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Indoor-outdoor environmental coupling and exposure risk to extreme heat and poor air quality during heat waves

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1. Introduction

Mortality and morbidity associated with extreme summer heat and poor air quality continues to be one of the most pressing human health challenges in cities and is likely to be exacerbated in the future due to urban growth and climate change. Heat is currently the leading weather-related cause of death in the developed world (e.g. CDC 2004), and future heat vulnerability for the elderly is projected to increase substantially in the coming decades (Sheridan et al., 2012). Recent extreme heat events such as the May 2015 heat wave in India that saw record temperatures near 50°C and resulted in more than 2500 deaths, have underlined the importance and urgency of the problem.

Traditional epidemiological studies of the health effects of heat and air quality focus on outdoor environmental conditions. This approach is suitable for assessing heat-health risks for populations that spend much of their time outdoors (e.g. homeless, construction workers, etc). However, as was the case of the European heat wave of 2003, the particularly vulnerable population was the elderly, and in particular, elderly who lived on the top floor of a building that lacked air conditioning (Mavrogianni et al., 2012). Typical urban residents spend more than 85% of their time indoors (Klepeis et al., 2001)—and some of the most vulnerable populations (e.g., the elderly) spend an even higher fraction of time indoors. While the indoor environment is coupled with the outdoor environment there are key differences both in terms of air quality and thermal conditions. With respect to thermal environment, for buildings without air conditioning, this coupling includes variations in indoor air temperature that depend on building construction characteristics, location within building (e.g. top floor, south façade), occupant behavior, internal loads, ventilation, and infiltration. Indoor air quality, on the other hand, is driven by the relative magnitude of each mode of air exchange (e.g. infiltration vs. filtered mechanical ventilation) and emissions and secondary reactions of air pollutants indoors. Hence, there is a need to better understand the relationship between indoor and outdoor environments, and how this relationship is affected by occupant behavior and building construction and management practices. In the case of air conditioned and mechanically ventilated buildings a scenario of particular interest is that of coincident heat waves and power outages producing very unhealthy indoor environments.

This paper discusses a newly funded research project that addresses these issues, with an emphasis on assisted living facilities using the city of Houston Texas, USA as the research test bed. It will introduce some of the key mechanisms that drive differences in indoor and outdoor conditions and present some early findings related to risks of coincident heat waves and power outages or equipment failures in buildings.

2. City and facility selection for study

The city of Houston Texas (USA) presents important human health challenges from the combined perspective of harsh summer climate, dense urban population, and poor air quality. At a population of more than 2.2 million it is the 4th largest city in the US. It has a humid subtropical climate punctuated by a summer filled with high temperatures [a majority of summer days above 32 °C (90 °F)] combined with high humidity (most summer mornings have greater than 90% humidity). As a dense city with extensive manufacturing, oil refining, and more than 400 petrochemical facilities, Houston routinely experiences poor ambient air quality, and high levels of ambient ozone, in particular. Cumulative health risks of heat and poor air quality, especially in neighborhoods in east Houston in close proximity and downwind of the Ship Channel where refineries and hundreds of chemical plants are located, are likely large.

There are roughly 200,000 elderly residents in the city of Houston (US Census, 2010). While this represents a relatively modest fraction (~10%) of the total population, it is a particularly vulnerable population with respect to the risks of extreme heat and poor air quality. For this study we chose to focus on the at-risk elderly population residing in assisted living facilities. Figure 1 illustrates the locations of long term care facilities in the Houston metropolitan region superimposed on a map of average relative risk to extreme heat. Locations of ozone monitoring stations are also shown for reference.

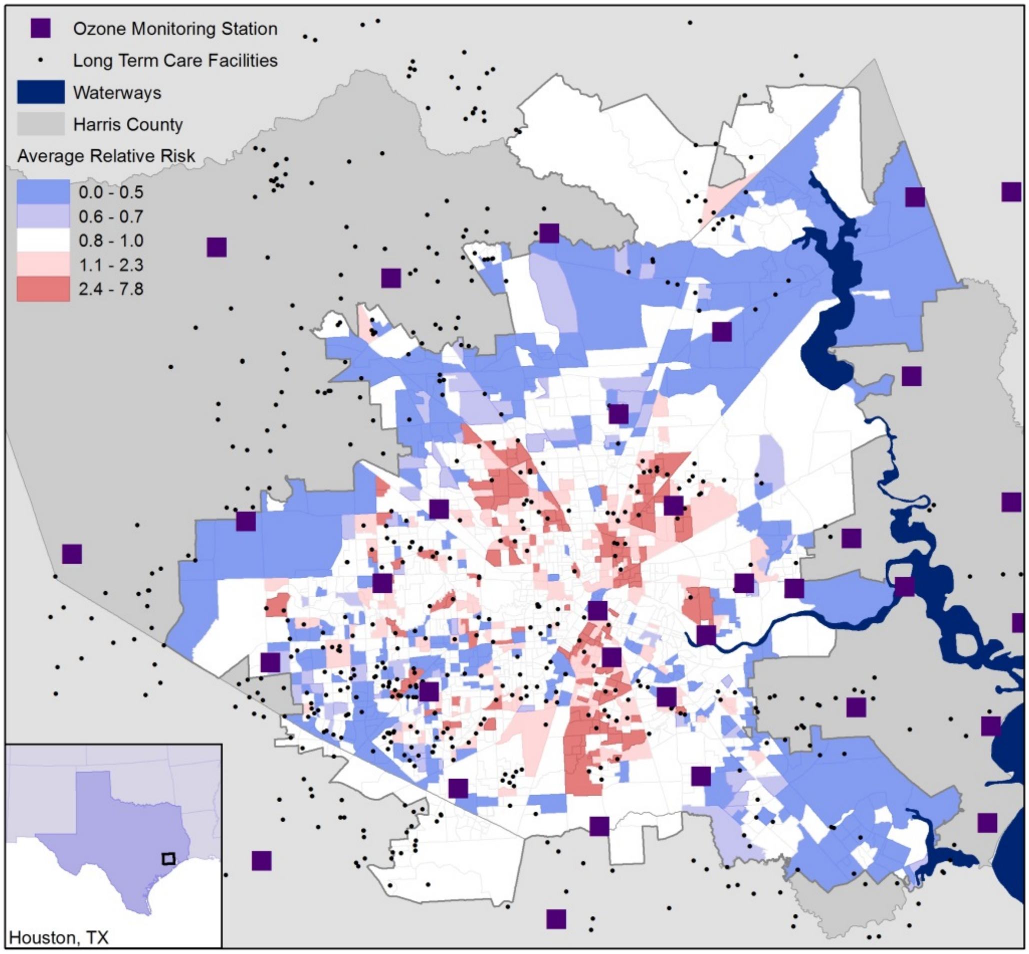

Fig. 1 Locations of the ozone monitoring stations (source: TCEQ, 2014) and the Long Term Care Facilities (source: HDHHS, 2014) are shown on the map of an average relative risk of heat-related mortality in Houston (adapted from Heaton et al. 2014).

3. Urban heat and air quality as drivers of health outcomes

Urban population growth, densification of urban activities, and global climate change are key drivers of the urban atmospheric environment, with significant implications for human health. In mid-latitude cities, the effects of these drivers are particularly evident with respect to air pollution and urban heat in summer. There are many pollutants in the urban environment that pose health concerns. One that is particularly important for the elderly population is ozone. Numerous epidemiological studies have reported associations between ambient ozone levels and respiratory hospital admissions in the elderly (Spix et al., 1998). In addition, meta-analyses have reported a relationship between short-term ambient ozone exposure and mortality (Ito et al., 2005) with significantly larger effect estimates found for the elderly.

Climate change is projected to increase severity, frequency and duration of extreme heat events (IPCC, 2012). Additionally, the urban heat island (UHI) which is partly driven by emission of heat from anthropogenic sources, may amplify climate change in cities (Sailor and Pavlova, 2003). Since ozone concentrations are controlled in part by weather conditions, such as temperature, winds, and relative humidity, ambient ozone concentrations may also increase under climatic change.

4. Linkages between outdoor and indoor conditions

While extreme heat and poor air quality have well-established health consequences (e.g., Fernandez et al., 2006) the vast majority of prior studies have had a limited focus on exposure to outdoor conditions and vulnerability of the general urban population. There is a growing recognition, however, that much of the exposure to unhealthy environmental conditions (heat and air quality) may occur indoors. While indoor environment is generally mediated by Heating, Ventilation, and Air-Conditioning (HVAC) systems, the indoor air is tightly coupled to outdoor conditions, particularly with respect to pollutants such as ozone that, while short-lived, are only partially removed by HVAC systems. Furthermore, exposure to certain ozone-initiated reaction products is a serious human health concern. This research addresses the lack of understanding of how building design, operations, occupancy, and various mitigation strategies alter the relationships between indoor and outdoor pollutant concentrations and exposure. It also investigates risks associated with the fact that building systems designed to operate under current climate conditions may be unable to maintain thermal comfort in a changing climate, and may fail during extreme heat events, leading to potentially devastating effects for populations most at risk.

4.1 Infiltration and forced ventilation

Exchange of air across the building envelope influences both indoor air quality and building energy consumption for space conditioning. While the role of air exchange in affecting energy consumption is straight forward, implications for indoor air quality are complex. Respiration of occupants combined with emissions of pollutants from indoor combustion sources, cleaning products and interior materials/finishes requires ventilation with clean air. However, the outdoor ambient air in an urban setting is often polluted by primary emissions from vehicles and other sources as well as secondary pollutants resulting from reactions within the urban airshed. Hence, air exchange has the potential to bring unwanted outdoor pollutants indoors. While single family residences generally rely on infiltration for air exchange, multi-family residences often require (by building code) explicit mechanically-forced ventilation. In hot climates residences will also employ air conditioning systems to provide much needed cooling in summer. Air conditioning and ventilation equipment perform two functions to condition the building air. First, these systems use air filters to remove particulate matter from the intake (or recirculating) air. Second, they provide for cooling. While air conditioning is increasingly prevalent in developed hot climate cities there are several circumstances under which building residents remain vulnerable to heat indoors. First, it is not uncommon for poor and elderly residents to self-ration the use of air conditioning to reduce financial burdens. Furthermore, air conditioning systems are more prone to failure during periods of extreme outdoor air temperatures, and the utility infrastructure is at risk for black-outs associated with excessive loads on the electric grid during extremely hot weather.

4.2 Secondary reactions

While exposure to ambient ozone is a health concern, indoor concentrations of ozone are generally lower than those outdoors. This is due in part to surface reactions and deposition that take place as ozone-laden air passes over external building materials and through HVAC filters. However, indoor emissions of volatile organic compounds (VOC) from sources such as furniture, carpets, and painted surfaces can react with ozone forming secondary pollutants that may be as important as ozone with respect to human health. Thus, in evaluating the coupling between outdoor and indoor environments it is critical to take into account potentially hazardous secondary reaction products such as formaldehyde.

4.3 Role of occupant behavior and facility management

As suggested above, building management practices and occupant behavior both play important roles in mediating the connections between outdoor and indoor atmospheric environments and occupant exposure to extreme heat and poor air quality. The type, magnitude, and timing of mechanical and natural ventilation affect the exchange of indoor and outdoor air in complex ways. While filters are generally intended to remove particulate matter from the air, filters heavily loaded with organic compounds may actually provide an additional ozone scrubbing effect associated with deposition and surface reactions (Hyttinen et al., 2005). Thus, replacing filters during the high ozone season may actually have an adverse effect on indoor concentrations of ozone.

Assisted living facilities have a number of other management practices that can affect indoor air quality. This ranges from the routine use of high volatile organic compound (VOC) emitting cleaning supplies to periodic maintenance such as painting and replacement of carpets. It is not uncommon, for example, for an assisted living facility to repaint a recently vacated apartment in preparation for a new occupant. Such apartments are typically rented out to new residents within a fairly short time, after the paint has cured substantially, but is still a potentially high emitter of VOCs that react with ozone to produce potentially harmful byproducts. Also, the relative timing of HVAC operations and maintenance and cleaning may play an important role in how indoor and outdoor air interact chemically.

5. Methods

The research approach for this project includes five interconnected components: a) use results from prior studies in conjunction with new regional scale modeling to establish an understanding of how a warming climate and changing emissions will affect extreme heat and ambient ozone concentrations; b) use quantitative and qualitative social science research methods to characterize social vulnerability; c) measure thermal conditions and ozone concentrations indoors and outdoors at a sample of long-term care facilities to characterize diurnal patterns and relationships with building characteristics and occupant behaviors; d) use measurements to develop and validate indoor exposure models; and e) integrate results from the first four components in a comprehensive health outcomes modeling tool.

The combined effect of heat and ozone exposure using a joint model is a novel contribution here. The interactions among project components and information flow are illustrated in Figure 2.

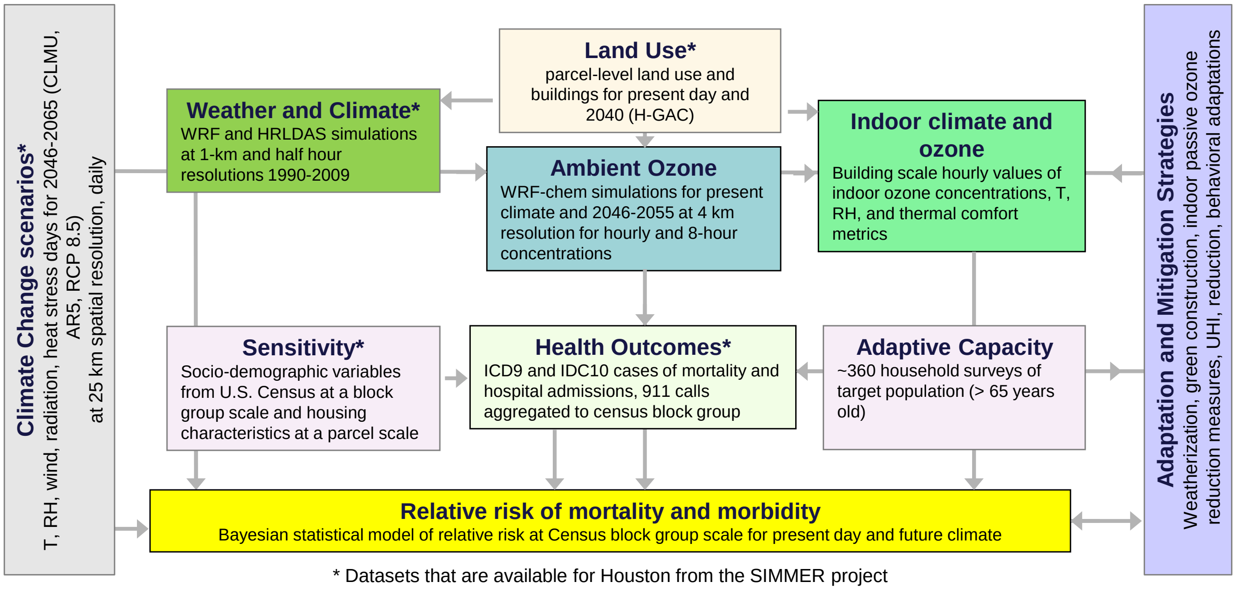

Fig. 2 Diagram of interconnections among project elements and data flow paths.

5.1 Measurements

Two types of measurements will be conducted in support of this project. First, we will be working with the Houston Health Department to recruit up to 15 assisted living facilities in Houston for on-site measurements. Indoor and local outdoor measurements will be conducted over a period of at least 3 months during the summer. At each facility we will measure concentrations of ozone, indoor thermal and air quality conditions, ventilation rates, ozone penetration rates, and outdoor weather conditions. We will also collect details on facility construction, equipment, and management practices as well as occupant behavior, particularly with respect to activity patterns indoors and out.

We will supplement the existing literature on the role of building products in indoor air quality through laboratory measurements geared at exploring the interactions that occur over time. For example, we will consider how VOC emission rates from a freshly painted or carpeted room decay over days to weeks and how that affects the reactivity of room air with ozone forming various undesirable byproducts. We will also explore the residence time of cleaning products with respect to their reactivity with infiltrating ozone.

5.2 Modeling

We will use modeling to explore current and future characteristics of ambient ozone and temperatures across Houston, and the implications of a warming climate for indoor air quality. This assessment will focus on the sample of assisted living facilities, taking into account specific building construction characteristics, operations, and occupant behavior. Building-specific measurements will be used to assess penetration rates of outdoor ozone and its reactivity in the indoor environment. As all of the assisted living facilities under study have installed air conditioning systems, the thermal environment aspects of this work will focus on simulations to explore heat risk associated with failures of air conditioning systems or loss of power in the electric utility grid.

6. Preliminary results and project status

Although the funding for this project was only formalized in June 2015, we have initiated several key aspects of this project: A stakeholder workshop is in the planning for early spring 2016; a list of potential facilities has been created for initial screening and recruitment; an apparatus for investigating reactivity of ozone in indoor environments has been designed and is under construction; and initial building simulations have been conducted to explore heat vulnerabilities in situations where a heat wave is coincident with equipment failure.

The initial building simulation analysis used downscaled climate change scenarios from the IPCC Fifth Assessment in conjunction with whole building simulations using the US Department of Energy's Commercial Benchmark buildings to explore indoor thermal comfort metrics [maximum indoor temperatures, Predicted Mean Vote (PMV), and Predicted Percent Dissatisfied (PPD)—see ASHRAE 2010] under normal operating conditions and conditions where the air conditioning system fails. These simulations were conducted for the current climate and for scenarios of climate in 2050. Results are tabulated in Table 1. See Sailor (2014) for an overview of the methods for these simulations.

Table 1. Thermal comfort metrics for Houston simulations (south-facing apartment on top floor) for the current climate, 2050 simulation, and 2050 simulation with enhanced UHI. Each result is presented for normal operations and for a scenario in which air conditioning fails during the hottest 3 day period (Aug 1-3).

Comfort Metric	Current		2050	
	Normal	Failure	Normal	Failure
Max Indoor Air T (^{o}C)	24.4	38.5	25.4	39.4
Max PMV	0.0	4.4	0.3	4.9
Avg. PMV	-0.2	2.0	-0.1	2.6
Avg. PPD	6.2	61.9	5.9	71.4

The corresponding trace of indoor air temperatures is presented in Figure 3 for the hottest 3 days of the simulation period (Aug 1-3). These results demonstrate that the existing air conditioning system is able to maintain indoor temperatures at the setpoint of 24 ^{o}C even in a heat wave. However, if the air conditioning system fails, the indoor air temperature profile shifts upward. By the 3rd day without power the indoor air temperature for current and future climates reaches 38.5 and 39.5 ^{o}C, respectively.

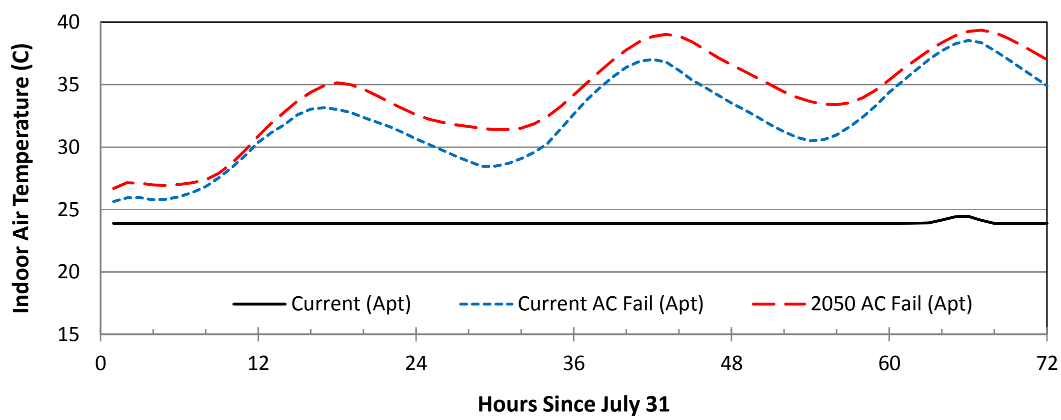

Fig. 3. Ambient and indoor air temperature evolution for the south-facing top-floor apartment (Apt) under conditions of normal operations and AC failure in Houston, TX.

As the research progresses we will announce findings on a project web site and publish in relevant journals. The key product of this project will be a comprehensive understanding of the relationships among outdoor environment, indoor environment, building characteristics, behavior, management/mitigation strategies, and respiratory health outcomes among older adults. This will translate into policy and building design/management/retrofit recommendations. We welcome opportunities to collaborate with other researchers with similar interests and projects.

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