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Climate change and growing megacities: hazards and vulnerability

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This paper is a review of geophysical and climatic trends associated with extreme weather events and natural hazards, their implications for urban areas and the effects of continued environmental modification due to urban expansion. It discusses how urban design, technological development and societal behaviour can either ameliorate or worsen climate-induced hazards in urban areas. Pressures – ranging from excessive rainfall causing urban flooding to urban temperature extremes driving air pollution – require more attention to understand, model and predict changes in hazards in urban areas. It concludes that involving different techniques for data analysis and system modelling is more appropriate for practical decision-making than a purely reductionist approach. Successfully determining the future environment of megacities will, however, require joint action with societally informed decision makers, grounded in sound scientific achievements.

1. Introduction and overview

From the earliest times, socio-economic factors and the ease of withstanding natural hazards in larger groups have led people to conglomerate. Throughout the world, from the smallest communities to the largest cities, these gatherings have formed self-replicating patterns of organisation (Batty, 2008; Hunt, 2005). However, as the Second UN Habitat Conference in 1996 recognised (UN, 1996), cities, 'especially in developing countries', can also be responsible for the degradation of regional environments with harmful impacts for people and ecosystems, including deterioration of health and safety, increased air pollution, inadequate sewage and water management distribution systems and modification of patterns and intensities of storms and floods (Grimm *et al*., 2008; Hondula *et al*., 2014; Hunt, 2009a). Risks from disease and pandemics coupled with increased exposure owing to population increase and climate change also have implications for future vulnerability of urban areas (Hunt *et al*., 2016).

While cities serve as important agents that provide economic (e.g. employment), social (e.g. education) and a host of biophysical benefits (e.g. access to clean water and sanitation), their increasing size also places undue strain on infrastructure, increases energy demand and has led to ecological degradation (Grimm *et al*., 2008). As this paper further explains, the increasing size and population of cities generally lead to worsening of environmental hazards. In addition, these factors extend the distances around cities where hazards can be exacerbated. This is why cities are also becoming more vulnerable to hazards produced by other megacities located upwind and by upwind environmental dangers, such as smoke from burning and pollutants from shipping (e.g. Cheng and Chan, 2012; Lin *et al*., 2014; Li *et al*., 2015; Zhang *et al*., 2011). As cities and clusters of cities, or conurbations, expand, their energy use (Madlener and Sunak, 2011) and pollution emissions increase (Akimoto, 2003). Cities can also alter the adjoining rural environment and the rivers and coasts that are so crucial to the livelihoods of small communities and natural ecosystems (Aguilar, 2008; Ehrenfeld, 2000; Georgescu *et al*., 2009; Lee *et al*., 2006; Li *et al*., 2016a; Salvati *et al*., 2012; Shao *et al*., 2006; Yang *et al*., 2016a). In particular, although recent estimates indicate cities take up less than 1% of the Earth's landmass (Schneider *et al*., 2010), they are responsible for a disproportionate amount of long-lived greenhouse gas (GHG) emissions (Satterthwaite, 2008; UN, 2007).

This paper is first a review of current and projected extreme weather event trends and associated natural hazards, as well as of most recent studies in the field. Second, the authors consider the effects of these occurrences on urban hazards and their impact on urban environmental vulnerability and sustainability. The conclusions highlight how studies of hazards and vulnerability provide the basis for estimating impacts and policy development.

2. Trends in climate-related hazards

Trends in climate-related hazards will be discussed in two subsections focusing mainly on their relation to regional climate extremes and urban growth (Figure 1).

2.1 Extremes in regional climate and environment

New observations and earth system models are showing how the climate has varied in the past in different characteristic ways (IPCC, 2014). Weather patterns are determined not only by

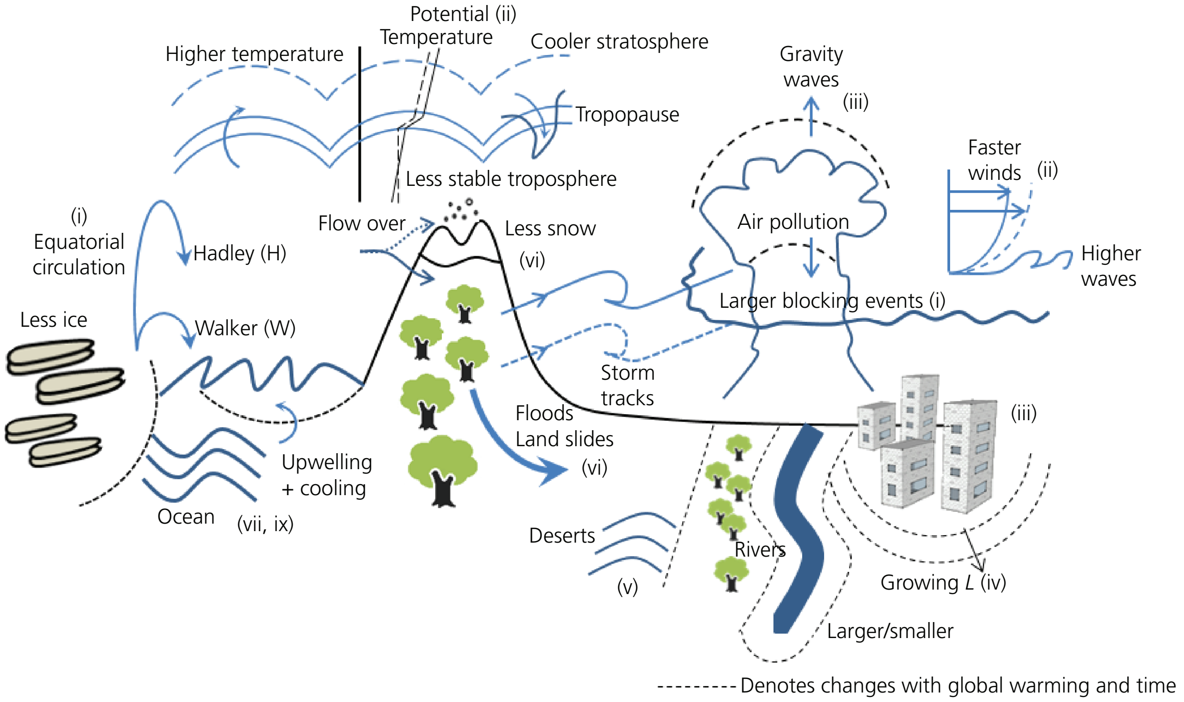

Figure 1. Main natural effects and hazards influenced by climate change. Atmosphere – large fluctuations in ocean basin scale circulations (i); vertical wind, temperature profiles (ii); intense air pollution (iii). Land – growth in urban areas (iv); desertification (v); reduced snow and land ice, with more floods on mountainous terrain, causing landslides and flooding (vi). Ocean and water – changes in coupled ocean–atmosphere circulations in tropics and polar regions (vii); rivers systematically growing or shrinking (viii); variable sea level rise (ix). *L*, size of urban area

climate, but also by orographic factors and other elements of the earth climate system with their own intrinsic variability (Schellnhuber *et al.*, 2004). Over millennia, familiar atmospheric circulations such as temperate westerly winds and subtropical trade winds have persisted, even through ice ages (Houghton, 2015). However, although hemispheric oceanic circulations such as the Gulf Stream have endured, there have been large fluctuations, affecting ocean temperatures in subarctic regions (Broecker, 2010). Observational evidence reveals local climatic effects associated with natural variations in atmospheric winds and ocean currents over annual and decadal periods – for example, the El Niño–Southern Oscillation – and movements and variability of zones of forestation and desertification, such as the once-in-a-century southward movement of the Sahel in the 1970s.

Palaeoclimate models, and biochemical measurements, now show that humans have also played a role in influencing the regional variability of climate, originally through agricultural and forestry management and, more recently, through the development of built environments and GHG emissions (Hunt, 2005; Lentz *et al.*, 2014). For example, the magnitude of the current melting of the Arctic summer ice and glaciers across the world is larger than what has occurred naturally since the last ice ages about 10 000 years ago. The conclusion of IPCC (2014) is that this trend is likely to be the result of human effects, although high levels of internal variability can mask or interrupt the visibility of anthropogenically induced changes (Swart *et al.*, 2015). A schematic diagram illustrating the diversity of natural effects and hazards influenced by climate change is shown in Figure 1.

IPCC (2014) concludes with high confidence that globally averaged near-surface temperatures will remain essentially constant for centuries even if anthropogenic emissions were to stop completely, unless there is a considerable net removal of carbon dioxide from the atmosphere. Furthermore, the continued decline of biological species associated with a changing climate is likely to endure unless the current trend in climate change begins to reverse. Recent measurements suggest that ice sheet temperatures may have already risen to the point where polar and mountain ice sheets and glaciers are beginning to fracture and slide into the ocean at a sufficient volume rate that they may continue to do so, even if the global average temperature of the forthcoming 200–300 years returns to what it was in 1850. This would cause significant sea level rise of several metres over the next millennium, resulting in catastrophic flooding and associated impacts on global society (IPCC, 2014). The current scientific majority view is that unless the future level of human influence on climate were to decline sometime during this century through global action (therefore halting the current rise of carbon dioxide emissions by or prior to mid-century; see the study by Stern (2006)), the aspects of the climate system (e.g. biosphere) will begin to change irreversibly (Lenton *et al.*, 2008). This is the assumption of much current policy-making and is the subject of this review. However, this notion is not shared by the entire scientific community (Lawson, 2008). For example, while Solomon *et al*. (2009) argue that ice cap loss, hence sea level rise, is irreversible due to the longevity of atmospheric carbon dioxide emissions and already-risen ocean temperatures, Notz (2009) defends that there is no 'tipping point' for the loss of Arctic summer sea ice; therefore, sea ice is more likely to recover if climate warming is stopped by reversing carbon dioxide emissions to pre-industrialisation levels (if not prior to), as supported also by Tietsche *et al*. (2011). Conversely, the irreversibility of the ice sheet loss covering Greenland and the West Antarctic cannot be ruled out (Notz, 2009).

Recent analysis of climate prediction models and observational analysis indicate that while short-term trends (i.e. decadal scale or less) may not necessarily reveal long-term trends, the effects of increasing carbon dioxide emissions have played an important role in global warming, generally exceeding 0·1°C/decade, since the middle of the previous century (Tollefson, 2016). Of key relevance for urban areas are the effects on the variability of climate, including their impacts on the global environment and society. Atypical events include 'extreme' events, defined broadly as events that differ from average weather and climate and/or that may persist over longer periods. Other atypical events are the significant changes in trends, including those owing to the occurrence of extreme events (Hov *et al*., 2013; IPCC, 2012). There are significant similarities between the main features of climate variability and other complex systems. An important characteristic is that, as fluctuations increase in frequency and magnitude, the non-linear interactions between the various components of the processes under investigation become more significant. In addition, physically based reductionist models become more reliable than purely statistical extrapolations based on past events (Hunt *et al*., 1996, 2012).

An example of short-term, high-magnitude events is strong convective updrafts and downdrafts, resulting from higher surface temperature, deeper troposphere and cooler stratosphere, which lead to higher rainfall intensity (now reaching 200 mm/h, double its value 10 years ago in South-east Asia; see the studies by the Hong Kong Observatory (2016), Wong *et al*. (2011) and Lee *et al.* (2010)). Consequently, increased frequency of lightning has been observed (Hunt *et al*., 2010; ten Hoeve *et al*., 2012) with a wider global distribution extending to the Arctic regions, as demonstrated by regular monitoring from satellites and globally from ground networks. This trend is leading to enhanced fire risk, forest degradation and destruction, more rapid run-off and consequential drought in some mountainous areas. These trends in convective storm events are associated with alteration in the changing nature of tornadoes with increased maximum wind speeds and greater widening of the affected regions (Elsner *et al*., 2015; Hunt and Hangan, 2013), particularly in south-eastern USA. However, observational analysis for other portions of the USA indicates a decreasing or near-zero trend in tornado temporal variability since 1950 (Guo *et al*., 2016), highlighting the importance of regionally based impact and vulnerability analysis.

Equally important types of extremes include periods of very warm or cold weather, rainy or snowy or very windy, which occur more frequently and persist over considerably longer periods than observed historically (Heim, 2015; IPCC, 2014; Matthews *et al*., 2016; WMO, 2013). Model simulations combined with physical arguments and exploratory analysis of recent global weather anomalies have concluded that such 'blocking' events will occur more often and last longer (Cassou and Guilyardi, 2007; Li *et al*., 2012). Sometimes, these events occur in a region simultaneously as climatic anomalies in other regions (Cheung *et al*., 2012). A recent notable illustration was the extreme 2010 flooding in Pakistan, which was associated with blocking in western Russia and persistent high temperatures in Moscow. Importantly, not all global computer models have come to this conclusion (Pelly and Hoskins, 2003).

Global climate modelling has progressively become more useful (i.e. since the 1970s) as spatial resolution has improved, leading to better representation of the key regional variations of planetary climate. The incorporation of urban canopy models within earth system models enables improved understanding of the interacting components of the earth system jointly with human activities (e.g. Li *et al*., 2016b, 2016c). Deficiencies in the representation of the marked trends and fluctuations in regional climate remain, such as mountainous regions (with reduced snowmelt and extremes in flooding) and polar regions associated with ocean–atmosphere–cryosphere interactions, and in modelling the lower tropical atmosphere, including the particular effects of urban areas at high spatial resolution (Shaffer *et al*., 2016).

2.2 Climate change and urban growth leading to increased hazards and vulnerability

Although the great cities of the world were largely founded for furthering trade, they were also designed, in part, to protect their citizens from natural and artificial hazards, including those associated with extreme weather conditions (Hunt 2009b, 2013). However, urban hazards may become greater, as human activities change and the overall size of the city (denoted by diameter L in Figure 2) grows. In Asia and Africa, an additional 16% increase in the total urban population is expected for both continents by 2050 (UN, 2014) (for more information on increase in urban population see World Bank (2017)). This is a significantly faster rate than that at which global climatic parameters are changing, such as the annual average temperature increase relative to pre-industrial values (doubling over about 70 years) (for Chinese megacities, see the study by Chan and Yao (2008)). These changes are likely to lead to increased energy use and emissions of pollution. In addition, recent research has shown that projected impacts on near-surface temperature within urban areas are of the same order of magnitude as the effects due to large-scale climate change (Georgescu *et al*., 2013, 2014), underscoring the significance of cities as instruments of adaptation and mitigation.

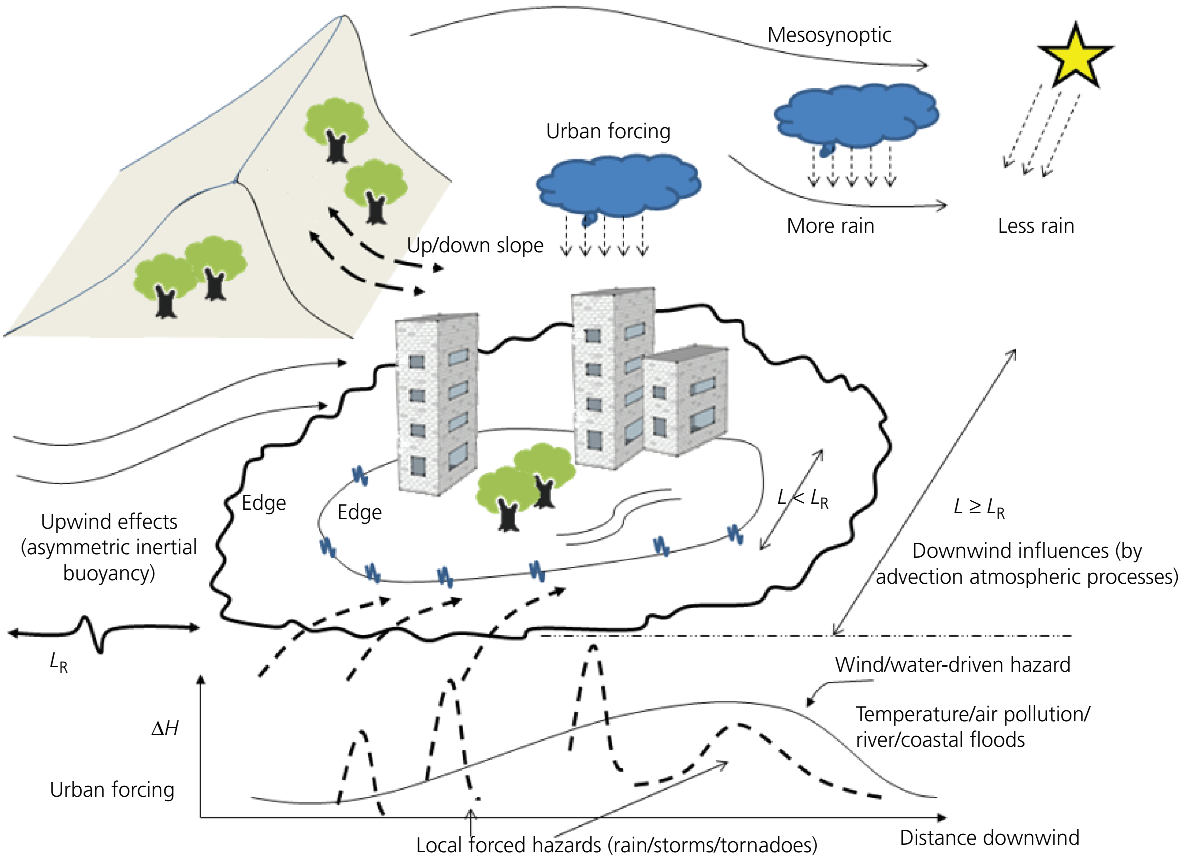

Figure 2. Increased hazards (ΔH) in urban areas in relation to urban forcing. When the size of the urban area (L) becomes equal to or greater than L_R (i.e. Rossby radius), the overall climatic hazards become typically more asymmetrical with a significant skew in the downwind direction. In this diagram, air motion is from left to right, and, as shown in the graph at the bottom, air pollution, mean temperatures and cumulative wind-driven hazard(s) increase with the distance downwind

Even with no change in the form of or the type of activities within a city, as the built-up area (i.e. size) and energy use increase, differences in temperature and humidity between the urban and rural areas grow significantly. Atmospheric flows are changed as a result of increased convection and turbulence. In desert areas (such as central China), strong inversion layers and dust lead to trapping of air pollution. In addition, the larger the city, the larger the total emissions of air pollutants and the higher the concentration (approximately in proportion to L; Figure 2). As their size increases above the characteristic 'mesoscale' distance – that is, Rossby radius, L_R (Hunt *et al.*, 2004) – the influence of the earth's rotation becomes significant at mid-latitudes. The physico-chemical properties of the air and water, and many aspects of the biosphere, depend on the relative sizes of green and built-up areas (Figure 2). Changes in these properties also depend on the buildings and planning of cities, their infrastructure and people's social behaviour patterns and government structures (e.g. Eakin *et al.*, 2017), which vary between regions and countries and among large and small cities or even rural areas. In addition, most people spend about 80% of their time indoors, where environmental factors (e.g. temperature, air circulation and quality and humidity) are generally designed for much of the time to be markedly different from those outside (Rupp *et al.*, 2015; Sailor, 2014). Indoor environmental control affects energy use and the actual levels of temperature and air quality experienced by occupants (Hunt and Li, 2014), but have consequential implications for outdoor environments (e.g. Salamanca *et al.*, 2014; Taleghani *et al.*, 2013).

In 'low-rise' megacities, the average heights of buildings are approximately constant (e.g. in Europe, Africa and some US cities such as Phoenix, Arizona), although most now have one or more central business districts, which have incorporated buildings of greater vertical dimension. However, in 'high-rise' megacities in Asia and South America, the average level of buildings has continued to rise relative to the narrow spaces between buildings. In both types of megacities, as L extends over 30–100 km, it becomes comparable with the size of the L_R mesoscale weather patterns (Hunt *et al.*, 2004). Over this distance, winds tend to change direction as air passes over the city and continues to affect the atmospheric boundary layer and patterns of precipitation downwind (Cheng and Chan, 2012; Li *et al.*, 2013a).

In low-rise cities whose forms, with few exceptions, are not changing significantly, the populations are increasing, approximately in proportion to the area – that is, L^2 (Hunt *et al.*, 2011). But in high-rise cities with rising population densities, the total population is rising at a faster relative rate. Consequently, stationary energy sources such as those used in heating/cooling/servicing buildings and for supplying industries and water (of particular relevance in California; see the study by Andrew (2009)) are increasing slightly more rapidly than L^2. However, the additional energy used for transportation (except in cities with high usage of public transportation that are also more likely to integrate technological advancements – such as those mentioned by Carrington (2016)) is increasing significantly more rapidly as cities grow. Because the lengths of journeys in urban areas increase with L, and the population and incomes are increasing as L^2, the heat released per unit area by transportation is increasing in proportion to L (Hunt *et al.*, 2011). The energy for buildings, industry and road transport is generally supplied from outside built-up areas. New low-carbon-dioxide energy sources will therefore be necessary to avoid the contribution of urban areas to global emissions of harmful pollution (Kammen and Sunter, 2016).

The thermal environment affected by the city is determined by the heat capacity of buildings, differing properties of urban land surfaces (e.g. absorption or reflection of solar radiation), local heat emission from energy systems (e.g. air conditioning (AC)), heat from transportation (Sailor, 2011) and other anthropogenic sources such as reradiation from buildings and traffic. Equally important is the reduced ventilation caused by wind resistance of buildings and, in some cities, the reduction of solar radiation produced by dust and particles of air pollution. These factors, which can be modified by planning, building design and operation of urban systems, alter the surface and temperatures inside and outside buildings (Georgescu *et al.*, 2015). During summer periods, temperatures are raised inside the urban area for longer periods compared with rural areas, whose temperatures decrease at a faster rate after sunset. The average temperatures over 24 h in urban areas can exceed rural temperatures by 5°C or more, with serious implications on energy use and health, although this value has considerable geographical and seasonal dependencies. Importantly, the urban heat island (UHI) phenomenon in high-density cities such as Hong Kong is rather due to anthropogenic impacts, whereas in low-rise, less compact cities, the temperature increase is additionally governed by the re-emission of energy absorbed by the built environment (Yang *et al.*, 2016b). While the UHI can reduce the need for heating in cold seasons, its effect will considerably increase energy use for cooling purposes during the summer (see US Department of Energy, 2013). Compounding the aforementioned changes in the physical environment are implications of, for example, extreme heat events (EHEs) in cities, with broad health consequences (Hajat *et al.*, 2007, 2014; Hoshiko *et al.*, 2010; Huynen *et al.*, 2001; O'Neill and Ebi, 2009). But if streets are covered with trees, or roofs with vegetation, the shade and evapotranspiration lower daytime peak urban temperatures (Georgescu, 2015; Li and Norford, 2016; Maggiotto *et al.*, 2014; Middel *et al.*, 2015; Tan *et al.*, 2016; Yang *et al.*, 2016c). In large south-eastern Asian cities (e.g. Li *et al.*, 2013b), the UHI typically exceeds 2°C at night. By contrast, in large cities in continental climates (with populations greater than five million people) during high-pollution episodes in winter, the urban temperatures can be lower compared to rural areas throughout the diurnal cycle.

The effect of heat release in the city also affects the variation of temperature as the air moves across the city, with maximum values where high-rise buildings are concentrated in the centre of the city and towards the downwind side. The larger the city, the greater this effect is. Over the neighbourhood scale of 1–3 km, temperatures are raised or lowered by parks, rivers, buildings and the presence of other urban forms (Connors *et al.*, 2013; Declet-Barreto *et al.*, 2013). A distribution of smaller parks lowers the average temperature more than a few large parks (Bohnenstengel *et al.*, 2011) and reduces the impacts of heatwaves as shown in mortality statistics for New York City (J. Huang, personal communication, Hong Kong University, Hong Kong, 2013). Such considerations bring to light the significance of urban design and form (Connors *et al.*, 2013; Zhou *et al.*, 2011), which necessitate discussion within a broader urban sustainability framework than has been acknowledged to date (Georgescu *et al.*, 2015).

2.2.1 Example 1: energy use in a desert urban area

An example of the complexity by which urban areas can modify environmental hazards is associated with the heat emitted by AC systems. Physics-based modelling simulations accounting for the variation in people's behaviour have been confirmed by variations in observed temperatures. The results quantify the amount of electricity used on diurnal time scales during a number of EHEs in a rapidly urbanising semi-arid metropolitan area (Phoenix, Arizona), indicating that cooling from AC contributes about 53% of the overall daily electricity requirements during these periods. Electricity consumption peaked during late afternoon hours (roughly 3–6 p.m., locally), when the demand for AC approached two-thirds of the total hourly demand (Salamanca *et al.*, 2013).

The multilayer building energy modelling (BEM) system, dynamically coupled to an atmospheric model, was designed to predict cooling/heating energy demand (i.e. the energy demand associated with ambient meteorological conditions) and has been applied at city scale for contemporary and future conditions associated with urban expansion (Salamanca *et al.*, 2014, 2015). However, the BEM system alone is not able to predict the total energy demand because the human behaviour consumption element (i.e. the energy component that is not associated with the meteorology and therefore depends entirely on human behaviour) needs to be accounted for separately.

Salamanca *et al.* (2013) estimated the human behaviour consumption (i.e. base load), analysing citywide observed monthly mean electric loads for a specific year. For the Phoenix metropolitan area, minimum observed electric loads occurred during March and November, coinciding with moderate environmental weather conditions. These two months were considered the baseline months with negligible heating/cooling electric consumption. In this way and based on observed data, the diurnal cycle of the human behaviour consumption was computed, coupled with the meteorological component and used to calculate both electricity consumption and its contribution to the region's UHI (Salamanca *et al*., 2013, 2014, 2015).

With higher peak temperatures and longer hot periods anticipated in future summers, electrical demand by AC systems will have to be met by energy plants and the electric grid (Huang and Gurney, 2016). Reliable energy forecasting methods, such as the simulations described above, will be needed for resource planning of rapidly growing urban areas, particularly in the extreme conditions of semi-arid environments. Complicating such situations is the positive impact on air quality associated with the destabilisation of the planetary boundary layer (due to heat emission from AC units), which promotes night-time vertical mixing and underscores challenges of urban adaptation (Georgescu, 2015; Sharma *et al*., 2016). Therefore, compensating effects on thermal, air quality and other indicators underline the need for comprehensive markers that characterise the totality of urban-induced effects.

From an energy perspective, AC use is greatest during the same periods of extremely high temperatures that cause higher transmission losses and reduced thermal efficiencies at electric generation facilities. During a 2006 heatwave, electric power transformers failed in Missouri and New York, causing interruptions of the electric power supply. In addition, more than 2000 distribution line transformers in California failed during a July 2006 heatwave, causing loss of power to approximately 1·3 million customers. Research ascertaining the potential for individual and institutional adaptive strategies to lessen impacts due to extreme heat and, in particular, impacts on human health risk caused by blackouts is necessary to establish support tools aiding the development of novel protocols for heat risk emergency response monitoring and planning (Kuras *et al*., 2017). Thus, increased cooling demand may increase the occurrence of peak loads coinciding with periods when generation efficiencies are lowest. Furthermore, the effects of high temperatures may be exacerbated when wind speeds are low or night-time temperatures are high, preventing transmission lines from cooling. This is a particular concern because night-time temperatures have been increasing at a faster rate than daytime temperatures (e.g. Georgescu *et al*., 2013).

Comparison with observational data has demonstrated that the physics-based modelling system is an effective tool for assessing (indoor) urban cooling requirements, which involves evaluating electricity consumption for different urban growth patterns and under extreme summertime weather conditions. These studies will be crucial for the development of reliable projections on future cooling needs and environmental consequences of rapidly urbanising regions under various climate scenarios (Bartos and Chester, 2015; Georgescu *et al*., 2012, 2014) that strategically incorporate adaptation and mitigation strategies alleviating energy demand (Georgescu *et al*., 2014; Salamanca *et al*., 2016).

2.2.2 Example 2: Asian and subtropical cities

These cities have shown how, when very low regional temperatures occur, temperatures can become even lower in urban areas as a result of air pollution or sand storms reducing solar radiation. The provision of heating that compensates for the cooling results in higher air pollution, subsequently exacerbating hazards associated with extreme low temperatures. The main hazards associated with pollutants in urban areas also arise from high concentrations of contaminants from industry, transport and agriculture, as well as particulates arising from natural sources (e.g. wind-blown sand or noxious gases from lakes) (Jacobson, 2012; Li *et al*. 2015, 2016a), and may cause serious health implications (Pope and Dockery, 2006).

As winds transport pollutants into an urban area, concentrations tend to increase in the downwind direction. At high temperatures during summer months, particularly in the tropics, climatic variations can induce low winds and high temperatures, which may be raised further by high emissions from static and moving sources, such as episodes in Athens in 1987 (Matzarakis and Mayer, 1991) and Moscow in 2010 (Shaposhnikov *et al*., 2014) and others in Beijing and Shanghai (Huang *et al*., 2010; Wang and Gong, 2010). Because road vehicles are the main source of polluting gases and particles in urban areas, and because journey distances (particularly for low-rise cities) increase as cities expand, emissions of air pollutants per unit area also increase in proportion to the diameter L. The transport of atmospheric boundary layer pollutants leads to the degradation of air quality downwind, over distances that, in some meteorological conditions, can extend hundreds of kilometres (Cheng and Chan, 2012).

As air pollutants are transported across the city, while some gases increase in concentration, others such as nitrogen oxides undergo chemical transformation and are reduced in the centre while increasing in the outer regions. Overall, the magnitude of the pollutant concentration increases with L. With anthropogenic climate change as an additional forcing agent, the sources of pollutant and heat increase in urban areas can be compounded by, for example, widespread use of AC in buildings and vehicles. Both hazards are worsened by lengthy periods of calm conditions, which are projected to occur with increased frequency under a future climate characterised by increased occurrence of synoptic-scale blocking (Cassou and Guilyardi, 2007; Li *et al*., 2012).

2.2.3 Example 3: amplification of hazards in urban areas

Natural hazards arising outside urban areas are changed significantly within them. In some situations, different urban hazards act in combination. In the presence of high winds, including tropical cyclones (TCs) and tornadoes, although the resistance of buildings reduces the mean wind speeds over the urban areas compared with outside, locally, wind speeds can exceed rural wind speeds in gaps between buildings, and turbulent gusts are amplified (Britter and Hunt, 1979; Oke, 1987). In addition, because significant numbers of high-rise buildings are being built in often highly populous coastal cities that are subject to impacts from TCs, there is concern about the growing vulnerability of their inhabitants (McGranahan *et al*., 2007; Pielke, 2007). Although global climate change is increasing the average sea surface temperature and the average tropopause height, there is not yet any conclusive statistical evidence about the projected strength and frequency of TCs. However, there is evidence that the trajectories of those major TCs that reach land are changing and reaching latitudes lower than those they reached previously (e.g. in northern Malaysia). In general, the resistance to the airflow caused by the built environment tends to deflect onshore winds parallel to the coast while amplifying peak near-surface winds (Chan and Chan, 2015; Hunt *et al*., 2004). As urban areas expand, this trend is likely to be amplified, which may also reduce the onshore movement of TCs. Coastal agricultural regions, either surrounding or within urban areas themselves, that rely on TC rainfall may be negatively affected if precipitation is reduced sufficiently, potentially resulting in increased irrigation demand to meet required yields.

Hydrological extremes in the form of drought and flood can be amplified in urban areas. The return period of intense precipitation over short periods (100 mm/h) in Asia has decreased (e.g. from 37 to 18 years according to Hong Kong Observatory (2016); cf. Wong *et al*. (2011) and Lee *et al*. (2010)). The peak intensity of rainfall is likely to occur not only in geographical areas where the surface air flow converges, which can happen in mountains, but also within megacities, which affect regional climates (Benson-Lira *et al*., 2016; Chow *et al*., 2016; Holst *et al*., 2016; Georgescu *et al*., 2012; Shepherd *et al*., 2011; Smith *et al*., 2013). The prediction of rainfall and flooding in the low-lying and almost completely urbanised areas of the island of Singapore is improving as a result of detailed computational models and a dense network of real-time data (Chow *et al*., 2016; Pereira *et al*., 2014). Deeper convection caused by climate change effects on the troposphere makes such events more likely in future. Important impacts are also evident below the land surface–atmosphere interface. Decreased precipitation and increased evaporation associated with longer periods of droughts and high-temperature episodes are depleting underground reservoirs and natural aquifers. In India, reduced monsoon rains are lowering water levels in some lakes and rivers. Water shortages tend to be exacerbated both within and around expanding urban areas, particularly in Asia and Africa, where some city aquifers are now more than 30 m below ground level (Morris *et al*., 2003).

Flooding hazards in urban areas are partly caused by more rapid run-off from distant ice- and snow-covered mountains caused by global warming, or by agricultural practices such as reducing tree cover, which has been found to correlate with vulnerability against flooding (see the study by Pauleit *et al*. (2005) for a UK example). The results are seen in overflowing rivers and watercourses and in unconfined areas such as streets and fields. Many secondary effects occur in urban areas such as landslides, weaker foundations, collapsing structures (e.g. in Boulder, Colorado, USA, the floods of 2013 resulted in more than US$1 billion in property damage) and loss of land into coastal seas, depending on local geography and infrastructure. In the Philippines, these secondary effects are found to influence the overall movement of floodwaters and the extent of danger to communities (DOST, 2012). The Tropical Cyclone Haiyan in 2013, upon reaching southern Philippines, caused unusually large damage to buildings and trees, in large part because over the shallow coastal waters, wind stress drove a large surge, lifting rocks from the seabed and transporting them several kilometres inland. Importantly, urban design strategies that include the incorporation of man-made rivers, reservoirs and planned flood areas have been shown to reduce local flooding hazards relative to surrounding areas, highlighting the importance of engineered infrastructure resilience as a potential adaptive mechanism.

Other hydrological hazards occur with wind- and earthquake-induced surges and waves (or tsunamis) onto coasts (Fernando, 2008). Such hazards flood urban areas along coasts and along canals connected to the coasts (as occurred with Hurricane Ike; see the study by Kennedy *et al*. (2011)). Arctic coastal communities are now at risk from tsunamis generated by seismic activity that has until now been suppressed by sea ice. The examination of the tsunami waves of 2004, 2010 and 2011 in Asia and the Pacific has illustrated how such hazards are affected by similar physical and natural changes of climate (Klettner *et al*., 2012). As the tsunami in March 2011 reached the east coast of Japan, significant variability in the wave amplitude was observed and in the surge movement (backwards and forwards up the shore) before flooding of urban areas and the industrial plant at Fukushima.

3. Discussion and conclusions

This paper examines how extreme natural and artificial hazards in the atmosphere, hydrosphere and on land are becoming more severe and more frequent as global climate changes. The review emphasises the changing patterns and greater spatial variability of these hazards over different geographical and climatic regions. As a result, the observed trends and patterns of hazards are diverging from those of past decades and centuries. Existing models suggest that this divergence will grow in the future, with more intense, longer-duration and more frequent extreme events. The extent of the increase and variability in climate-induced hazards varies between regions and for each specific hazard (Table 1).

In growing megacities, these factors include their surface area extent, urban population and growth rate, urban design/technology, socio-economic factors and overall societal behaviour.

In considering the major physical and natural causes of hazards, this paper also describes and analyses their societal effects, and future work will examine the impacts on policy development. The concept of societal effects extends beyond the useful, but essentially passive, concept of vulnerability. For example,

Table 1. Relating environmental hazards to urbanisation and climate change factors

Types of natural and artificial hazards arising from extreme environmental variations (positive or negative denoted by +/–) and/or increased persistence and/or increased frequency in	(*a*) Wind speed (+/–) (*b*) Temperature (+/–) (c) Natural and artificial pollutants/radiation in the atmosphere, land and water (+) (*d*) Hydrological processes – for example, flooding, sea level rise/ drought (+/–) (*e*) Primary and secondary geophysical hazards leading to environmental hazards – for example, earthquakes/tsunamis, volcanoes/landslides, floods/landslides, storm surges/floods, sand storms/air pollution (+) (*f*) Biological/environmental – for example, disease, desertification (+)
Urbanisation and vulnerability effects	Amplification or reduction of natural hazards (listed above); hazards associated with infrastructure and human activities in urban areas (dependent on size, location, design and economy of urban areas); complex hazards associated with natural and human influences on global, regional and urban environment – for example, higher/lower winds; higher temperatures, increased air pollution and increased/decreased water pollution; shortages/excesses of water
Examples of significant hazards in large urban areas	Coastal and/or riverine cities New Orleans (*a*), Houston (*a*), New York (*a*, *e*, *f*), Bangkok (*d*), Dhaka (*a*, *d*), Tokyo (*a*, c, *e*), Hong Kong (*a*, c, *d*), Jakarta (c, *e*, *f*), Manila (*a*, c, *d*), Paris and London (*b*, c, *f*) Inland cities Phoenix (*b*, c), Beijing (*b*, c, *f*) Xian/other cities in central western China (*b*, c, *e*), Moscow (*b*, c, *f*), Athens (*b*, c, *f*)

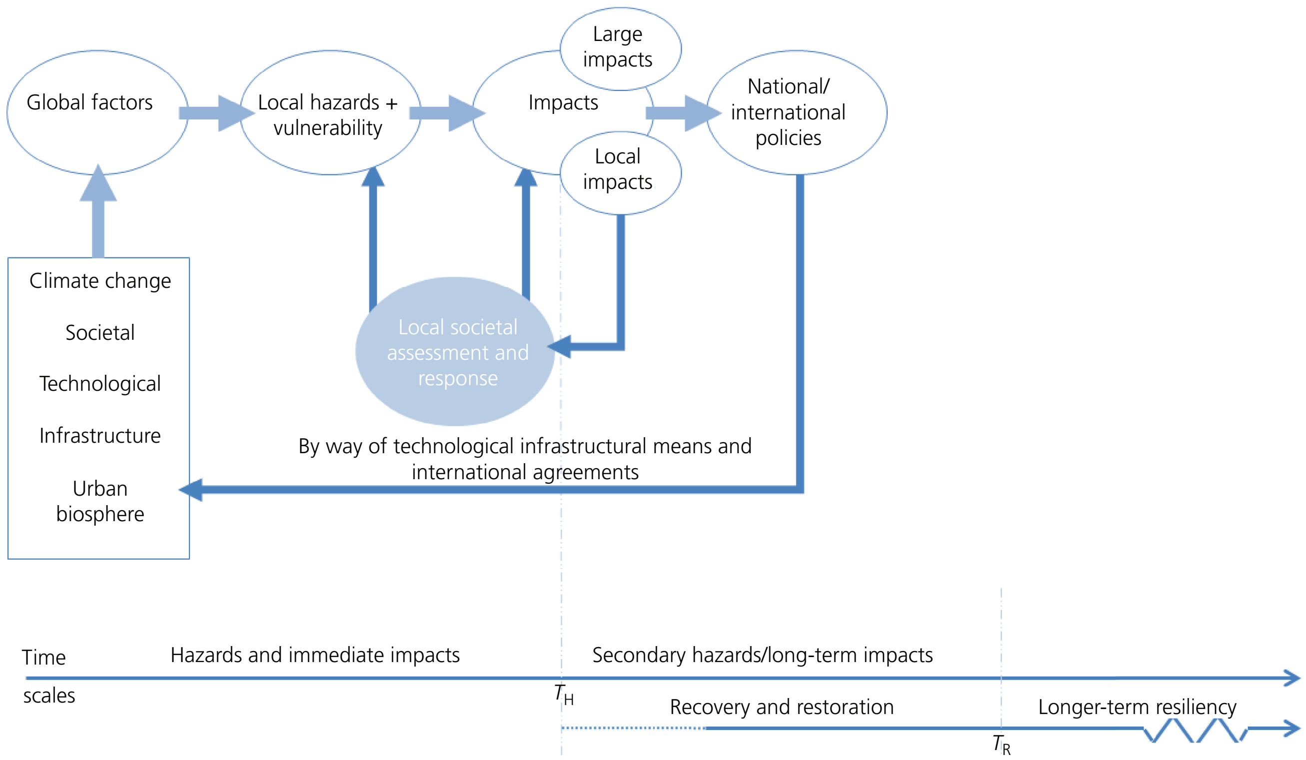

Figure 3. System diagram for effects of hazards, impacts and policies associated with global climate change, growing urban areas and societal responses (T_H, period of hazards; T_R, period of long-term impacts and recovery)

communities have shown increasing capability to obtain and use information in advance of and during hazards (e.g. Hondula and Krishnamurthy, 2014) and are increasingly adept at moderating hazard impacts (e.g. reducing the magnitudes and social impacts of floods in urban areas; see Lagmay (2015)). The recovery of communities following hazards can reduce long-term impacts. Equally significant are the urban–biosphere interactions surrounding and within megacities, which have vast effects on health and the agriculture/forestry municipalities in Latin America and South-east Asia.

The diagram shown in Figure 3 illustrates how the 'dynamical-systems' methodology (e.g. Wilson, 2000) facilitates a holistic overview (Smuts, 1926) and informs decisions about the empirical or scientifically based interactions, the various factors that influence or control some broadly connected collection of processes and organisations. Here, the authors are considering the links between global and regional climate changes and the processes and hazards that affect urban hazards, impacts and potential ameliorating policies (see Hunt (2009b) for complex relationships between these). The review presented here includes an appraisal of the impact on health, in particular the combination of temperature extremes and intense air pollution from traffic, heating and AC use and particulates entering cities from rural or upwind urban areas. The authors stress the value of comprehensive policy development accounting for place-based variability (Table 1) and therefore directly address compensating effects on thermal, air quality and other indicators that characterise the totality of urban-induced effects. Simultaneously, the authors acknowledge that wedge-type approaches (e.g. Pacala and Socolow, 2004) can provide insight into optimising the efficacy of urban policies, favouring some strategies over others.

The authors assert that involving different techniques for data analysis and system modelling is more appropriate for practical decision making than the purely reductionist approach that builds up semi-empirical models and connects them to basic data of all the various factors (e.g. Hunt *et al*., 2012). The utility of such methods should ensure increasingly pragmatic approaches to planning the form(s), size(s) and overall future growth of built environments, as well as the development of appropriate policies for green infrastructure and societal behaviour that will lower energy use. To achieve success, however, will require action that is in concert with societally informed decision makers, grounded on sound scientific achievements. Collectively, these actions will determine the future environment of megacities.

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