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Future cities in a warming world

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ABSTRACT

More than half the global population are already urban, and the UN and other organisations expect this share to rise in future. However, some researchers argue that the future of cities is far from assured. Cities are not only responsible for 70% or more of the world's CO_2 emissions, but because of their dense concentration of physical assets and populations, are also more vulnerable than other areas to climate change. This paper attempts to resolve this controversy by first looking at how cities would fare in a world with average global surface temperatures 4 °C above pre-industrial levels. It then looks at possible responses, either by mitigation or adaptation, to the threat such increases would entail. Regardless of the mix of adaptation and mitigation cities adopt in response to climate change, the paper argues that *peak urbanism* will occur over the next few decades. This fall in the urban share of global population will be driven by the rise in biophysical hazards in cities if the response is mainly adaptation, and by the declining attraction of cities (and possibly the rising attraction of rural areas) if serious mitigation is implemented.

1. Introduction: conflicting views on urban futures

In 1930, only 29.4% of the Earth's population lived in cities, but by 2011, that share had risen linearly to 52.1%, according to United Nations (UN) estimates. The UN expect this linear growth to continue, so that by 2050, 67.2% will be urban dwellers, or given the UN global medium fertility population estimate for 2050 of 9.6 billion (United Nations, 2014a, 2014b), 6.4 billion people will live in cities. Already, the UN estimated that over 350 million people in 2010 were residents of 'megacities', i.e. cities with populations of 10 million or more, with a further billion people living in cities of 1–10 million. The largest cities were also forecast to grow fastest, while cities in the <0.5 million size class would lose share. Urban theorist Batty et al. (2012) has even forecast that by the year 2100, the world will be 100% urban.

Samet (2011) examined the future of cities using complexity science. He also concluded that the share of the global population in megacities would continue to rise, with cities of over 100 million residents appearing by the year 2050, although these huge cities of the future would have much lower urban densities than cities of 1–2 million. Kourtit and Nijkamp (2013) argued that not only is the global growth of megacities an inevitable outcome of 'the forces of globalization and competition', but also that megacities are desirable, in that the benefits from efficiency and productivity increases they provide greatly exceed the costs from increased pollution and congestion.

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Not all urban scholars would agree with this optimism regarding future urban growth. Rees (2012) argued bluntly that: 'Techno-industrial societies and modern cities as presently conceived are inherently unsustainable.' He viewed high-income cities as 'concentrated nodes of material consumption and waste production that parasitise large areas of productive ecosystems and waste sinks lying far outside the cities.' In brief, high-income cities are both a drain on non-renewable resources and a source of pollutants. He concluded that the optimistic view of city futures given above is far from assured. Another writer who has questioned the uninterrupted trend towards a larger share of the global population urbanised in ever-larger cities is Orr (1999). Orr's pessimism stemmed not only from unsustainability considerations, but also because of the difficulty in governing very large cities. For both Rees and Orr, however, the emphasis is either on the unsustainable consumption of cities, or on their socio-economic problems, not on the global environmental change effects *on* cities. The problems they highlight are important, and socio-economic urban problems will likely be exacerbated by climate change. For Fry (2011), on the other hand, many cities may simply have to be abandoned in the face of climate change, and new cities built.

The remainder of the paper is organised as follows. Section 2 considers what is likely to happen in cities, particularly large ones, *if* action on climate change in the coming decades is ineffective, and average global temperature rises to 4 °C above pre-industrial. This is a real possibility, given the inactivity over the more than two decades since the first Intergovernmental Panel on Climate Change (IPCC) report alerted the world to the dangers of anthropogenic climate change. This possible future is in line with the IPCC's (Stocker et al., 2013) high emission scenario, with radiative forcing 8.5 W/m^2 by 2100 (The radiative forcing gives the change in energy flux to Earth compared with the pre-industrial era, taken as 1750; Stocker et al., 2013.). Even the IPCC intermediate emission scenarios could give a rise of 4 °C by 2100. For comparison, present-day anthropogenic forcing relative to pre-industrial times is about 2.3 W/m^2. The latest IPCC report regularly projects climate variables out to the year 2100, and sometimes out to 2300. We similarly need to take this long view of cities, since many are already centuries, if not millennia, old. Further, major changes to urban infrastructure would also take many decades to achieve. One researcher, Tonn (2004), has even advocated 1000-year planning, which given the longevity of CO_2 in the atmosphere, and the possibility of irreversible loss of the Greenland ice cap over the next millennia or so (Hansen, Sato, Russell, & Kharecha, 2013), may be increasingly needed.

In Section 3, we look at what can be done to avoid the threat to cities posed in Section 2, by examining social and physical approaches to both mitigation and adaptation in an urban context. Finally in Section 4 we discuss the most probable future for cities under a changing climate. Regardless of the mix of adaptation and mitigation cities adopt in response to climate change, we argue that *peak urbanism* will occur over the next few decades. This fall in the urban share of global population will be driven by the rise in biophysical hazards if the response is mainly adaptation, and by the declining attraction of cities (and possibly the rising attraction of rural areas) if serious mitigation is implemented.

2. The threat: cities at 4 °C warmer

A rising share of the world's people are living in cities, as already discussed. At the same time, cities, because of their dense concentration of physical assets and populations, are more vulnerable than other areas to climate change (Gasper, Blohm, & Ruth, 2011). City governments are becoming aware of this, which is why cities are in the forefront of responses to climate change (Inayatullah, 2011). This section examines the various risks facing the world's cities should global surface temperatures rise towards 4 °C above pre-industrial values. Cities will, of course likely still face the perennial urban problems of unemployment, inequality, crime and congestion. How these problems will change under a 4 °C temperature rise is difficult to predict. Instead, this section will examine in detail three biophysical hazards (urban health, urban flooding, and geological hazards) about which there is some consensus. Different cities will face different risks; even for a given threat, such as sea level rise, different coastal cities will face varying levels of risk. Already, large numbers of the world's cities face various natural risks. United Nations (2014b) has presented a table showing which of the world's cities with estimated populations of more than 750,000 face various natural hazards. The hazards selected were cyclones, droughts, earthquakes, floods, landslides, and volcanoes. A city was judged to be at 'high risk' from a given hazard if 'it is located in grid cells ranking in the top three deciles of the global risk distribution in terms of frequency of occurrences of one or more specified natural hazards'. A number of cities are already at high risk from three or more hazards, and more than 60% presently face at least one risk. The climate-induced hazards discussed in this section will generally add to these pre-existing hazards. Increasingly, researchers distinguish between risk, as discussed in this section, and *vulnerability*, the susceptibility to harm from hazards, which can vary greatly for different urban groups (Gasper et al., 2011). Sections 3 and 4 will discuss vulnerability in more detail.

2.1. Urban health problems

The health problems discussed in this section are not new, but are likely to be much more severe as global temperatures rise. Or, as Blashki et al. (2011) put it: 'Rather than heralding a suite of new diseases, climate change is likely to amplify existing disorders and health inequities'. Climate change to date has probably already led to increased urban health problems, notably from heat stress in heatwaves. Other urban health problems which are likely to worsen with rising temperatures are the severity of air pollution episodes and the spread of tropical diseases to more temperate areas, both urban and non-urban, and mental health problems. A further possibility is an increased risk from pandemics in large cities.

Most large cities are subject to the Urban Heat Island (UHI) effect, which raises urban temperatures above that of the surrounding area (Peng et al., 2012). The UHI effect arises from a number of causes. Kleerekoper, van Esch, and Salcedo (2012) listed seven, including lower evaporation because of sealed surfaces (roofs, roads, parking spaces), waste heat release from energy use, lower outward longwave radiation to space because of blockage by tall buildings, and higher heat storage by buildings with large thermal mass. The exceptions include cities in desert areas, where evaporative cooling from urban trees and gardens can give these cities lower temperatures than the surrounding region. The UHI produces higher daytime than nighttime temperature increase effects. Further, summer temperature rises are much higher than winter ones. For the 38 largest US cities, Imhoff, Zhang, Wolfe, and Bounoua (2010) found an average 4.3 °C rise in summer, compared with only 1.3 °C in winter. The extent of impervious surface area explained most of the difference between cities.

Human populations are *already* subject to heatwaves which can kill thousands. Further, according to the latest IPCC report (Stocker et al., 2013): 'Models project near-term increases in the duration, intensity and spatial extent of heat waves and warm spells'. The 2003 European heatwave is estimated to have resulted in an excess mortality of up to 80,000, and the 2010 Russian heatwave in around 54,000 (Wolf & McGregor, 2013). Most of the fatalities were urban residents, particularly older people. Climate change is expected to raise even further both the frequency and intensity of heat waves in the coming decades (Hansen, Sato, & Ruedy, 2012). Populations, particularly in the developed countries, are ageing, and as cities get larger, the UHI intensity is also rising. A recent paper (Li & Bou-Zeid, 2013) argued that synergistic interactions will occur between UHIs and heat waves, compounding the heat stress effects. Also, as shown by de Munck et al. (2013), attempts to ameliorate the deleterious effects of summer heat by air-conditioning can amplify the UHI of a large city like Paris. Those without access to air-conditioned buildings, and those who must work outside, would then experience even greater risk from heat stroke.

A recent study has even argued that continued global temperature rises could eventually lead to human abandonment of large regions of the presently inhabited world (Sherwood & Huber, 2010). Heat stress, they argued, 'imposes a robust upper limit' to climate change adaptation, because, at a 'wet bulb temperature' (the temperature recorded by a thermometer wrapped in a wet cloth) of 35 °C and above, humans (and other mammals) lose the ability to dissipate metabolic heat. At an average global temperature rise of 7 °C, the habitability of some regions, especially at lower latitudes, would be called into question. While such global temperature rises may be a long way off, prolonged heat stress could occur much sooner in cities with both strong UHI intensity and humid climates.

Other, existing, health problems are likely to become more serious if both the growth and number of large cities increases and climate change continues. As Jacob and Winner (2009) have stated: 'Air quality is strongly dependent on weather and is therefore sensitive to climate change.' Climate modelling research has shown that climate change alone is likely to raise summertime surface ozone concentrations in future by 1–10 parts per billion (Jacob & Winner, 2009). The highest emission IPCC scenario likewise assumed rising levels of tropospheric ozone concentrations (van Vuuren et al., 2011). The deleterious health effects are more likely to be felt in large cities and during pollution episodes. The effect of climate change on fine particulate matter levels is less certain, but could also be problematic. Any rise in bushfire frequency or severity near urban areas would also worsen particulate pollution.

Some diseases presently confined to tropical areas are likely to spread to more temperate regions. One that has been extensively studied is the spread of malaria; temperature rises are likely to see malaria spreading to the urbanised regions of North East China and North East US (Piontek, Müller, & Pugh, 2014). In large cities, the UHI effect could be expected to encourage this shift. Finally, Monteiro, Chimara, and Chaui Berlinck (2006) have argued that big cities are 'shelters for contagious disease'. Big cities can support infectious diseases such as chicken pox or measles that would naturally be eradicated in smaller settlements. And as Davis (2006) has stressed, the unsanitary conditions in the vast slums of low-income mega-cities are ideal breeding grounds for infectious disease outbreaks. Such pandemics would be even more of a risk if multiple climate change-related crises lead to a further deterioration in public health measures. As Bowles, Butler, and Friel (2014) stress, 'alterations to socio-economic systems' may put the greatest pressure on future health services.

2.2. Urban flooding risk

Much of the global population lives near the sea coast, and most of the world's large cities are sited either on the coast or on rivers. Further, the share of the global population living in areas of low elevation above sea level is rising (McGranahan, Balk, & Anderson, 2007). Global sea levels are projected to rise by as much as 1 m by the end of this century (Stocker et al., 2013), although prominent climate scientist James Hansen thinks that 2 m is more likely (Hansen et al., 2013). Low-lying coastal cities are vulnerable to rising sea levels, particularly in conjunction with storm surges, as happened to coastal New York and New Jersey during Superstorm Sandy in October 2012. Total storm damages there were estimated at $30–50 billion, as rail subways flooded, thousands of homes were destroyed and millions lost electricity services. Storm intensity and frequency could also rise as climate changes (Stocker et al., 2013). Climate change could convert a 100-year storm surge into a 3–20 year surge (Tollefson, 2012). Nelson (2013) listed seven major cities (Dhaka, Manila, Bangkok, Yangon, Jakarta, Ho Chi Minh City, and Kolkata), all in Asia, as facing 'extreme' risk from 'climate-related natural disasters and rising sea levels'.

Many large cities (e.g. Alexandria, Bangkok) are situated on the deltas of major rivers, which have been dammed for hydropower, water supply, or flood control. Large dams trap sediment, which not only reduces reservoir storage capacity, but also greatly reduces sediment deposition in the river delta. Some of these cities are sinking because waves and tides remove soil faster than the reduced sediment load can replace it. Such sinking increases the danger from flooding. Syvitski and

Higgins (2012) report that Bangkok, situated on the delta of the Chao Phraya river, was sinking 10 centimetres annually, and even after remedial measures is still subsiding at 2 cm per year. Global sea level rise and heavy fresh water withdrawals from coastal aquifers add to this problem.

2.3. Geological hazards in cities

Ongoing climate change can even greatly increase the risk to cities from a variety of geological hazards. In the distant past, according to McGuire (2010), rapid climate change was associated with increased geological activity including 'volcanic and seismic activity, submarine and subaerial landslides, tsunamis and landslide 'splash' waves, glacial outburst and rock-dam failure floods, debris flows and gas-hydrate destabilisation.' McGuire further stressed that these risks are not only a problem for the far future: 'the ongoing rise in global average temperatures may already be eliciting a hazardous response from the geosphere.'

A few cities, such as Naples and Seattle, are near active volcanoes. Rising temperatures will thin glaciers (such as that on Mt Ranier) which could 'destabilise vast chunks of their summit cones, triggering mega-landslides capable of flattening cities such as Seattle and devastating local infrastructure' (Ravilous, 2010). Warmer weather can also cause landslides due to glacier and permafrost destabilisation. Land and mud slides are already a serious risk in many cities (United Nations, 2014b), particularly for informal settlements built on hill slopes in low-and middle income countries. For Chinese cities, Zhou and Zhao (2013) have shown that the urbanisation process itself increases the risk from induced geological hazards.

2.4. Discussion

Most large cities with high per capita energy use will have to cope with increasingly severe heat waves in future, and for some cities, other risks as well. Cities with significant low-lying regions will be at increased risk from rising seas and storm surges. Some of these low-lying cities will also have to cope from increased flooding from hinterland regions, particularly delta cities. A number of cities are already prone to geological hazards such as volcanoes and earthquakes. In a few of these cities, on-going climate change will increase the chances for geological disaster.

Cities can be ranked on their risk from various climate induced hazards. Hallegatte, Green, Nicholls, and Corfee-Morlot (2013) have done this for floods (from both land subsidence and changing climate) in major coastal cities. They found the greatest risks were for cities around the Mediterranean, in East Asia, and the Gulf of Mexico. Piontek et al. (2014) went further, and pinpointed 'climate impact hotspots', those regions where climate change would severely impact several sectors (represented by declines in crop yields and river discharge, spread of malaria, and ecosystem change) simultaneously. Although they examined only a subset of climate-induced problems, it represents a first step in trying to forecast the multiple impacts at the regional level.

3. Responses: adaptation, mitigation, or both?

Cities can respond to the threat of serious climate change by adaptation, mitigation, or a blend of the two. Both of these options can be roughly separated into physical and social approaches, although the distinctions are far from clear-cut.

3.1. Adaptation

Cities, as we have seen, differ greatly in the direct biophysical threats from serious climate change, although in a interconnected world, even the most-fortunately located will still face problems from increased internal and international migration, and adverse effects on the international economy. Some cities, such as Venice, already face threats from rising water even without the influence of any climate change. But the most commonly discussed form of physical adaptation, the construction of flood or storm barriers, such as those already installed (London, the Netherlands coast, and St Petersburg, Russia) or under construction (Venice) are very expensive. Such 'tech fix' approaches, although sometimes perhaps warranted, also tend to foreclose non-technical solutions to the threats facing cities for two reasons. First, as discussed below, they can be very costly, and so can divert resources from non-technical approaches. Second, it will be difficult to muster support for such measures if the public (and their policy-makers) are led to believe that such fixes can obviate the need for fundamental social change in the face of a changing climate. Further, given their high costs, it can take many years to evaluate options, plan, finance, and construct the project.

In the wake of the disastrous superstorm Sandy in New York, a proposal for two barriers, including one 8 km in length and 6 m high at the entrance to the harbour, was costed in 2013 as between $US7 and $US29 billion, depending on the design. Even this elaborate construction would do little to protect coastal Long Island. A general criticism of such schemes is that coastal protection of high value areas can raise the risk for nearby unprotected areas. Nor would it protect against long-term sea level rises or flooding from the hinterland (Tollefson, 2013). Further, if the past is any guide, it will encourage further coastal development in vulnerable areas of New York because of the perceived lowering of risk. This example illustrates the limits to physical adaptation, even for a wealthy city like New York. For the cities of low income countries, such an option could not even be considered. Tanzania, for example, with a per capita GDP only 3% of that for the US (see Table 1) could not afford such costs for its multi-million coastal metropolis, Dar es Salaam, even though flooding and shoreline erosion are

Table 1
GDP, fossil fuel use, and CO_2 emissions per capita for selected countries, 2011 (International Energy Agency, 2013).

Country	Per capita GDP (PPP[a] USD 2005)	Per capita fossil fuel CO_2 (tonne/year)	Per capita primary energy use (GJ/year)
World	10,105	4.50	78.7
Australia	37,260	17.43	226.0
China	7615	5.92	85.0
Eritrea	515	0.09	5.9
Ethiopia	980	0.07	16.7
Kuwait	47,900	30.07	483.2
Norway	46,760	7.69	237.8
Tanzania	1260	0.14	18.8
UAE	42,300	21.02	350.9
US	42,385	16.94	293.9

[a] PPP = purchase parity pricing.

already serious problems (Kiunsi, 2013). In such poorer cities, flood protection measures, such as improved drainage for the city centre or well-off areas, can make flooding in other areas worse (Douglas et al., 2008).

Another example of physical adaptation would be desalination plants for cities facing decreasing supplies of fresh water in future. Desalination plants are already very common in the world today, particularly on islands and in the Middle East, and were built to accommodate expanding urban populations and higher per capita water use, rather than a changing climate. This example shows that many methods for physical adaptation to climate change are already being used for other reasons. Physical adaptation to changing events is a natural response for cities. Like seawalls and new drainage infrastructure to reduce urban flooding, only the intensity of deployment will change.

Physical adaptation can even be counter-productive. As discussed, heat stress would be a major health problem in many cities, exacerbated by both intensification of UHI in cities, and rising frequency of heat waves. Private adaptation in the form of air-conditioning would not only add to the UHI effect, but would be of little use to those who must work outside for prolonged periods. Any grid overloading during heatwaves could require load-shedding, raising difficult ethical questions. Energy-intensive desalination plants will likewise exacerbate global warming. Physical adaptation may also present a *moral hazard*, in that not only could it lead to more settlement in, for example, low-lying areas, but it could also reduce incentives in high-income nations for strong mitigation measures.

As mentioned, the difference between social and physical adaptation is not always clear. For example, re-locating electrical equipment from basements, and providing more back-up generators as a response to flood risk, contain elements of both. Other cases are more clear cut. Already cities are responding to the increased frequency and severity of heat waves by education programmes and other changes to health services. The latest IPCC report on climate adaptation (Field et al., 2014), devoted Chapter 8 to the problems of urban risk and adaptation. Even though the tone is generally upbeat, the report also hinted at possible problems arising from conflicts between different urban groups. One huge urban group are the one billion urban slum dwellers, who as Davis (2006) has described it, have little choice but to live 'on a steep, unstable hillside, along a polluted river or in a dangerous flood plain. It is only a matter of time for natural disaster to strike.'

3.2. Mitigation

In general, physical mitigation projects would not take place in cities (although they would be largely financed by urban residents). Exceptions include rooftop photovoltaic and solar hot water installations, and proposals to paint urban roofs and pavements white, discussed below. Conventional methods for decisive action to mitigate climate change, as in the IPCC low emission scenario (van Vuuren et al., 2011), include cutting emissions of CO_2 (the most important greenhouse gas) through large increases in energy efficiency, or far more use of alternative energy sources (renewable or nuclear). Also important in this scenario are large-scale carbon dioxide reduction policies, especially carbon capture and storage. Another possibility, considered in some detail for the first time in the latest IPCC report (Stocker et al., 2013) but not included in any scenario, is solar radiation management.

The potential for energy efficiency is large, and energy efficiency gains have been recorded in many areas, including power generation efficiency, lighting, and building insulation. But despite these gains, global primary energy use and fossil fuel CO_2 emissions continue to rise (International Energy Agency, 2013). Devices may become more efficient, but if their numbers increase (as with road vehicles) or if they are used more, absolute energy use will grow. This growth arises partly because of the *energy rebound* effect: a more energy efficient device is cheaper to operate, encouraging greater use. Furthermore, energy efficiency gains can conflict with other valued measures of efficiency. In agriculture, energy efficiency can conflict with land use efficiency (yield per hectare), and in transport time efficient (faster) modes are usually less energy efficient (Moriarty & Honnery, 2011a). Also, although improving energy efficiency of given devices (e.g. light globes, vehicles, power stations) can help economic growth, the same may not be true for switching from car travel to more energy-efficient public transport, or from bottled water back to reticulated tap water. For this reason, efforts to implement efficiency gains of the latter type may encounter resistance.

As we have argued in previous publications (Moriarty & Honnery, 2010, 2011a, 2012a), the potential for non-intermittent sources of renewable energy, especially hydro and biomass energy, are limited. Large amounts of renewable energy would have to come mainly from solar energy, as even wind energy potential is limited (Moriarty & Honnery, 2010). Solar energy has a low return on energy invested compared with fossil fuels, or even other renewable energy sources (Brown & Ulgiati, 2011). Thus, energy storage will be necessary if solar energy is to provide nearly all energy (not just electricity), further lowering its energy return on input energy. Storing energy may well require conversion to hydrogen; this conversion, together with regular cleaning of the solar receiver surfaces, will need large amounts of fresh water. In the arid areas favoured for large solar farms, fresh water provision will itself usually be energy-intensive. The final energy return on input energy could be very low, except in some favoured regions. Nuclear energy has been losing share in the global electricity market for two decades, and now is down to a 11% share (BP, 2014). Further, Dittmar (2013) has argued that even a one per cent continued growth in nuclear power output would lead to uranium shortages in a few years time.

Both the IPCC report (Stocker et al., 2013) and Keller, Feng, and Oschlies (2014) considered that solar radiation management could at best be a partial solution to climate change. The IPCC stressed that neither the efficacy of the proposed approaches, nor the known side effects, are fully understood, and also pointed out the possibility of *unknown* side effects. Aerosol injection into the upper atmosphere is widely advocated for this purpose, but its use would reduce the output of solar energy devices that rely on concentrating sunlight, because the aerosols would cause scattering of the sun's rays. Passive solar energy and solar lighting would also be adversely affected. Further, global precipitation would be reduced, which could negatively affect both hydro output and bioenergy availability (Moriarty & Honnery, 2011b). In any case, it is of little use in reversing the effect of ocean acidification caused by rising CO_2 levels. Another ambitious approach often discussed is widespread afforestation, but Keller et al. (2014) found that afforestation would actually exacerbate global warming, because the benefit from atmospheric CO_2 reduction would be outweighed by a surface darkening of the afforested area, leading to more absorption of insolation.

It could be argued that even if each mitigation measure individually can only make a marginal difference, together they can be decisive for climate mitigation. But, as seen, individual mitigation measures can conflict with each other, and local mitigation measures can even conflict with global climate mitigation. An example of the latter would be the painting of urban roofs and pavement surfaces with reflective coatings, such as white paint, to increase urban albedo. Although it would marginally cool the urban area, one analysis suggested that it would do so at the cost of raising the global temperature (Jacobson & Ten Hoeve, 2011). It is now becoming clear that all conventional mitigation policies, including mechanical and biological carbon sequestration, will be of little help in stabilising climate before the mid-century or even later. Recent modelling work supports this conclusion (Myhrvold & Caldeira, 2012; van Vuuren & Stehfest, 2013). In presently high CO_2 emission countries, deep energy reductions will therefore be necessary, with profound consequences for OECD cities.

Can social mitigation help? As a case study, Druckman and Jackson (2010) examined a 'Reduced Consumption Scenario' for the UK, in order to determine how much lower the average household greenhouse gas emissions would be compared with present emission levels. All households were assumed to 'achieve a specific "minimum income standard" which is deemed to provide a decent life for each household type.' The reduced consumption scenario assumed household travel by car and aeroplane was completely eliminated, and each (well-insulated) household was closely matched to occupant numbers. Apart from good insulation for all dwellings ('cavity wall insulation, loft insulation, and double glazing'), no other changes to built form were assumed. Average household emissions in this egalitarian, 'necessary' expenditure only scenario, were reduced by 37% compared to actual year 2004 emissions. Since much larger energy reductions are probably needed, both for households and other urban energy use sectors, the changes needed will be even more fundamental.

Usually unrecognised is the social mitigation (albeit involuntary) of the presently low-emitting countries. If the world as a whole had the US level of per capita fossil fuel CO_2 emissions (which are well below the world's highest, see Table 1), total fossil fuel emissions of CO_2 in 2011 would have been 118 billion tonnes, instead of 31 billion tonnes. The world's belated attempts at physical mitigation have seen atmospheric CO_2 concentrations rise from 355 ppm in 1991, when the first IPCC report was released, to around 400 ppm in early 2014, when the fifth report was released. A very rough calculation based on cumulative emissions since 1760 gives an even starker result. If all the world had the same fossil fuel CO_2 burden as each present US citizen (roughly 1100 tonnes/capita) then atmospheric CO_2 levels would be around 400 ppm higher than they are today, or about *double* the 2014 value (BP, 2014). The world will never be able to provide the per capita energy levels prevalent today in the OECD countries (see Table 1).

3.3. Adaptation and mitigation

In summary, cities in poor countries will need to focus on adaptation, while in high income countries, a combination of adaptation and mitigation will be needed, with adaptation, especially social, the obvious short-term approach. But it will be necessary to take a system approach, and to make sure that local policies for both physical mitigation and adaptation are neither in conflict with the broader goal of global climate mitigation nor with each other. For the poorest cities, with already low per capita emissions, adaptation will be hindered by lack of resources. They will need help from the historically high-emitting countries that are largely the cause of the present predicament. But in the end, adaptation measures, whether social or physical, can only take us so far. Beyond a certain level of climate change, mitigation will be the only option (Hansen et al., 2013). Further, climate change may already be linked, at least indirectly, to increasing civil unrest violent conflicts

(Field et al., 2014). If the 4 °C temperature rise discussed in Section 2 does occur, these links can only strengthen, making adaptation much more difficult to implement.

A possible problem with implementing mitigation is that even if one country makes deep cuts in its emissions, very little benefit will accrue to it if other countries do not follow suit. Only for more localised problems such as urban air or water pollution, water recycling, or waste disposal, will the relevant region reap most of the benefit of efforts to alleviate these problems. Similarly, and in general contrast to mitigation, the benefits from climate adaptation efforts (for example, building sea walls) will accrue almost entirely to the city that makes them. Environmentally progressive cities that attempt deep reductions could find their efforts come to little if they are not followed by the rest of the world, which can only dampen motivation for mitigation. Fortunately, cities, even low-income cities, can reap some co-benefits from emissions reduction. Air quality can be improved (West et al., 2013), and reducing urban energy use will help reduce the UHI effect. Energy reductions can also give further benefits, such as improving energy supply security, making economies more resilient to supply disruptions or energy price shocks, and reducing the need for energy infrastructure investments.

4. Discussion: the probable future of cities

Section 3 discussed the feasibility and the limits of the various approaches possible for dealing with climate change. This final section examines the implications for the future of the world's cities. Cities appear to have great staying power: Alexandria, Athens, Beijing, and Rome have survived in some form for millennia. Today they each contain millions of residents, although the population of Athens fell to just an estimated four thousand in the early 19th century before rising to around four million today (Wikipedia, 2014). Apart from the enormous investment in money and energy for infrastructure projects that existing cities represent, many cities also have deep symbolic importance for their resident populations, for their nation, and even the world as a whole. In political discussions, the names of capital cities like London, Moscow, or Washington are often used as a shorthand for the countries as a whole.

Nevertheless, a number of cities in the historical record have been abandoned for either environmental or resource depletion reasons In recent times, we have seen the northern Ukrainian city of Pripyat, with some 50,000 inhabitants, evacuated after the April 1986 Chernobyl nuclear accident. In China, several sizeable cities were demolished to make way for the Three Gorges Dam. Other cities have declined because of multiple social, economic or political crises: the population of ancient Rome may have been a million at its peak, but declined to a few thousand after the collapse of the empire in the 5th century (Chandler, 1987). These examples show that we can expect that some cities will in future be abandoned for reasons other than climate change—if only because of the sheer number of cities—the UN (United Nations, 2014b) lists nearly 1000 cities of over 750,000 population. And although globally, cities overall are presently experiencing strong growth, there are simultaneously 'shrinking cities', those that are losing population and jobs, often to 'global cities' (Martinez-Fernandez, Audirac, Fol, & Cunningham-Sabot, 2012). However, a recent book claims that even global cities like New York and Los Angeles will face 'an uncertain future' (Halle, 2013).

The UN categorise population as either urban or rural, and expect urban growth to be especially rapid in Africa and Asia, two populous continents with presently low rates of urbanisation. An important component of this expected growth will be in-migration from rural areas. In China, for example, the rural population peaked in 1992 at 861 million, and the UN project it to fall to 335 million by 2050. The UN forecast little urban growth in the already highly urbanised nations of the OECD, and even the Latin American urban population, already at 80%, will only grow slowly (United Nations, 2014b). Like the UN, we expect global urban share to continue rising, but only for another decade or two. Beyond that time, it is likely that the urban share of the global population will start to fall from its peak ('peak urbanism': Heinberg, 2010), regardless of which of the two responses to climate change the world adopts: adaptation to ongoing climate change or strong mitigation. We examine each of these two options in turn.

Effective mitigation actions will be very difficult to achieve, as evidenced by the uninterrupted rise in both CO_2 emissions and atmospheric concentrations in the past two decades. One reason is the concerted effort by the fossil fuel industry and other interests, to block any serious action on climate change, not only in the US (Brulle, 2014), but also in oil exporting countries. This position has been aided by a difficulty stressed by Hansen et al. (2012): 'Earth's response to climate forcings is slowed by the inertia of the global ocean and the great ice sheets on Greenland and Antarctica, which require centuries, millennia or longer to approach their full response to a climate forcing. This long response time makes the task of avoiding dangerous human alteration of climate particularly difficult, because the human-made climate forcing is being imposed rapidly, with most of the current forcing having been added in just the past several decades.' Climate sceptics can thus point to the minor changes so far seen as evidence of the minor impact of likely change.

Another difficulty results from the inequitable global distribution of CO_2 fossil fuel emissions, as illustrated in Table 1. If low emission per capita countries also had low total emissions, this would be a minor problem. But today, China is the world's largest emitter, despite its relatively modest (but rapidly rising) emissions per capita (Moriarty & Honnery, 2012a). Countries like China and India will argue that OECD countries reduce emissions first; international agreement on effective action seems unlikely any time soon.

Because of these difficulties (and the problems facing physical mitigation discussed in Section 3.2), it is increasingly recognised that staying below the 'safe limit' of 2 °C rise above pre-industrial times is unlikely (e.g. New, Liverman, Schroder, & Anderson, 2011). Cities could well face the serious biophysical hazards discussed in Section 2 should greenhouse gas concentrations continue to rise. The cities at greatest risk from biophysical hazards are those that:

- Already face one or more high risks from natural hazards not directly related to climate change
- Face multiple risks from on-going climate change
- Have low financial or administrative resources for adaptation.

Social adaptation is already occurring in the face of urban problems like flooding and heat waves, and will be expanded. Physical adaptation can take decades to implement, and could worsen the risk for other parts of the city, or, if energy-intensive, could even add to global climate change. Eventually, all possible adaptive responses will be overwhelmed by on-going climate change—adaptation can only ever be a stopgap solution.

We argue that peak urbanism is also likely even if the world does implement serious mitigation policies. Given the limits of adaptation, the world will eventually have to implement effective mitigation, and the longer this action is postponed, the more drastic will be the measures necessary, since the risks from climate change will rise in a non-linear fashion with global temperature rise (Field et al., 2014; Stocker et al., 2013). Peak urbanism in this response to climate change will arise from the declining attraction of urban areas, independently of the less-severe geophysical hazards they will now face. Already, many cities face the perennial urban problems of unemployment, inequality, crime, congestion and air pollution, and even in the OECD, many face serious financial problems. Global primary energy use and real global GDP have been tightly coupled in recent decades, and technical fixes will likely prove largely ineffective (Moriarty & Honnery, 2012b). Even if decoupling occurs to some extent over the next decade, partly due to increased natural gas use, this will only be temporary, because of the decline in the ratio of net/gross energy. Future cities—at least cities in presently high energy-use countries—will thus have to make do with much lower GDP/capita, if they are to drastically cut their ascribed CO_2 emissions. If such 'degrowth' does occur, it is difficult to see much of a future for the type of jobs that characterise world cities, such as financial, insurance, and real estate services. Even many of the industrial jobs typical of Chinese cities could be in jeopardy.

The resultant declining attraction of urban areas raises the possibility of a future back-flow to rural areas—as happened after the cities of antiquity declined. At present, of course, the flow in Africa and Asia is the other way, driven by the same forces that depopulated rural areas in Europe and North America—industrialisation of agriculture and the lure of a better life in cities—but also by land resumption for bioenergy and export crops.

But sooner or later, it will become impossible for industrial agriculture to ignore either the heavy environmental costs it generates, or its heavy reliance on energy, especially oil (Weis, 2010). More ecologically sustainable, less energy-intensive agriculture will require a much greater labour force, and could cost more to produce. Agriculture in poor countries may no longer have to compete with the low-priced imports from industrial agriculture. Further, in both Europe and Latin America, there is growing recognition of the *multi-functional* nature of farming, including, in addition to food production, its 'contribution to ecosystem management, landscape protection, rural employment, fostering farming knowledge, rural life, cuisine maintenance, and regional heritage' (McMichael, 2011).

How, then, will the future of cities unfold? Overall, our main conclusion is that peak urbanism will occur in the coming decades. History provides many examples of the rise, then fall, and often rise again, of ancient cities, as with Athens, Rome, and Alexandria (Chandler, 1987). For the reasons above, we think that future declines are again in store for many cities. Each city will have its own trajectory, but some general statements are possible about specific city groups. In low-income cities, adaptation will reach limits sooner because of limited financial and administrative resources, even for existing problems. In this group, cities already facing natural hazards and/or most at risk from further climate change will fare worst. The greatest risks, as at present, will be borne by those in the slum areas of these cities.

In presently high-income cities of the OECD and elsewhere, both adaptation and serious mitigation of climate change will be needed. The future of these cities will need to be rethought, since they could well lose important functions as cities try to make themselves more ecologically sustainable. According to ecological footprint analysis, the world is in overshoot, using the resources of 1.5 Earths (Rees, 2012). Such a situation is clearly unsustainable, and suggests that the rise of cities over the past two centuries is itself a result of the fossil fuel bonanza, which for both resource depletion and global pollution reasons, cannot continue for more than a few decades.

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