Cities on the Frontlines of Climate Change Impacts and Response

In the wake of the Trump Administration choosing to initiate the process to withdraw the United States from the Paris Climate Accord, cities and regional governments within the U.S. have been individually reaffirming their commitment to adhering to the Accord. This review explores why it is in cities’ best interests to continue confronting climate change, illustrating why they are uniquely vulnerable and impacted by global warming. While cities cover only about one percent of Earth’s surface, their true footprint extends far beyond that – while cities generate 80 percent of gross world product (Estrada et al. 2017), they also consume 78 percent of global energy and produce, and are responsible for over 60 percent of CO$_2$ emissions. Cities will be increasingly affected by climate change both directly and indirectly, locally and through far-reaching supply channels. The economies, physical structures, food security, and energy consumption of cities are already undergoing significant impacts from climate change; thus underscoring the incentive many cities have in recommitting to global mitigation efforts.

Direct Effects

*Amplified Urban Heat Island Effect*

For centuries, researchers have reflected on the phenomenon now known as the ‘Urban Heat Island Effect,’ in which cities are measurably warmer than the surrounding countryside. This is caused by decreased vegetation in cities (less natural cooling from evapotranspiration), coupled with more buildings and built surfaces that absorb the sun’s heat. Recent studies point to the fact that the urban heat island effect is often excluded from climate projections, so while there may be an average increase in climate for a region of 1-2°C, in reality the increase can be twice that in urban centers. Additionally, studies are finding that the urban heat island effect is likely to amplify and worsen with climate change. Urban heat island impacts include increased energy use for cooling,
higher air pollutant emissions, human health risks and discomfort, lower water quality, and exacerbated heat waves – all resulting in compromised productivity (Estrada et al. 2017).  Projected decreases in GDP due to climate change alone are relatively small, but when factoring in local amplification from urban heat island effect, productivity in some cities may decline by more than 10 percent by 2100.  By ignoring the impacts of urban heat island effect, projections can significantly underestimate the true effects of global warming – not only on temperatures, but on economies.  When urban heat island impacts are factored in to economic projections, the true costs of global warming are 2.6 times higher than when urban heat island impacts are ignored.

On average (across the 1,692 largest cities in the world), the urban heat island effect currently adds 0.7°C to city temperatures, but with climate change it is projected to add close to 1°C additional warming by 2100 (Estrada et al. 2017).  And that is just on average across cities – some hot spots within the densest parts of cities experience warming significantly above average (an additional 3°C as opposed to the average near 1°C) (Koomen and Diogo 2015).  Business as usual scenarios show that when additional warming from urban heat island effect is taken into account the vast majority of cities are expected to warm by more than 3°C by 2050, and more than 5.5°C by 2100 – with over 25 percent of cities warming more than 7°C (Estrada et al. 2017).  This has sobering implications for human health (see *The Coupled Human-Climate System: Heat Stress and Mortality in a Changing Climate* in this Quarterly Research Review).

Estrada et al. (2017) also finds, however, that local actions to dampen the urban heat island effect can be an extremely important tool in combating this amplified warming.  Local mitigation efforts include increased vegetation in cities, green roofs (completely or partially covered in vegetation), cool roofs (constructed from lighter-colored materials that reflect more of the sun’s rays), and cool pavements.  Without local mitigation actions to reduce urban heat island effect, global mitigation efforts to reduce climate change are far less effective.  By replacing 20 percent of a city’s roofs with cool and green roofs, a city could offset 0.8°C of urban heat island effect, resulting in overall savings up to 12 times the cost of installation.  To carry out this degree of mitigation on the global scale, this scenario would cost 1.5 percent of global urban product, but would reduce losses from climate change by 9.7-18.3 percent.  Greater benefits can be achieved by scaling up these efforts, though the benefit-cost ratio is not as high.  However, this analysis only factors in temperature benefits, and not the other benefits provided by green roofs such as storm water management, reduction in air pollution, and health benefits.  The benefit-cost ratio would therefore be much higher for these scenarios if indirect benefits were also factored in (Estrada et al. 2017).
**Air Pollution & Human Health**

Climate change and air pollution are both rooted in greenhouse gas emissions, and therefore are integrally tied. Reactive air pollutant concentrations of particulate matter (PM 2.5) have been reported above healthy levels in cities all over the world (Figure 1). Increased air pollution associated with climate change is not only directly harmful to human health, but also chemically reacts with the epithelial lining fluid of the respiratory tract, compromising immune function, and predisposing the human body more towards allergic reactions to air pollution and other allergens (Lakey et al., 2016).

Predisposition towards more allergic reactions can be compounded by the fact that climate change has been demonstrated to increase the range, pollen production and/or sporulation of invasive allergenic plants and molds, all of which exacerbate allergies (Reinmuth-Selze et al. 2017).

Not only will air pollution continue to persist while we rely on greenhouse gas-producing energy sources and technologies, but due to climate change, new circulation patterns may further exacerbate exposure to extreme pollution in some cities such as Beijing. Large scale circulation changes (such as the upward shift of the Arctic Oscillation, and the weakening of the East Asia winter monsoon), are projected to create more frequent and persistent weather patterns and inversions that cause extreme haze episodes in Beijing (Cai et al. 2017).

**Sea Level Rise**

Another direct impact of climate change on cities is sea level rise. Buchanan et al. (2017) cite sea level rise as one of the most economically damaging consequence of climate change on cities, due to impacts such as loss of infrastructure, vulnerability to storms, long-term effects on municipal services, and potential contamination of groundwater. Houser et al. (2015) project that the most economically damaging consequence of climate change on coastal areas will be flooding amplified by sea level rise. Current projections of sea level rise this century estimate a median 40-fold increase in annual 100-year floods—meaning floods of a certain magnitude that used to occur once every
century are now expected to occur 40 times within a century. In addition to flood frequency, flood height is projected to increase significantly as well. There is variation across cities in how amplification of flooding will occur (whether more frequent 10-year floods vs. 500-year floods). San Francisco, New York City, Baltimore, Washington, D.C., and Key West will be disproportionately prone to more higher frequency (10-year) floods, whereas Seattle, San Diego, and Los Angeles will be prone to more lower frequency (500-year) floods. For example, 10-year, 100-year, and 500-year floods are projected to occur 148, 16, and four times as often in Charleston, vs. 109, 335, and 814 times as often in Seattle (Buchanan et al. 2017). Because city infrastructure has typically been locked in for decades or even centuries, urban populations are already having to face difficult decisions about when to reinforce infrastructure, and when to retreat from advancing sea levels. Cities can use research like that of Buchanan et al. (2017) to inform policy in light of what types of sea level rise flooding they can expect to see more of in the future (10-year vs 500-year).

**Indirect Vulnerabilities of Cities to Climate Change**

**Food Security**

Cities consume 78 percent of global produce (Estrada et al. 2017), the vast majority of which is produced well outside city limits. Cities have a far-reaching footprint of supply, and therefore their sources of potential climate vulnerability are global in scale. Research on causal mechanisms is ongoing, but many studies have indicated a significant impact on global food production caused by climate change. In some areas (Russia, northern Europe, and Canada) productivity is likely to increase due to longer growing seasons, but in hotter and more arid regions, climate change will likely compromise food security. Overall, crop yields for staple cereal crops such as corn, wheat, and rice are all projected to decrease with increasing temperatures. Varying precipitation, changes in snow runoff timing and quantity, drought, elevated evaporation and evapotranspiration, increased pest and disease ranges, more extreme weather events (like heat waves and flooding) all have significantly negative effects on crop productivity and food security (Gornall et al. 2010). Urban populations will therefore likely become increasingly vulnerable to changes in crop availability and prices, without much agency to control agricultural processes.

**Electricity Production**

As global warming accelerates, the heating and cooling needs of cities will also change. Under a business as usual scenario, researchers have found that while average generation of electricity is likely to increase by only a small amount by 2100 (a 2.8 percent increase), demand for peak load generation is likely to increase much more significantly (a 7.2 percent increase) (Auffhammer et al. 2017). Global warming will also exert more pressure on grids during cooling seasons due to increased reliance on air conditioning (Shen 2017). These additional demands in peak electricity generation can be seen across the country (Figure 2), but as the primary consumers of electricity with minimal agency
over energy production policies, urban populations will be more susceptible to any shortfalls in the abilities of electricity producers to meet peak demands. This finding underscores the incentive for cities to be leaders in pushing for sustainable energy systems and policies, such as increases in solar capacity, energy storage, and real-time prices, all of which can help shift energy use from peak to off-peak times (Auffhammer et al. 2017).

**Figure 2.** Demand for electricity during peak hours is projected to increase throughout much of the United States under a business-as-usual scenario (RCP8.5), with the largest increases in the South and West. Coloring reflects projected percentage increases in the daily peak, with an average increase of 7.2 percent (Auffhammer et al. 2017).

In summary, the threats posed to cities by climate change are significant, in part due to amplification of impacts within cities, and in part due to their far-reaching metabolism that connects them with susceptible systems all over the world. These impacts pervade all sectors (food, industry, real estate, water, etc.), and are often compounded by cascading effects (both direct and indirect). Economic analysis of these interconnected effects is poorly understood, both in terms of damages to quality of human life and the environment. Studies such as Estrada et al. (2017) and others are helping urban decision-makers gain a better understanding of how mitigation and adaptation are fundamental to urban environments succeeding in the 21st century of climate change.
**References**

Auffhammer, M., Baylis, P., and C.H. Hausman. 2017. Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. Proceedings of the National Academy of Sciences. 114, 1886–1891. DOI 10.1073/pnas.1613193114


**Mortality in a Changing Climate**

Historically, heat waves leading to distress, and in some cases death, for human populations were considered extreme events due to natural variability in the climate system. More recently, heat waves have received attention not only for the magnitude of their impact, but also as a new area of research in the context of climate change science (e.g. Chicago 1995, Europe 2003, Western Russia/Eastern Europe 2010). It is well understood that a shift in the average climate to a warmer world will produce a greater likelihood of extreme heat events, thus exposing greater populations of people to extreme heat. Understanding frequency, intensity, and duration of extreme heat events...
in the present and future climate is an active area of research, as is the expected impact of these events on human wellbeing. As the century unfolds, mitigation to limit greenhouse gas emissions combined with adaptive measures will save lives. There is an “adaptation gap” to climate change impacts where those with the means to build adaptive capacity don’t fully utilize their ability, as well as a gap for those of the most vulnerable populations such as the poor with inadequate access to suitable shelter, outdoor workers, and those with compromised health conditions including the elderly. Public health preparedness combined with early warning systems of heat wave events are key societal responses; however, the fundamental need is to stabilize the climate system by reducing greenhouse gas emissions to near zero this century.

Determining a Deadly Threshold

New work by Mora and colleagues reviewed studies on heat waves, heat stress, and mortality that were published between 1980 and 2014. The team confronted the difficulty in overcoming different ways heat events are defined, how heat related mortality is sorted out from confounding factors such as air pollution, and how to attribute mortality to climatic conditions. They devised a climatic threshold by analyzing 16 climate variables combined with a statistical method to separate climatic conditions that are lethal from non-lethal events. They identified two key variables related to the “deadly threshold”—average daily temperature and relative humidity (See Figure 1). For example the figure shows that daily averages over 30°C and greater than 80 percent relative humidity become deadly.

The study concludes that about 30 percent of the world population is already exposed to the potential lethal threshold for at least 20 days per year. Low vs. high projections of future warming (IPCC scenarios Representative Concentration Pathways (RCP) 2.6 and 8.5) increases the percentage of people exposed

\[1\] In this study, the definition of lethal and deadly: “...‘lethal’ as referring to climatic conditions during documented cases of excess mortality and ‘deadly’ when referring to climatic conditions that are projected to cause death.”
to the deadly threshold by ~48 percent and ~74 percent, respectively, by the end of the century. Succinctly put by Mora et al. (2017), “the boundary at which temperature becomes deadly decreases with increasing humidity...”

Earlier work by Sherwood and Huber (2010) on the theoretical limit or “peak heat stress” for human exposure also focused on temperature and relative humidity using a wet-bulb (T_w) metric. The paper explores the limits to adaptability in a changing climate from heat stress. Based on thermodynamics and human physiology, this study concluded that a T_w of 35°C for six hours defines a survivability limit. For heat to dissipate from a body core temperature of 37°C in humans, the surface skin temperature needs to be cooler, about 35°C. Without the ability to dissipate heat, the core temperature climbs and hyperthermia ensues, leading to death. The ability to lose heat to the environment can occur by conduction, net infrared radiative cooling, or via sweat and the resulting evaporative cooling. Conduction and evaporative cooling from the skin to the environment require the ambient wet-bulb conditions to be cooler. Heat transfer to cool the body is dramatically reduced when the ambient conditions are hot and humid.

Typically, wet-bulb maximum temperature T_{w(max)} is 26-27°C with very few instantaneous readings on Earth reaching a T_{w(max)} of 31°C; however these upper values are projected to increase with global warming. Sherwood and Huber conclude that present impact assessment models underestimate the human ability to survive in increasingly hotter environments. They also point out that the direct impact of a heat stress limit is not confined to humans, but also applies to both wild and domesticated mammals. As the world becomes more urbanized this century, an added concern is that the urban heat island effect will exacerbate the impact due to higher temperatures found in cities (See Cities on the Frontlines of Climate Impacts and Response in this Quarterly Research Review).

**Modeling Heat Waves in a Warming Climate**

The year after the devastating 2003 heat wave that killed thousands in and around Paris, a study was published by researchers at the National Center for Atmospheric Research on projected heat waves in the 21st century. Utilizing a global climate model, they showed that a world altered by increasing greenhouse gases produces a unique pattern of heat waves like the one over Europe in 2003 and Chicago in 1995 (Meehl & Tebaldi 2004). They compared a high emissions scenario for the period 2080-2099 to the baseline reference period of 1961-1990. The study found modeling evidence for greater intensity, duration, and higher frequency of similar heat wave events in a climate forced by a century of continued buildup of greenhouse gases. The pattern of the 1995 and 2003 heat waves were similar to those of the model simulations. Figure 2 shows observed and modeled results for the air mass over central Europe. The authors concluded that areas
subject to intense heat waves today will likely see continued intensification, and areas not known for heat waves today are potentially prone to greater impacts with global warming because these populations are not as well adapted to heat wave conditions from past experience. Twelve years after the Meehl and Tebaldi heat wave study, a new team led by Mitchell and colleagues utilized a high-resolution regional model to also examine the 2003 Paris event, explore attribution of the extreme event between human induced and natural causes, and explore the significance of attribution studies to estimates of loss and damages. They found that ~70 percent of the 2003 Paris heat wave event can be attributed to anthropogenic emissions rather than natural variability (Mitchell et al., 2016).

Tebaldi and Wehner (2016) compared emission scenarios RCP 4.5 and 8.5, and both to the reference period of 1996-2005, assessing one day and three day maximum and minimum temperatures. Minimum temperatures are important in providing nighttime relief from the daytime high temperatures. As the century unfolds in the model runs, both scenarios show an increase in the magnitude of extreme temperature events and greater land area affected; however deleterious changes under RCP 4.5 are much less than those in 8.5. Not surprisingly, this study shows that a great deal can be gained in the reduction of human health impacts by achieving a low emissions path. For example their study concluded that by 2075 under RCP 4.5 vs. 8.5, 95 percent of land areas would experience greater than a 1°C reduction in one-day heat extremes compared to a 1996-2005 reference period (Tebaldi and Wehner, 2016).

An Emergent Epidemic from Heat Stress

Complementing the more theoretical studies described above is an increasing body of literature on case studies in public health with linkages to climate change. One of the most vulnerable populations in the coupled human-climate system is the field worker. As with many climate related impacts, multiple stressors can be at play, creating an amplified effect not anticipated by factors considered in isolation. A combination of medical physicians, biochemical researchers, and climate experts have worked together in an interdisciplinary fashion to better understand the rise in the incidence of Chronic Kidney Disease (CKD) or heat stress-associated nephropathy among field workers. An important example of this new type of research focuses on how extreme heat events combined with
Worker conditions are related to CKD (explored in depth at the 2016 AGCI workshop ‘Health Impacts from Climate Change: The Importance of Health Partnerships’). Inadequate shade, rest, and hydration are confounding factors combined with hot and humid conditions already present in today’s climate, and are projected to worsen with global warming.

A study by Glaser and colleagues considered field worker populations in Central America and other locations around the world for a set of health conditions related to climate change. The heat exposure index used in the study, Wet Bulb Globe Temperature (WGBT) is used in establishing outdoor worker standards. As a point of reference, in the U.S., OSHA suggests 15-minute breaks per hour for WGBT of 26°C, and 45-minute breaks per hour for a WGBT of ≥30°C. The study focused on sugarcane field workers in parts of Central America where worker scheduled relief from high WGBT conditions is often not followed. Workers experience “heavy exertion, lack of shade, infrequent breaks, long work hours (in some regions), and lack of access to sufficient potable water during the workday.” Even though workers begin their day in the early morning, by mid-morning WGBT values can exceed 28°C. Further exacerbating the problem is hydration with high sugar content drinks rather than water (Glaser et al. 2016). The CKD study illustrates how improving worker conditions can make a significant difference; however, as shown by heat wave mortality studies, there are fundamental physiological limits.

Multiple Stressors and Impact Projections

Here we have discussed some recent research on the effects of heat waves on human health and mortality. But impacts in complex systems are not found in isolation. There has been an important evolution in the study of impacts on society more broadly due to climate change, as more observational data and better models are applied to the problem in a multidisciplinary manner. Moreover, these impacts are already having measurable impact. A study by Carleton and Hsiang (2017) explores how new data and analysis techniques are uncovering interrelated aspects of the human-climate system where “research has begun to illuminate key linkages in the coupling of these complex natural and human systems, uncovering notable effects of climate on health, agriculture, economics, conflict, migration, and demographics.” Policies measured against incomplete assessment of impacts are likely to fall short of what is needed to guide mitigation and adaptation investments for an uncertain future. The existential threat of climate change is real and increasingly being explored by studies such as those outlined here. As the evidence mounts for the need to avoid the impacts of climate change, so too is the body of solutions being proposed and implemented, from the exponential growth of clean energy to community-based adaptive strategies.
References