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# Implications of climate change for expanding cities world-wide

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## Abstract

This is a review of how the increasing population and green house gas emissions of the world's growing cities are changing the global climate and some of the most sensitive regional environments. Meteorological , environmental and social science studies show how cities are increasingly vulnerable to climatic and environmental hazards , and can become even more so as mega-cities grow to 50 -100 km in size , with populations of more than 30million. Experiences around the world show that practical actions to meet the policy objectives of mitigation and adaptation to climate change, resilience against hazards and long term sustainability and security are more effective when they are appropriately integrated. But community initiatives responsive to local environments will always be very important.

## Overview

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1. Since the first UN Habitat Conference in 1996, politicians as well as environmental scientists , meteorologists , and urban planners have begun to realise that the objectives of sustainability set out in the UN Brundtland report (1988) could only be achieved by understanding and dealing effectively with the interactions between cities and the wider global and regional environment. For example when London's government was reformed , one of its new responsibilities was for sustainability-a word that entered US legislation later in the Energy Act of 2005. This objective has become ever more critical as the proportion of the world population living in cities rises progressively during this century from 50% to about 60-70%. The cities' consumption of energy, material resources and contributions to green house gas emissions are rising, but in industrial countries not as fast , because cities, such as New York and London (Hunt 2005), generally use less energy per person than suburban and rural areas. The high concentration of people per square meter , about 100 -1000times the global average, makes these areas prone to natural hazards , some of which will be exacerbated by human induced climatic and environmental change. Although as the science and technology of hazard forecasting, disaster management and preventative design have greatly reduced the damage caused by such events in major cities ,the recent heat waves and floods in Europe and USA have shown that all societies can be vulnerable to extreme or unexpected hazards. But as always the latter provide important lessons for the future . Many new risks will

emerge as cities grow in size and population ; their environments may never have been experienced before as their local mesoscale meteorology and hydrology interact with changes in regional climate. The structures and open spaces of these urban areas may take on new forms and uses;it has been suggested by Head (2006) that these areas in densely populated countries such as China will only be sustainable if they grow much of their own food , which may be possible in tropical regions by hydroponic crops on buildings.

The scientific study of these developments should be based on the progress that has been made both in urban and mesoscale meteorology (eg Fernando et al 2001,Bornstein 1987, Gayev & Hunt 2007) and in regional and global modelling and prediction of climate change, seasonal variability and extreme weather events ( IPCC 2007 , Hunt et al 2007). The first aim of this paper is to link some of the results of these studies in order to draw some conclusions about the likely changes in meteorological and hydrological hazards in urban areas both as the climate changes and the sizes of urban areas grow. Mesoscale meteorological models are used to study the climate and environment for specific local areas under the influence of the weather, environment and climate outside the areas. These boundary conditions are defined by local observational data or results computed from global models using global data . This ‘localised’ approach is complementary to the ‘down-scaling’ method in which climate models for regions extending over distances of up to about 1000km are used in conjunction with global models which provide the outer boundary conditions.

Localised modelling is demonstrably effective where climatic and environmental changes are strongly influenced by local topography and by marked variations in the local surface conditions, including those produced artificially. Such models over scales of hundreds of kilometres have explained how trends in average synoptic scale flows when interacting with the special topographic and surface features of polar regions so as to induce a large regional rise in temperature rise of 3K over the past 50 years more than triple the global average .(eg Orr et al 2008). Downscaling results have so far only been partially successful in modelling variations in regional climatic trends, especially regional variations in precipitation. (eg Najac 2008;Terray & Cassou-private comm.; Smith 2008) Local mesoscale modelling and observational studies of the moderate global warming trend in London show that it is greater than in the rest of southern England . But the temperature trends are quite complex because as numerical simulations show , they are affected on the mesoscale by nearby hills, coasts , and local hot-spots such as airports, and the 1-3km microscale by parks, rivers , buildings etc .(Bohnenstengel et al 2009).

In this , as in other fields, estimating risk requires considering a range of possible hazard scenarios , and also considering under what critical conditions these cause sudden increases in the impact on the physical and social structure of built-up areas.(See table1) Policy makers also need to know what kinds of options to consider based on these estimates. Cities have been abandoned in past climates , such as Mohenjo-daro in Pakistan which was destroyed and rebuilt seven times (www.wikipedia.org); indeed some coastal communities and Island states are considering the same fate today.

The international community and some regions and cities around the world are beginning to act on the causes of climate change by changing their future energy and transportation policies so as to limit GHG emissions (eg UK climate change act 2008) Industry initatives are developing as a result of these and the other imperatives of shortage of fossil fuels and need for security.(eg Globe 2008). But the policies are not being introduced fast enough to reduce the steady rise in global temperature from its baseline in 1850 (the upward trend is more marked over land areas eg www.metoffice.gov.uk). This is likely to exceed 3K by the year 2100 . The dangers are now well known (Schellenhuber et al 2005) .

Consequently many governments and cities are also introducing parallel policies for adapting communities , industries and agriculture to the likely consequences of climate change.(eg UKClimate Impacts Programme 2009). The Netherlands (2008) following a major review of their risks plans to raise its dykes to allow for the eventual rise in sea level of several meters-corresponding to the worst case scenario of melting of polar ice-caps. UK and German measures were reviewed in www.ucl.ac.uk/environment-institute.

There are common elements and concepts in the main technical, economic and administrative policies for dealing with climate and environmental risks (eg in infrastructure, and operational risk management ).Connecting and in some cases integrating these policies can make them more effective socially and economically, as well as practically . (eg Parker and Penning Rowsell 2005) . This approach also contributes to measures for long term sustainability (for example introducing renewable or high efficiency energy systems in new housing developments) - as some cities and regions have demonstrated already. The environmental advantages and implications for reducing climatic and environmental hazards in urban areas through connected policies are discussed in the final section. .(Stern 2006, Hunt 2009). See table 2.

## 2. Climate Change , Environmental Risks and Urbanisation

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### 2.1 Factors contributing to risks.

The main types of meteorological, hydrological, or environmental hazard (see table1) that cause damaging impacts on communities are associated with :high wind speeds (U); raised water levels (h) caused by local precipitation , river discharges or wind induced surges and waves along coasts; high temperatures (T) associated with regional meteorology and artificial effects of produced by changes in surface properties and heat emissions from energy systems; high concentrations (C) of atmospheric pollution arising from natural sources (sand, gases from lakes…) and from artificial processes of industry, transport and agriculture etc. These hazards, whose magnitude is denoted generically by H, cause impacts on the physical and societal structure of communities , including their physical infrastructure, as well as their health and social and economic capacity .But the magnitude of the impact ,(denoted by I) depends on H and also how well all these aspects of the community are adapted to reduce the impact of the hazard and to recover afterwards, ie its resilience or lack of vulnerability (Adger 2006, Crichton,2007)

These hazards are firstly associated with regional weather and climate , and with environmental effects that are independent of any local urban effects (even though urban areas world wide are affecting the global climate!). Their impacts are denoted by Io. Regional effects may be caused by global warming, or by significant regional amplification -mentioned above.

In urban areas significant extra hazards and impacts are caused by differences between the physical, chemical and biological effects on atmospheric processes in the urban area and those outside it. These additional impacts are denoted by /\I. Estimates of impact risks also require considering which hazards can occur simultaneously and which also can interact to increase I , as occurs with high winds, floods and waves. But other combinations may be very unlikely depending on the climatic region and the geography. In urban areas different hazards can combine to enhance /\I , such as when high urban temperatures worsen illnesses caused by high air pollution concentrations, as occurs in African and European cities like Athens . Climate change and urban factors can also exacerbate the impacts of rare but damaging geophysical hazards ; tsunami impacts on coastal cities will increase with sea-level rise and may in future occur on arctic coasts as sea ice melts. Conversely geophysical hazards can exacerbate environmental risks such as the effects of solar bursts on the electrical systems that maintain the environment of high density cities-a concern for certain Asian cities during the next sun-spot cycle in about 2012.

Primary hazards can trigger equally damaging secondary effects , some of which are come from natural processes such as precipitation induced mud slides in cities on mountain slopes .Others are environmental effects caused by the disruption of the city’s systems , such as overflow from sewage treatment plant and drains leading to widespread water pollution. Medical, social and economic impacts are of increasing concern to policy makers , since they determine whether communities can recover before the next hazard event occurs. Failure to do so threatens their long term viability.(Hunt2009) .See table1. Insurance companies are now as concerned with the social capacity of communities as by precautions for reducing the physical impacts of extreme events.

## 2.2 . Estimates

Multi-disciplinary meteorological, environmental , engineering and social science studies are needed to estimate these hazards and impacts separately and in combination; both for present climatic and urban conditions, and as these change in the future. Numerical simulations are required for quantitative predictions of a few cases , while simplified modelling provides interpolation , extrapolation and comparisons between a range of simulation results . Also it enables estimates to be made of future trends ,as in table1.

Note that estimates of trends for impacts from primary hazards are based on models of local meteorology and environmental processes, and on civil engineering studies of critical conditions in urban areas, particularly associated with high winds and floods. But estimates of secondary impacts also derive from system engineering concepts and societal models of resilience. (eg Moser 2007). Some impacts are only significant when the hazard exceeds a critical value, Hcr, which , as recent disasters have shown , depends on the strength of the precautions and engineering defences that were in place at the time. But for other hazards , such as higher temperatures caused by global warming and the urban heat island (Oke 1978) and higher air pollution concentrations (eg Jacobson 2002), adverse impacts I on the well being and environment of cities increase progressively as the hazard magnitudes H increase , whether separately or in combination. Recent analysis of future climate models suggests that the occasional blocking events associated with high temperatures will be more frequent , and some in Europe may even last for 20 days-with very serious effects on urban areas as well as water resources over the whole region.(Cassou and Gulyardi, 2007) .An associated critical feature of the changing structure of the troposphere (Gaffen et al 2000) is the lessening vertical stability and deepening and strengthening of convection (except over regions where this is limited by urban induced aerosols Ramanathan et 2007).This causes more intense rainfall events and flash flooding typically over scales of about 30km.

As the size L of an urban area increases , its energy use and pollution emissions increase approximately in proportion to the square of L. Thus as the wind advects the heat and pollutants across the area the peak urban temperature (and also peak concentration) increase (Oke 1978) ; more markedly in North American cities with tall buildings than in European low rise cities. The length scale over which these hazards are significant , denoted by LH, will therefore grow at broadly the scale L of expanding cities. But as the Paris heat wave of 2003 demonstrated there are sufficiently large local variations in the urban temperature on scales of 1km, that it even determined the local pattern of mortality.(Murray 2007).In this case these hot spots effectively determine the average mortality impact per unit area over the city ,</\I>, which is expected to increase as L increases. A similar increase with L would be expected for the impact on mortality of air pollution . Unlike heat ,which diffuses to the ground, pollutants can be advected far downwind of cities. In local sea-breeze and valley circulations ,as in Phoenix, they move 30 km upslope and return at night to build up the concentrations further. But this kind of local effect will becomes relatively less significant as L increases .

Many observational and numerical studies (eg Bornstein 1987,) have shown how over larger cities the airflow , temperature profiles and precipitation patterns differ appreciably between those in the centre and the outside the urban areas. Fluid dynamical studies of perturbed stratified flows with the Coriolis effects of the Earth's rotation (Orr et al 2005; Rotunno 1983)shows that the changes in the direction and speed of the airflow only become substantial when the length L exceeds the 'Rossby Radius 'LR , which is about 30km at night and up to 100km by day. This is the distance over which the urban area affects the boundary layer flow upwind and around the urban area. But (Collier 2005) when L is comparable or exceeds LR, the airflow and patterns of precipitation downwind of large cities are perturbed for distances larger than LR. LR is also the distance over which the boundary depth varies with the variation in surface heat flux across the urban area, particularly at night-though this is a controversial question .(EU Cost 715, 2007)

For 'mega' cities of the future L will exceed LR , which will then become the characteristic scale of the flow variation , such as jets of increased wind speed around the periphery .These are also areas of marked convergence and divergence , so that the patterns of precipitation change . Both depend on the wind direction and its strength relative to the thermally induced wind , which can be greater at night (eg Plate 1980). The significant consequences for urban climate and environment of cities when they reach this mega scale is just beginning to be studied , for example in an EU project led by Prof Baklanov of Riso, Denmark.

It is equally important to consider how increasing scale affects the operational , social and economic capacities of cities to deal with hazards .Clearly where climatic and environmental hazards , as well as those caused by industrial accidents and malefactors are localised over scales LH, and if L exceeds LH, larger cities have relatively greater resilience. This also implies that the threshold Hcr increases for hazards to have a serious impact. But where the hazards extend across the city , such as with fluvial flooding in low lying cities , (ie LH =L) , and if L is so large that people cannot leave in the time scale of the hazard , then policies to increase the size of such cities should also include investments in security measures eg refuges above the floods.Multi-disciplinary modelling of these scenarios is an urgent research priority everywhere. (Hunt et al 2009).

## 3. Policies and Actions

Policies to deal with the impact of climate change and environmental hazards aim broadly to reduce their physical causes and to minimise their impact on society and the natural environment.It is now generally accepted , but not universally, that most effective policies for mitigation and adaptation should also contribute to the long term sustainability of the regions which they affect. Because of international trade and transportation , and communications these effects are distributed world wide.eg adaptation measures to reduce deforestation and mud slides in an industrial country are impacting on the environment and adaptation in developing countries from where timber is imported. The UN Earth Summit Declaration and Biodiversity Convention in Rio in 1992 provided the international framework for these policies and specifically committed governments to sustain the world's natural environment .But leading politicians and economists do not seem to understand this commitment in their advocacy of climate change policies based only on minimising their 'opportunity' costs into the future. (Lawson 2008;Hunt 2008)

Table 2 lists the main ways in which governments, communities and industry are working to implement the three main policy objectives of mitigating GHG emissions, reducing the impacts of climatic and environmental hazards over the short and long term, and generally promoting sustainability. For these measures to be successful they also need to ensure the acceptance of these measures and the continuing security and stability of the communities and organisations , especially during periods when significant changes to societies and individuals may occur ; such as having to move or change their housing, change jobs, or in the extreme case leave their region or country.The experience of organisations and communities that have successfully met some of these goals is that they have provided continual information ,(including demonstrations of new developments ) , future projections and , where possible, appropriate warnings about hazards (which can be personalised through modern communications and computer translation into all local languages-as is done in India).

Most of the action areas in the table can contribute effectively to the three goals; but this is more likely to be achieved if it is planned deliberately for each type of action area, with appropriate consultation. However to achieve such integration current forms of public consultation focussed on specific actions (eg one traffic scheme or one wind farm at a time ) may have to change in order to consider a range of actions and wider sustainability criteria-a highly controversial proposed by the UK government in its recent Planning Act(2008) establishing an Integrated Planning Commission.

Cities and urban communities recognise that their populations' energy requirements produce more than about 80% of the world's GHG emissions , and therefore have an overwhelming responsibility to contribute to their mitigation. Because of the compactness of cities and their existing infrastructures , their populations currently produce less ghg per head at present than those in non-urban areas. The same factors also provides opportunities for the necessary global reductions by about 60% to prevent excessive global warming . (IPCC 2007) .Mitigation measures now being introduced for urban areas include improved buildings to reduce their energy use (and/or regulating it as in Japan where much less air conditioning is now mandatory w.globeinternational.org) and reducing heat loss from and heat gain ( with new materials , use of ventilation design,and plant coverings), solar renewable energy , use of waste heat from power stations , non-fossil transportation energy, (eg hydrogen), efficient and non-polluting public transport, and progressively substitution of telecommunications for personal transport (eg by more teleworking).The energy measures contribute to the adaptation objectives of reducing heat urban heat island (as can be experienced by comparing the radiated heat from older and from the latest 'green' buildings (Sabatino et al 2009).They also contribute to energy security , especially where communities introduce separate local power networks. Transportation measures reduce air pollution , especially along roads in large cities where poorer people live with high incidence of bronchial diseases.

Other measures involving land use, building and planning also contribute to the three policy objectives .The appropriate use of biofuels (including industrial solar-CO2-algae growth -being applied in Arizona's desert), developing (and not reducing) natural areas in cities,and expanding tree planting (at lower latitudes especially) can reduce GHG emissions , reduce hazards of high temperatures and flooding .Certain pollutants are also reduced . In South India greening city areas has enhanced rainfall and provided new, and more secure, sources of sustainable energy. Perhaps larger urban areas could be developed , provided they have within them significant green spaces to meet some of the adaptation objectives.

A remarkably effective integration of measures in Netherlands involves placing wind turbines on dykes along the coasts, so that the costs of adaptation are contributing to the costs of the foundations of the turbines.

There are of course long traditions in local communities for providing energy, food and protection , so that integrated measures are quite natural to them. Also as meteorologists well know people in communities understand local weather , and are a bit suspicious about scientific predictions of climate change. But throughout the world people have now accepted the advantages of using modern weather and environmental forecasts. This should give scientists and policy makers confidence that through continued explanation and demonstration of successful practical measures, most communities and organisations will respond to the advice of science and technology to collaborate in dealing with the great challenge of climate change.

References to come later.

Table 1: Changing impacts on cities of climate and environmental change and increasing scale of urbanization

| CAUSES | IMPACT OVER TIME of climate/environmental change | IMPACT OF INCREASING SCALE of urbanization L (Note $\frac{L}{L_H} \uparrow ; \frac{L}{L_R} \uparrow$ ) |
|---|---|---|
| PRIMARY HAZARDS | | |
| Wind (U) | $(I_0 + \Delta I)^* \uparrow$ | $\Delta \hat{U} \uparrow \quad \Delta \hat{I} \uparrow$<br>$\frac{L}{L_H} \uparrow \Rightarrow < \Delta I^* > \downarrow$ |
| Flood (h)<br>(i) Precip<br>(ii) Fluvial/Coastal | $(I_0 + \Delta I)^* \uparrow$ | (i) $\frac{L}{L_H} > 1 \Rightarrow < \Delta I^* > \downarrow$<br>(ii) $\frac{L}{L_H} \sim 1 \Rightarrow < \Delta I^* > \uparrow$ |
| Heat (T) | $I_0 + \Delta I \uparrow$ | $\Delta T \uparrow , \frac{L}{L_H} \sim 1,$<br>$\Rightarrow \Delta \hat{I} \uparrow , < \Delta I > \uparrow$ |
| Pollution (C) | $I_0 + \Delta I \uparrow$ | $\Delta C \uparrow (?) \Rightarrow L_H \sim L \Rightarrow$<br>$\Delta \hat{I} \uparrow , < \Delta I > \uparrow$ |
| SECONDARY AND GEOPHYSICAL HAZARDS | | |
| Physical/Environmental Effects | $(I_0 + \Delta I)^* \uparrow$ | $\frac{L}{L_H} \uparrow \Rightarrow < \Delta I^* > \downarrow$<br>$L_H (L) \uparrow \Rightarrow \Delta \hat{I}^* \uparrow$ |
| Societal/Economic loss of capacity | $(I_0 + \Delta I)^* \uparrow$ | $\langle H_{CR} \rangle \uparrow$ as $\frac{L}{L_H} \uparrow$ |

| | | |
|---|---|---|
| | $\bar{I}$ ↑ (?) | $\Rightarrow <\Delta I^*> \downarrow$ |
| CONCLUSION | $\overline{\langle \Delta I^* \rangle}$ ↑ or ↓ | |

Note: (i) $I^* = I_{CR}$ for $H > H_{CR}$ ; $I^* \approx 0$ for $H < H_{CR}$ ,the critical hazard threshold

(ii) $\Delta \hat{I}$ is peak impact ; $\bar{I}$ is time average over many events ; $<\Delta I>$ is spatial average over urban area

Table 2: Policies and Actions for Climate and Environmental Hazards in Urban areas

| OBJECTIVES | Mitigation of Green House Gas Emissions | Adaptation | |
|---|---|---|---|
| ACTIONS | | Short-term (+Resilience) | Long-term (+Sustainability) |
| Energy and Resource Efficiency | Fast, Local → | Health Security ($\Delta T \downarrow$) $\Delta C \downarrow$) → | ✓ |
| New Power Sources (± Networks) | Renewable (F) →<br>Nuclear → | Resilience Security →<br>→ | ✓<br>(?) ✓ |
| Land use,buildings, Planning | Bio/Ag/For/Urban → | Reduce Hazards → | ✓ |
| Transportation & Communication | Non-fossil efficiency/use TR→Com ? | $\Delta C \downarrow$ Hazard Security | Economics |

Note:(i) Actions for climate change also contribute to and link with resilience, resources, security, economics, and social capacity (also affected by integration)

(ii) Varying time scales for different actions

(iii) Continual information and warnings needed for all policy objectives.

(iv) Response and recovery systems needed for all hazards-can be common for most cases.