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Toward precision governance: infusing data into public management of environmental hazards

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ABSTRACT
Precision governance is an administrative capacity in which policy decisions are enhanced with information about individual and collective preferences and contexts. We introduce the prospects for precision governance of natural hazards through the use of both big and individual data technologies, describing what is enabled and what concerns arise with their use. We ground our perspective with a topical focus on mitigating the health risks of high temperatures in the chronically hot setting of Phoenix, Arizona, USA. A study examining individually experienced temperature data provides compelling evidence that the transition towards data-driven precision governance will enhance hazard preparedness and response efforts.

KEYWORDS Governance; hazards; heat; health; sensors

1. Introduction

One of the essential functions of government is to protect public safety. Government and the public at large are now paying more attention to the health impacts of natural hazards. Government agencies often play a central role in helping communities prepare for, respond to, and recover from events like tornadoes, floods, and snowstorms. The growth of the digital era, and all of its technological and computational affordances, make it possible for public agencies and other actors to employ *precision governance* in their efforts to protect communities when such hazards occur. Johnston et al. (2013) defined precision governance as ‘the ability to design governance infrastructure – the collection of technologies and systems – to represent individual and collective choices and policy preference into augmented societal policy decisions.’ Here, we add to the notion that the individual and collective policy preferences that would ideally be incorporated into a precision governance approach also include latent preferences and needs of individuals and groups based on fine-scale differences in circumstances and experiences.

Those involved in protecting the public when hazards occur, from officials to non-profits to individuals, are increasingly able to customize preparation and response efforts based on historical and real-time data. The incorporation of a variety of data

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sets and streams can improve community and individual readiness for natural hazards as well as decision-making when events are imminent or occurring. Furthermore, the public is increasingly demanding improvements in these efforts from government agencies (Kapucu 2009). Thus, improvements in hazard-related interventions might not only limit unwanted consequences of these events but also improve the relationship between the public and government. Moreover, the network of individuals and organizations involved in hazard preparedness and response is both large and complex (Robinson et al. 2013), and the benefits of precision governance-oriented strategies could aid in the coordination of the many actors that play a role in protecting communities.

To discuss the prospects for data-driven, evidence-based public management of the risks associated with hazards, we draw examples from our local experiences in Maricopa County, Arizona, the anchor of the hottest large metropolitan area in the United States. In this locale, a hazard of concern for public health agencies is extreme heat. The growing availability of health and exposure data and our ability to analyse and interpret these data in meaningful ways has the potential to transform the manner in which local agencies respond to the serious threat of this hazard.

We are interested in two aspects of the use of data in governance: first the preparation and then the decision-making. Regarding preparation, the operational question is how to thoughtfully and intentionally build a governance infrastructure that collects the appropriate data, analyses it to be useful, and then communicates it to those who need to make decisions. Regarding decision-making, the question of interest is how the behaviour of government agencies, collaborators, and the public adjusts when information is readily available that can influence how they organize or act. From a public health perspective, developing a robust evidence base that informs the design and deployment of effective intervention measures that protect the public when hazards occur continues to be a priority of researchers and practitioners alike. Yet, the key evidence to foster effective evidence-based public health management of environmental hazards, particularly those related to weather and climate, is largely absent (Hess et al. 2014).

2. Case study context: extreme heat in Maricopa County, Arizona

High ambient temperature is an environmental health hazard that has received increasing attention from researchers and policymakers in recent years given the prospects of increasing global and urban temperatures (Luber and McGeehin 2008; Hondula, Georgescu, and Balling 2014; Winkler et al. 2015). An association between temperature and a wide range of adverse human health outcomes including mortality has been documented across many geographic settings (McMichael et al. 2008). Notable extreme heat events in the past few decades have resulted in hundreds (Chicago, 1995) to tens of thousands (Europe, 2003) of deaths over time periods spanning days to weeks (Semenza et al. 1996, Conti et al. 2005). Direct financial impacts on the healthcare system from an individual heat event in a single geographic location can exceed tens of millions of dollars (Knowlton et al. 2011; Lin et al. 2012).

In the United States, extreme heat ranks among the leading weather-related causes of death, responsible for more fatalities each year than most other natural hazards combined (Berko et al. 2014). Few localities in the United States face higher temperatures each year than the Phoenix, Arizona metropolitan area, a region that is home to more than 4 million people and that faces summertime daily maximum temperatures regularly exceeding 40°C (104°F). Heat continues to exert a considerable public health toll among residents of greater Phoenix: the Maricopa County Department of Public Health reported 433 heat-related deaths over the period 2010–2014 and Petitti et al. (2015) reported a total of more than 8,500 heat-related hospitalizations and emergency department visits over the period 2008–2012. Extreme heat disproportionately impacts certain communities and populations in Maricopa County including those with low incomes and ethnic minorities, outdoor workers, homeless, those without home air conditioning, and individuals using drugs or alcohol (Harlan et al. 2012; MCDPH 2014).

Returning to the definition of precision governance, in the context of extreme heat, the *individual and collective choices* of interest are (1) the behaviour changes that reduce the risk of adverse health outcomes and (2) the occurrence (or lack thereof) of adverse health outcomes. The *societal policy decisions* of interest are the plans and programmes that agencies implement with the goal of limiting unwanted consequences. In central Arizona, these societal policy decisions include the Extreme Heat Emergency Response Plan of the Arizona Department of Health Services, the coordination and activation of the Phoenix Heat Relief Network of cooling centres and water distribution facilities by the City of Phoenix and the Maricopa Association of Governments, the operation of a surveillance programme by the Maricopa County Department of Public Health and the issuance of extreme heat warnings to the general public by the Phoenix forecast office of the National Weather Service. At longer time scales, educational campaigns and infrastructure modifications (e.g. increasing tree/shade cover, implementing white and cool roof technology) are the major efforts described in policy and planning documents that are intended to reduce impacts (e.g. Chow, Brennan, and Brazel 2012).

3. Constraints on hazard management

Many of the public management strategies for extreme heat already operate under the paradigm of increasing the precision of governance (albeit at a coarser scale than the one we imagine in this manuscript), leveraging a large literature that has accumulated over the past several decades. For example, public warning systems for heat are often designed based on city-specific threshold temperatures derived from epidemiological analysis (e.g. Pascal et al. 2006) and educational campaigns employ messaging built from the same evidence base (e.g. White-Newsome et al. 2014). The risk-assessment studies that contribute to this evidence base are often performed at a regional or citywide scale, which matches the scale at which heat occurs (e.g. the meteorological features associated with heat are hundreds or more kilometres in their spatial extent) but does not match the scales relevant for heat exposure such as individual households, parcels, or even smaller spatial units (Ruddell et al. 2009). Communication of the threat of heat also tends to be based at the regional scale: warning messages are often targeted to entire counties or groups of counties and disseminated to broad areas (e.g. the entire viewing audience of a local television or radio news outlet).

As a consequence, we contend that the preparation for – and response to – hazards is limited by information that is often too coarse to guide the most efficient deployment of resources to those in need despite the positive intention of hazard management plans and response actions. The fact that heat continues to exert a considerable public health burden in our geographic focus area of central Arizona, as well as many other municipalities around the world, indicates that there are still ample opportunities to improve our approach to dealing with high temperatures in terms of preparedness and response efforts. We hypothesize that a transition to a governance framework centred on greater precision would be an effective strategy for reducing impacts moving forward. In such a framework where individual preferences and contexts are the basis for preparation and decision-making, new design possibilities can emerge. Targeting, customization, and personalization of response efforts could be especially beneficial in the light of time and resource constraints that are common in government agencies involved in hazard management (e.g. Hu and Kapucu 2016).

A prime example of the shortcomings of current societal policy decisions for heat and their influence on individual collective choices is early warning systems, which are a centrepiece of heat preparedness strategies in many localities (Lowe, Ebi, and Forsberg 2011). In the current approach, where (typically) one broad warning message is communicated to the entire population of a city or other large region, the conditions do not exist for a message recipient to easily understand or explore what specifically the warning may mean in the context of their individual life, needs, and preferences. We believe that this lack of precision at least partially explains why evidence of behavioural changes in response to heat warnings has been scant despite generally high awareness of warnings (e.g. Kalkstein and Sheridan 2007; Bassil and Cole 2010).

Perhaps more concerning is the perception reported in some of these studies that many individuals believe that they are not at risk from heat and/or the warning message is not intended for them. While the physiological evidence is quite clear – individuals exposed to high temperatures for a prolonged period of time are at risk of illness or death – individuals who do receive warning messages about heat are, in fact, quite *unlikely* to experience any harm from heat: the average American, for example, spends approximately 90 per cent of his or her time indoors (Leech et al. 2002), much of which may be spent in climate-controlled settings (at work, at home, or in transit). The delivery of repeated heat warnings to a significant portion of the population that is not physically 'experiencing' heat during much of their daily activity could build latent complacency regarding the seriousness of the hazard that may leave them unprepared when they partake in activities that expose them to high temperatures. This latent complacency builds as a result of repeated false alarms from weather warnings (Barnes et al. 2007).

Most of the research related to false alarms for natural hazards concern high-visibility events like tornadoes and floods: a false alarm in these cases is defined as the hazard not materializing (e.g. a tornado did not happen or occurred in a different location than was forecast/warned). In the case of heat, we suggest that a different type of false alarm occurs. Weather forecasts for heat are highly accurate; a true 'false alarm' almost never occurs. Instead, the false alarm occurs at the *individual* level – an extreme heat event occurs but does not result in any notable impacts for certain people. In a 2009 study of heat-vulnerable communities in Maricopa County, 63 per cent of survey respondents indicated having zero heat-related symptoms of any kind (Hayden, Brenkert-Smith, and Wilhelmi 2011). When considering the scale at which extreme heat events occur (multiple cities or regions), the *individual* false alarms are more likely to be the norm than the exception. Although debate continues regarding the validity of a false alarm-complacency mechanism in real-world hazard situations (Barnes et al. 2007), it seems more likely than not that some portion of the many individuals who do not believe that heat is a risk to them are of this mindset because they have repeatedly experienced heat and heat warnings in the past with no adverse health effects.

As a result of coarse information about the public health impacts of extreme heat, misguided or inefficient planning, policy-making, and decision-making can also occur at the agency level. Concerns about the health impacts of heat motivate local, national, and international policy aimed at reducing outdoor temperatures, whether through efforts to reduce the urban heat island effect in cities or decelerate emission of greenhouse gases worldwide (e.g. Solecki et al. 2005; Patz et al. 2005). Given that there is a clear association between high outdoor temperatures and adverse human health outcomes, the notion that reducing outdoor temperatures (or limiting future increases) will have benefits for health seems logical. The scientific literature is only recently, however, beginning to examine how outdoor temperatures relate to the entirety of a person's heat exposure (Kuras et al. 2017). Without a rich understanding of the relationship between outdoor temperatures and experienced temperatures, some public policies concerning the health impacts of heat may be misdirected. In urban areas, for example, focusing urban heat island mitigation strategies on central business districts (where the heat island effect is most intense) may not be the optimal strategy for reducing adverse heat-health outcomes because those may not be the places where the most vulnerable individuals tend to experience high temperatures through the course of their daily lives (because that is not where they live, work, or recreate). The resources invested in such programmes could yield greater benefits for health if they were invested in energy affordability or home weatherization programmes for those who are unable to use air conditioning on a regular basis. The reverse may also be true, but the coarseness of the information currently available in most settings makes it impossible to fully evaluate the trade-offs between certain strategies and properly account for health benefits versus other important dimensions of urban heat like energy and water use, real estate, tourism, and other commercial activity.

4. Data-driven governance

Advances in data collection and accessibility as well as computational power and resources have dramatically accelerated our ability to understand environmental hazards like heat in the nuanced, specific manner that is necessary for effective precision governance. These advances can direct transformational changes in the public management of hazards within the next 10–20 years.

Epidemiological and geographical analyses of the social and environmental risk factors for adverse health outcomes related to heat exposure have benefitted tremendously from improvements in computational power and data accessibility. It is not uncommon for heat-health studies published in recent years to incorporate data sets involving tens of millions of health records, satellite imagery with spatial resolution of tens of metres or better, and/or social and infrastructure data sets at the household and parcel level for entire metropolitan areas (e.g. Rosenthal, Kinney, and Metzger 2014; Morabito et al. 2015). The studies provide the evidence base that makes it possible to target intervention measures for heat to the communities where the benefits will be disproportionately highest as well as shape those intervention measures to the specific needs of at-risk populations. There is already evidence that some jurisdictions are utilizing the output of this research in their hazard management plans (e.g. the San Francisco Department of Public Health: https://www.sfdph.org/dph/EH/climatechange/ and Minnesota Department of Health: http://www.health.state.mn.us/divs/climatechange/extremeheat.html).

Computational advances continue to improve our ability to understanding the physical dimensions of environmental hazards as well. For example, complex models that require significant computing infrastructure are being used to simulate how changes to infrastructure, the land surface, and the atmosphere (e.g. building design, land use change, increasing greenhouse gas concentrations) will impact thermal environments at scales ranging from individual buildings to the entire globe (e.g. Ohashi et al. 2015; Zhao et al. 2015). One emerging theme from this research is that, with respect to urban heat island mitigation, there is not a 'one-size-fits-all' approach – mitigation strategies that are effective in some locations, like green roofs, are likely to be ineffective or inefficient in others (e.g. Georgescu et al. 2014).

A technological advance that has captured the interests of researchers and decision makers is the increasing accessibility (and decreasing cost) of small but reliable electronic devices that are suitable for recording environmental data such as air quality and temperature. These devices have the potential to provide foundational data sets and feed into real-time information management systems for hazard responders that provide the level of detail imagined in our conceptualization of precision governance. Examples of these devices range from mobile sensors that can be attached to clothing or the exterior of a bag, smartphone technology that is carried in purses or in individuals' pockets or hands, and stationary sensors embedded and camouflaged into societal or natural infrastructure such as lamp posts and trees (Khan, Imon, and Das 2015; Hart and Martinez 2006). Yet, another data source includes smart home temperature monitoring technologies such as the Nest thermostat. Data from these types of sources can be crowd-sourced or pooled to better understand at-home thermal conditions and potentially hazardous heat exposure (Chan et al. 2008; Muller et al. 2015). The emergence of these technologies has allowed researchers to collect large amounts of data for which, previously, only crude estimates or models were available.

Information about heat exposure at the human scale has become attainable due to the increasing capacity for researchers to harness the sensing potential of the public, and reciprocally, public interest (or at least cooperation) in participatory or research-oriented monitoring efforts. Engagement in such efforts has multiple motivations. For one, research and governmental institutions may ask members of the public to help collect environmental data by distributing sensors and/or asking individuals to record systematic observations (Conrad and Hilchey 2011). Second, members of the public or community groups may initiate an environmental monitoring effort to advocate for better management of health hazards or environmental conditions (Minkler et al. 2008). Similarly, citizens may voluntarily input observations into mobile smartphone applications to share information about traffic congestion or weather hazards, or in contrast, passively contribute data through smart devices that track environmental and meteorological conditions along with location information (Kamel Boulos et al. 2011). Finally, some individuals are motivated to collect their personal environmental data so as to have a better understanding of their own activities and exposures. This type of monitoring aligns with the 'quantified self' movement that also includes activities like tracking one's weight, measuring exposure to harmful chemicals, or recording the number of steps walked each day (Swan 2009).

An important dichotomy can and should be drawn between spatially explicit and personally explicit environmental data collected by and/or about the public. Spatially explicit data are place dependent and can be gathered passively by smartphones (e.g. Overeem et al. 2013), home-monitoring devices, or by citizen volunteers that regularly record data or make observations in a certain place or along a transect (e.g. Muller et al. 2015). These data are useful for environmental justice efforts that can target excessively hot and marginalized areas of a city (Declet-Barreto et al. 2013) or for higher resolution weather forecasting (Muller et al. 2015). Personally explicit data are person dependent and are recorded wherever the individual happens to be at the time of measurement. For example, an individual may record a car accident, incident of cardiac arrest, or fine particulate matter levels wherever he or she is located at a given time (Kamel Boulos et al. 2011; Minkler et al. 2008). Personally explicit data allows researchers and decision makers to know precisely what conditions members of the public are actually experiencing as they go about their daily lives.

In the context of extreme heat and individual-level intervention, data of interest for researchers and decision makers include the personally explicit ambient air temperatures that individuals experience as they go about their daily lives (hereafter referred to as individually experienced temperatures, or IETs; Kuras, Hondula, and Brown-Saracino 2015). Already, a small number of research teams have utilized small, portable, personal-sensing technology to more precisely and intentionally collect heat exposure and vulnerability data from members of the public (see Basu and Samet 2002; Bernhard et al. 2015; Kuras, Hondula, and Brown-Saracino 2015). Other research groups have creatively used temperature data to identify periods of time when participants were moving between indoor and outdoor settings and therefore exposed to different amounts of air pollution (Nethery et al. 2014) or to assess the relationship between indoor and outdoor temperature and distress calls by attaching temperature monitors to paramedics' bags (Uejio et al. 2016). These efforts have yielded critical insights into hidden vulnerabilities that may otherwise be misclassified through more blunt and conventional monitoring technologies. In the future, these approaches will likely be expanded to include a wider range of variables that are important to consider for human heat stress, including sunlight, wind, humidity, and activity level, but already lay the groundwork for considerable advancements in the type of information that can improve preparation and response.

5. A study of IETs

5.1. *Methods*

To explore how personally explicit environmental data could be used for precision governance interventions, we conducted a study of IETs in the Phoenix area following Kuras, Hondula, and Brown-Saracino (2015). Currently, the framing of many extreme heat intervention measures does not directly take into account individual-level differences in exposure. We sought to determine if individuals living in the same city experience the same heat events differently. The study took place from 20:00 13 September to 20:00 20 September 2014 to capture IETs under warm season conditions. With the exception of 2 days during the study period with unseasonably low temperatures related to the remnants of Hurricane Odile, mean daily temperatures in Phoenix ranged from 30.5°C (87°F) to 35.1°C (95°F) during the study week as measured at Sky Harbor Airport (KPHX). Five greater Phoenix neighbourhoods were selected to provide contrasts in geography, vegetative landscape, demographics, and socioeconomics. From among those neighbourhoods, eighty residents were recruited to participate in the study through information bulletins posted in local businesses, flyers distributed on the street, and emails sent through Homeowner associations and neighbourhood groups. Research participants were equipped with Thermochron iButtons (DS1921G-F5#) that measured and recorded instantaneous air temperatures at 5-min intervals during the study week. Participants were asked to clip their iButtons to a belt loop or bag such that the device was continuously exposed to the surrounding air, thus recording the time series of ambient air temperatures that were also physically 'experienced' by participants as they went about their daily lives, regardless of time spent indoors or outdoors, clothing, or recreational activity. In addition, participants were asked to record any period of time in which they were not carrying their iButtons (these data removed prior to analysis). IET data were later averaged to 15-min intervals for reporting purposes and pseudonyms were used to protect participant confidentiality. All times are reported in Local Daylight Time.

5.2. *Results*

In line with the findings of other personal heat exposure assessments, temperatures recorded at KPHX overestimated IETs of research participants, especially on hot days (Figure 1, Kuras, Hondula, and Brown-Saracino 2015; Bernhard et al. 2015, Basu and Samet 2002). However, the highest IET measurement from among any participant

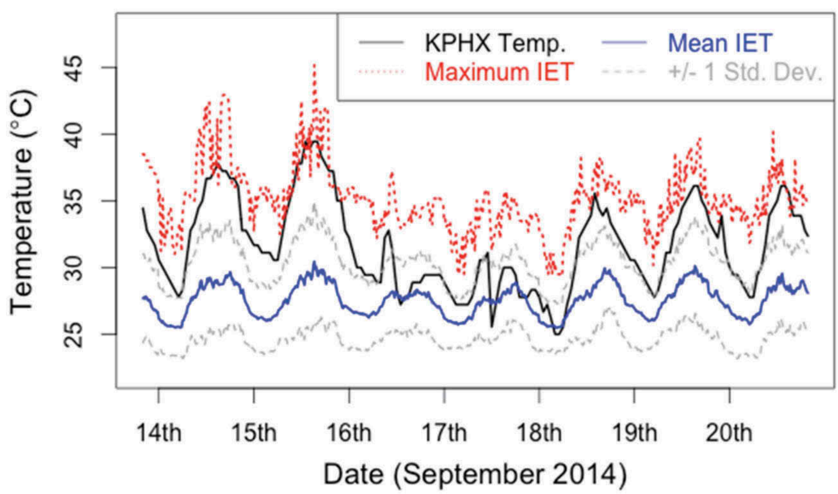

Figure 1. Temperatures recorded at Phoenix Sky Harbor International Airport (KPHX, solid black line) and mean individually experienced temperatures (IETs, solid blue line) from 13 to 20 September 2014. One positive and negative standard deviation from the mean (dashed grey lines) and maximum IET (dotted red line) are presented as well.

was consistently recorded at or above KPHX temperatures (maximum IET in Figure 1).

To illustrate the utility of IET data in providing precise information about who is experiencing high temperatures and when, we focus on IET data for Monday, 15 September, on which temperatures recorded at KPHX ranged from 30.6°C (87°F) to 39.4°C (103°F) (Figure 2). Again, the majority of participants recorded IETs multiple degrees lower than outdoor temperatures while the hot outliers were exposed to temperatures mostly in excess of conditions at KPHX, especially during the night-time hours.

For each hour on Monday, IETs in the top 5 per cent from among all participants were examined to identify the individuals who experienced the highest temperatures. We focus on three individuals, Dolores, Hunter, and Iris, with contrasting time periods of high exposure to demonstrate how IETs can help refine our intervention strategies (Figure 3). Dolores had among the highest percentage of IETs in the top 5 per cent (36.4 per cent of all her Monday measurements), followed by Hunter (29.2 per cent of Monday measurements) and Iris (20.8 per cent). A number of observations concerning patterns of exposure can be made by comparing the IETs of Dolores, Hunter, and Iris on Monday. First, high IETs during the night-time period suggest that some participants did not use or have access to home cooling devices. This observation applies to Dolores, whose morning IET tracked KPHX temperatures more closely than Hunter and Iris. Dolores recorded similarly high night-time IETs, which further supports the suggestion that she did not use a home cooling strategy. Second, occasional and short spikes in IETs suggest that some participants were exposed to heat for only small durations at a time. Around 3 P.M., Dolores experienced one of these peaks, as did Iris from 6 to 7 P.M. Third, some participants experienced high temperatures for sustained periods of time during the daytime

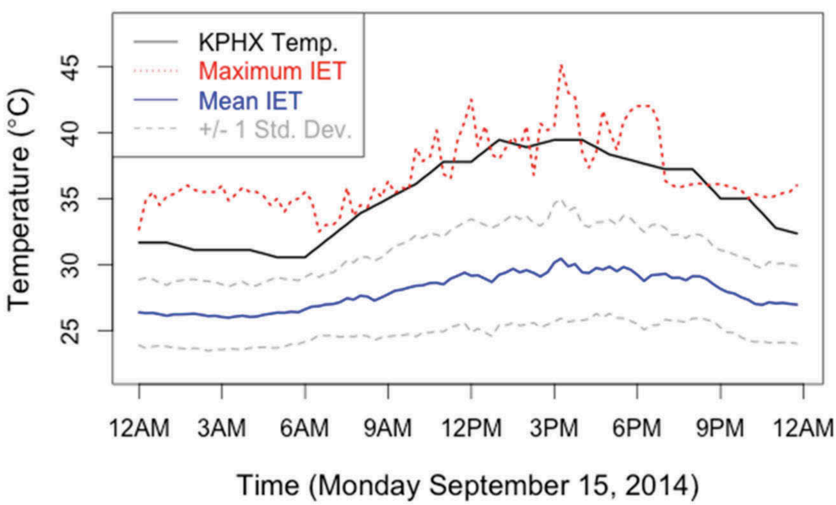

Figure 2. Temperatures recorded at Phoenix Sky Harbor International Airport (KPHX, solid black line) and mean individually experienced temperatures (IETs, solid blue line) on Monday, 15 September 2014. One positive and negative standard deviation from the mean (dashed grey lines) and maximum IET (dotted red line) are presented as well.

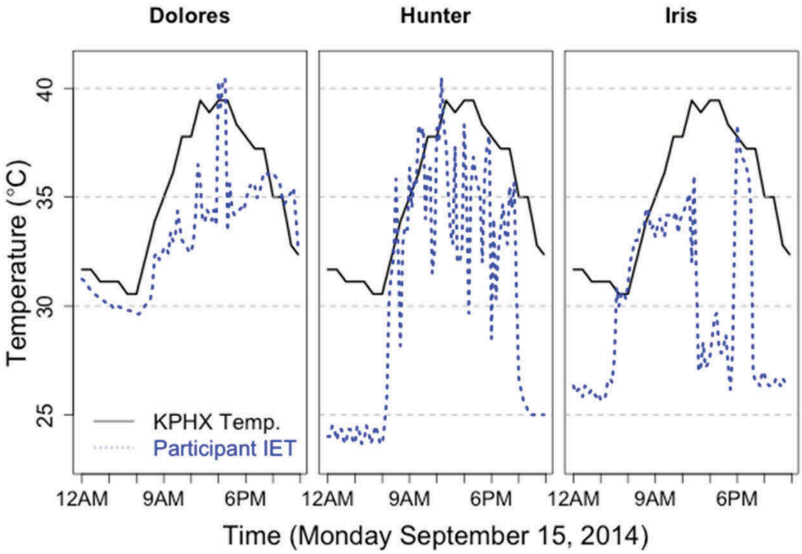

Figure 3. Individually experienced temperatures (IETs, dotted blue lines) of three selected participants as well as temperatures recorded at Phoenix Sky Harbor International Airport (KPHX, solid black line) on Monday, 15 September 2014.

hours. Hunter broadly recorded high IETs from 7 A.M. to 8 P.M., although the variability in his IETs suggests that his thermal conditions changed frequently throughout the day. Iris more consistently recorded high IETs from 4 A.M. to 12 P.M. although it was the IETs from 4 to 8 A.M. that were among the top 5 per cent from all participants in that time range. Both cases of more sustained heat exposure may have been due to occupational or lifestyle factors. For example, Hunter or Iris may have worked in a hot restaurant kitchen or taken long walks outside.

5.3. *Discussion*

On an individual scale, IET data can enable interventions in which members of the public that opt to passively record their experienced temperatures receive tailored information about heat-health risks and resources. For individuals like Dolores who have high IETs during the overnight hours, information that enables the individual to have expanded access to home cooling devices would lower the risk of heat-related illness. Such interventions may include assistance with cooling bill payments, weatherization, and air conditioning repair. For individuals such as Dolores and Iris that are exposed to high temperatures sporadically and for a short amount of time, personalized heat-health warning messages may avert a heat emergency distress call. These messages could be triggered when individuals have exceeded a predetermined and personalized threshold for heat-health risk and could inform individuals of their current risk and provide useful suggestions such as nearby cooling and hydrating resources (e.g. cooling centres, air-conditioned public spaces with water fountains, cafes, convenience stores) and heat-health advice (how to stay hydrated, how to identify symptoms of heat stress, and how to seek medical attention). For those like Hunter and Iris who experience sustained high temperatures for a longer period of time, similarly tailored messages may have a positive impact, especially if they also provide information about heat-health risks and resources associated with occupation or lifestyle.

On a collective scale, IET data can assist health agencies and emergency managers to better identify and engage at-risk populations at critical intervention points by revealing temporal and spatial patterns of exposure and vulnerability. With more precise information about who experiences high night-time temperatures, short peaks, or sustained periods of high temperatures, decision makers can more effectively target a heat-exposed population or place with the appropriate short-term information resources or longer term cooling, hydrating, educational and economic resources meant to proactively prevent heat stress.

On a hot day such as Monday, 15 September 2014, a blanket heat warning would not necessarily provide useful, or meaningful information to Dolores, Hunter, Iris, or, as we can infer from heterogeneous IETs reported elsewhere (Kuras, Hondula, and Brown-Saracino 2015), many residents of the Phoenix metropolitan area. Such contrasting experiences in heat exposure necessitate a transition towards precision governance in which we more effectively target the people, times, and places of highest vulnerability with evidence-based, tailored, and useful interventions and management of this public hazard.

6. Ethical considerations for precision governance

Evidence-informed policy should be better positioned to address public problems than policy based on anecdotal experience or informal beliefs (Quade 1975). Yet, governance relies on a combination of truthful claims and the representation of values, with participants engaged in rational discourse aimed at reaching universally acceptable decisions (Habermas 1996). More data should mean less arguing about 'facts,' with greater energy devoted to discussing values and the interpretation of uncertainty. A more colloquial expression of the relationship between facts and values in political discourse has been expressed as 'everyone is entitled to his own opinion, but not to his own facts,' a quotation often attributed to the late US Senator Daniel Patrick Moynihan. As a sentiment emerging from the golden age of policy debate during which Senator Moynihan was a key player, the quote efficiently parses the politics/administration dichotomy and the relationship between values and evidence, between beliefs and facts: we may differ on what the best course of action ought to be, but we can surely agree on what *is* is. The attraction of this idea has recently been revived in the context of political controversies such as 'climate science denial,' in which disagreements about values (e.g. Are humans responsible for future generations and other species? What is a tolerable rate of climate change for the planet's ecosystems and people? Should individual freedom of choice be subservient to collective well-being?) are often being shielded behind disputes about the fact of anthropogenic influence on climate. In this environment, disagreements between facts and opinions become conflated and resolution becomes seemingly impossible.

It is in such an arena that we can understand the appeal of greater precision in governance through more data, more detailed analytics and increasing certainty over 'the facts.' We now have the ability to measure phenomena like heat exposure more precisely, continuously over time and space, to assemble data that dwarfs the data limits of previous generations. Scientists and analysts are regularly improving their methods for interpreting these data and extracting actionable information from them. Despite these advances, there are several ethical reflections that practitioners, governance participants, and decision makers should consider when seeking to advance the greater use of data in support of governance.

First is to understand the limitations of what data and analysis can reveal about truth, regardless of the volume of data accumulated. It is tempting to believe that, with massive volumes of data from very large numbers of individuals, big data provide an increasingly clear picture of all relevant entities. However, depending on the methods for data collection, some people will fail to be represented in big data regardless of the volume collected. In this setting, prior concerns over the digital divide take on a new dimension where the experiences of some people are not captured in current data collection methods. In proposing a concept of the 'digitally invisible,' Longo et al. (2017) suggest that big data analysis based on smartphone use, Internet of Everything devices, and electronic payment transactions will be biased against those in societies who do not regularly use those devices and cards. Benoit (2015, np) has called this problem 'the myth of N = All' and argues that it presents a particular challenge in the context of growing use of data for policy-making.

Second, data-driven governance should acknowledge the post-positivist observation that there is no airtight distinction between facts and values, and that data collection and analysis is a product of the biases and subjective worldview of the researcher (Fischer 2003). What to study, how to study it and what is seen when it is studied are all influenced by the researcher's values. Also, data can only be translated into actionable information through judgments made by analysts or decision makers (Majone 1989). There is no algorithm or artificial intelligence that can substitute for the presence and necessity of values-based decision-making.

Privacy and security are also crucial concerns. One challenge involves the difficulty of protecting personally identifiable information in anonymized population data sets, a computational process alternatively referred to as re-identification or de-anonymization. A different privacy issue emerges in the context of informed consent. Debates continue as to whether it is ethical to conduct research on people without their expressed consent – a subject normally the domain of research ethics committees – because the data in question involve public statements on social media sites. De-anonymization is one challenge (Zimmer 2008), as is the taking-out-of-context of public statements made by identifiable individuals (Boyd and Crawford 2012). Manipulation of variables that affect 'research subjects' became an area of concern in 2014 when the news feeds of over 600,000 Facebook users were modified to test the theory of emotional contagion (Kramer, Guillory, and Hancock 2014). Concerns were raised following the publication of the study that the research involved 'practices that were not fully consistent with the principles of obtaining fully informed consent and allowing participants to opt out' (Verma 2014).

The use of large data sets to identify correlations as an aid to predict future events (or how to react to them) has emerged in domains ranging from policing to lending. Predictive policing involves analysing high volume and continuous data flows, including social media and telephone metadata, to predict where future crimes are more likely to occur, so that police forces can allocate resources accordingly. Concerns have been raised about over-prediction of crime, police bias, a lack of evidence that such systems actually reduce crime, and the abdication of decision-making to opaque algorithms promoted by for-profit firms (Joh 2014). New firms have emerged that provide credit-worthiness evaluations of potential borrowers based on their social media presence. 'Digital redlining' is the process of identifying locations or networks to exclude individual or groups from things like access to credit (White House 2014). In both cases, previous protections – e.g. against unlawful search, or fairness in credit evaluations – are being challenged by the use of data and advances in technology. Ultimately, precision governance should not be seen as a substitute for human decision-making that replaces or limits discretion by either the bureaucrat or the citizen. Rather it can serve to augment informed decision-making. Towards that end the question becomes first whether or not these information interventions are useful at achieving each party's desired outcome, and second, what training or additional context is needed to increase the likelihood that both groups will understand the strengths and limitations of the precision governance approach.

Finally, the call for precision governance acknowledges prior experience with personalization in public management and service delivery (Needham 2011). Identified largely with the Blair government in the United Kingdom, personalization was applied to a range of policy areas including social services, healthcare, and education. Through personalization, citizens were given greater control over the delivery of public services with the intention of improving people's lives, increasing efficiency, and focusing on the needs of the client from their individual perspective. Despite its strong support across the political spectrum, Ferguson (2007) notes that 'some of its implications may be less than benign both for those who provide social work services and even more so for those who use them.' Personalization derives from the earlier concept of 'street-level bureaucrats' (Lipsky 1980), identifying the public servants who deal directly with the clients and targets of service delivery and who often exercise discretion in service delivery by being its closest connection to their needs. But where street-level bureaucracy envisions the embodiment of discretion within the purview of the public servant, dealing one-on-one with a client across the desk, personalization at the scale of whole societies risks stereotyping individuals based on data correlates. While precision governance can serve to make policy interventions more relevant to the individual, it must guard against stigmatizing them as 'at-risk' or 'in-need.'

7. Discussion and opportunities for precision governance

The role of information in the design of good governance infrastructures is increasingly important, as data are a public good that can be used to serve a public purpose (see Johnston et al. 2013). An informed public has always been seen as central to realizing the potential of democratic governance but *it has always been treated as an assumption, not as an intervention.*

In the preceding sections, we have described how the coarseness of existing interventions for natural hazards, and specifically extreme heat, leaves us short of the notion of precision governance we can imagine with the rich data sources and data-driven tools becoming available today and in the near future. We have also presented the results of a case study based on individual experiences demonstrating that there may be a strong opportunity gap in the management of health risks associated with high temperature exposure that could be addressed with innovative governance infrastructures. To conclude, we present hypothetical use cases for individual-based data about heat exposure as a means of illustrating the possibilities of precision governance. The types of improvements that are possible include overarching elements like better communication, tailored messaging, proactive engagement of at-risk populations at critical intervention points, and generation of feedback loops that promote learning and improve decision making. We do not intend to prescribe specific preparation or intervention strategies, as their design requires a much wider array of perspectives and expertise. Instead, our goal in imagining the cases below is to demonstrate how the movement towards precision governance creates opportunity spaces to ask new and important questions about connecting people, government, and technology for public protection from hazards.

Our first case imagines individualized information about heat delivered through mobile platforms. Such an intervention based on information enables the self-regulation of individuals to avoid extreme heat by using emerging sensor technologies. In the context of extreme heat, the data of interest are the temperatures that people experience and their resulting physiological state as they go about their daily lives. In cases of overheating, individuals should minimize their exposure well before any adverse physiological symptoms are noticeable. Certain smartphones are already able to alert users when they – the phones themselves – become too hot for safe operation of the internal hardware. But soon analogous technology could be available to alert phone *owners* when they – the people – are in danger far earlier than the onset of physiological symptoms.

Indeed, mobile technology already serves as the basis for enhanced communication of warnings related to weather, geologic, and terrorism-related hazards through the Wireless Emergency Alert (WEA) system managed by the Federal Emergency Management Agency and other federal organizations (see Casteel and Downing 2013). Currently, WEAs are not issued for extreme heat. This may be an appropriate policy decision as the nature of the hazard posed by heat is different than that posed by an oncoming severe thunderstorm or tsunami – unusual sheltering or evacuation procedures are not needed by a majority of the population. But could WEAs related to heat be effective for a small portion of the population who are likely to, or do experience, severe heat conditions for a prolonged period of time? If those individuals could be detected and alerted, what type of information could be delivered to them that would facilitate their decision-making process for seeking relief? We find it easy to imagine that it will soon be possible to use information about heat exposure that could be streamed in real time, to communicate directly with those at risk or others who could intervene. The information could very well improve the effectiveness of strategies for lowering risk ranging from better timing of taking breaks and drinking water to accessing nearby cooling and medical resources. We suggest that these improvements would occur because contextualized information would be more likely to compel behaviour change than a broad message.

A second use case where we envision that change in governance of hazards could occur concerns the ability of organizations to evaluate their performance in hazard preparedness and response. While there is little doubt that the short- and long-term initiatives for heat risk reduction currently in place in jurisdictions across the world have had substantial benefits, there is as of yet no means for systematic documentation of the collective benefits of these initiatives for public health. Evaluating programmes strictly based on records of health outcomes can only provide correlative evidence of success, and disentangling the benefits of the interventions from other factors that may influence health outcomes has proven to be a methodological challenge for the field thus far (Toloo et al. 2013; Boeckmann and Rohn 2014). This severely inhibits the ability of organizations – including government agencies – to know which strategies are most helpful and cost-effective as well as to accurately forecast what the future public health burden of heat may be in a given area. In our local setting, an important operational decision for protecting vulnerable populations from extreme heat is establishing the opening and closing hours for cooling centres. With data about thermal exposure at the individual level becoming available, it may be possible to provide more precise scheduling guidance. Individual-level data also make it possible to directly study or monitor in real time the changing thermal conditions of populations of interest when certain intervention measures are enacted. Compared to the current baseline of having no, or only very coarse and unreliable, indicators to evaluate heat intervention measures, this would seem to be a vast improvement. Further, because quantifying the impact of heat adaptation strategies is absent from much of the literature aimed at projecting the public health burden associated with climate change (Deschenes 2014; Hondula et al. 2015), developing these types of evaluation metrics can also inform efforts to construct long-term adaptation and mitigation plans and policies.

In summary, our observations of the state of modern hazards governance, and the results from our studies and others with personal ambient temperature sensors, suggested that generalized approaches to heat preparedness and response are not as efficient as the precision approaches possible with information interventions because many people experience heat differently on the same day. The design of this type of information intervention for precision governance that includes data preparation, analysis, targeted communication, and then local responses can serve as a model for many other governance challenges that will likewise benefit from the increased availability of data that can be used for public good. To do so effectively will require that governments invest in building capacity in precision governance as a best practice and essential competency. Governments have historically faced the challenge of viewing information technology projects as 'special circumstances' instead of a necessary capacity, leading to the propensity to view contracting-out for IT services as the most efficient mechanism. The developing field of data analytics risks tumbling down the same slope, where external experts hold the reins of the new powerful technologies, with those inside government left to ponder the meaning of these new analytic techniques. Seeing information technology or precision governance as external to the primary functions of government is short-sighted. Building information and data capacities within government must be seen as a generational challenge in training and practice (Johnston 2015).

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