to understand macro-scale transport processes, and to explore the potential of new evaporative cooling materials.

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The Physics in Natural Ventilation of Cities and Buildings

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EXTENDED SUMMARY

Asian cities are mostly taller, denser, deeper and larger than those in the West, and the magnitudes of building drag or urban heat island circulation and their effects on city ventilation are also stronger. The physics of urban climate in these large cities is complex, as a combined result of local circulation and synoptic winds modified by the mountainous topography and land/sea breeze, if any. Natural ventilation of a city refers to the penetration and distribution of rural air into an urban canopy layer. The weakened city ventilation has become one major reason for worsening urban warming and air pollution in cities. Two distinct situations need to be considered, i.e. when the synoptic wind is strong; and when the synoptic wind is weak respectively. For the former, designers are interested to manage city ventilation for removal of the urban heat, moisture and pollutant, or retain of urban heat and moisture. The latter become mostly the conditions for the worst urban extreme heat or haze scenarios to occur. Natural ventilation of a building refers to the introduction of outdoor air into a building by natural forces such as wind and buoyancy. High-rise buildings present an interesting challenge as the top of the building may be in the urban roughness layer or even beyond the atmosphere boundary layer.

Many excellent review papers exist on relevant urban airflows (e.g. Roth, 2000, Britter and Hanna 2003, Arnfield, 2003, Belcher 2005), but not specifically on city ventilation. City ventilation is mainly driven by winds and buoyancy forces such as slope flows, sea-land breezes, etc. The importance of city ventilation may be seen by long recognition that the restricted air flows were the causes of the all major pollution disasters (Brimblecombe and Sturges, 2009). Rigby et al (2006) presented a rose analysis showing the influence of boundary layer ventilation. The wind speed in London is often found to be lower than in a rural area, whilst occasionally accelerated due to urban heat island effects (Lee, 1979).

The purpose here is to review the status of our understanding of the physics in city ventilation under both strong and weak wind conditions. It is known that understanding the urban air flows in calm wind conditions is crucial, as most urban heat wave and severe air pollution episodes occur when wind calmness and inversion coexist, leading to formation of a heat dome or urban heat island circulation. Heat dome comprises a convergent inflow at the lower atmospheric level, divergent outflow at the upper, and a dome-shaped flow field resulting from entrainment and overshoot at the top. Numerous field studies worldwide have confirmed the existence of UHIC during the day and night in many cities. It is interesting that though a strong wind would destroy the heat dome and breakup the inversion, a weak wind may only elongate the dome to become a plume or dome shadow, transport the pollutant downstream to other cities. How such a weak wind impact on the dome formation has not been well studied.

Examples given here including wind weakening phenomenon in a dense high-rise city (Peng et al. 2018), the roles of heat dome formation on urban extreme high temperature events,

spread of SARS CoV virus when there is inversion, and the urban heat domes (Fan et al 2017) and their merging (Fan et al 2018). Different methods are available for investigation, i.e. simple theoretical estimates (Fan et al 2017), water tank models (Fan et al 2016), city scale CFD (Wang and Li, 2016), and meso-scale WRF (Wang et al 2017).

It is concluded that there is a need to establish the need and an approach for designing city climate and environment as for buildings, for example, designing building density and height in a city for better urban climate, and between-city distance needed to avoid regional haze formation.

KEYWORDS

Natural ventilation, city ventilation, fluid mechanics, heatwave, heat dome, urban climate

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