The vulnerability of global cities to climate hazards[1]

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ABSTRACT This paper examines the vulnerabilities of three global coastal cities – Mumbai, Rio de Janeiro and Shanghai – to climate hazards. The paper highlights system characteristics that, in unique combinations, create place-based vulnerabilities to climate hazards. It describes these vulnerabilities then discusses the implications of the results for city planners and managers. A concluding section assesses some of the political obstacles to better disaster preparedness.

KEYWORDS: climate change, climate variability, natural disasters, mega-cities, urban poverty, urban planning

I. INTRODUCTION

Global cities are engines of economic growth and centres of innovation for the global economy and the hinterlands of their respective nations. The foundations of prosperity and prominence for most global cities lie in their long-standing commercial relationships with the rest of the world. Most global cities are located on or near the coast, which has facilitated trade and contributed to their wealth They are also often located in low-lying areas near the mouths of major rivers, which served as conduits for commerce between interior agricultural and industrial regions and the rest of the world. As it happens, these locations place global cities at greater risk from current and projected climate hazards such as cyclones, high winds, flooding, coastal erosion and deposition, and sea-level rise.(1)

Global cities are also important centres of population concentration and growth. According to Brockerhoff, just 25 years ago less than 2 per cent of the global population resided in "megacities" of 10 million or more inhabitants.(2) Today the proportion exceeds 4 per cent, and by 2015 it will top 5 per cent, when megacities will likely house 400 million people. The phenomenal growth rates that most low-income country megacities experienced from the 1960s to the 1980s have now somewhat tapered off, but because lower rates are being applied to higher population bases, the absolute numbers being added to their populations are still high. The fact that so many people reside in megacities near coastlines, and that these cities continue to grow, underscores the importance of assessing the vulnerability of such cities to coastal climate hazards.

Recent incidents have highlighted the vulnerability of urban areas in general to climate hazards. Hurricane Katrina in August 2005 effectively obliterated much of the Gulf Coast of Mississippi and flooded large portions of New Orleans, resulting in the evacuation of all residents and more than 1,000 deaths. The flooding was greatest in African-American neighbourhoods, and in the aftermath there were widespread accusations that the slow and ineffectual government response reflected a racial bias.(3) In July 2005, Mumbai, India, was struck by a cyclone that dumped 94 centimetres of rain in 24 hours, also leaving more than 1,000 dead, mostly in slum settlements. In terms of casualties, an even more devastating set of flash floods and landslides in Caracas and the north coast of Venezuela in December 1999 killed 30,000 people and affected another 483,000.(4) Each of these events underscores the vulnerability to climate hazards faced by the urban poor, especially those living in sub-standard housing in the most vulnerable locations.

Researchers at the Centre for Research on the Epidemiology of Disasters (CRED) have tracked an increase in almost all disasters, with the time trends for climate-related disasters, including floods, windstorms and droughts, showing the greatest increase, well above all geological hazards.(5) There are two factors behind this rise in climate-related disasters. One is regional increases in the severity and periodicity

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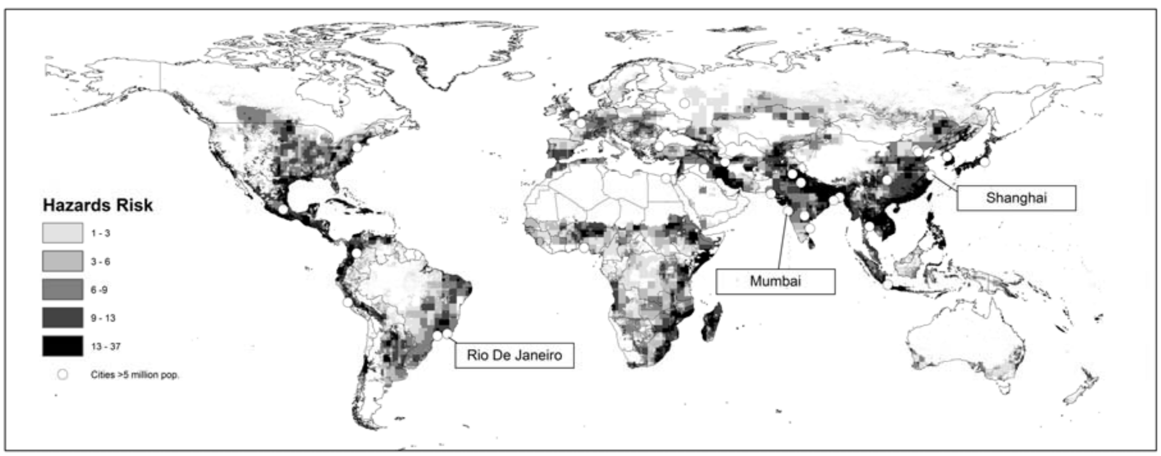
of hazard events.(6) For example, in the Atlantic and Pacific cyclone-generating areas, increased sea surface temperatures associated with global warming are responsible for an increase in the intensity and duration of tropical storms (although not necessarily an increase in their frequency).(7) The second factor – as alluded to above – is the large and growing proportion of the world's population that is living in cities and towns near the coast or in drought-prone or low-lying areas, and which consequently is exposed to these hazards. Research by McGranahan et al. finds that more than 600 million people (or 10 per cent of the global population) reside in coastal zones of less than 10 metres elevation, and that 13 per cent of them, or 77 million people, reside in megacities.(8) This combination of increased hazards and exposure results in greater numbers of disasters that claim lives and cause major economic losses.

The emphasis of climate change policy has largely been on mitigation. As necessary as these efforts are, it is clear that more attention needs to be given to adaptation to the climatic changes that are already underway, and which will be exacerbated by future emissions of greenhouse gases. Rayner and Malone argue that "…*the record and prospects of achieving emissions reductions suggest it would be prudent to expand the repertoire of climate change policies, if only because our past emissions and the timetable for any plausible reduction programme mean climate change is already upon us*."(9) Among other elements, disaster preparedness and management plans are vital components of an adaptation strategy. But to design these, we need a better understanding of which people and systems are vulnerable to what kind of climate hazards; also what makes them vulnerable, and where they are located.

In the following section we briefly describe the vulnerability framework applied in this paper. In Section III, we then apply the framework to an examination of three cities that are particularly vulnerable to multiple climate-related hazards: Mumbai (formerly Bombay) in India, Rio de Janeiro in Brazil, and Shanghai in China (Figure 1). Conclusions from this research are provided in Section IV.

Figure 1. Large Cities in Relation to Current Climate Related Hazards



Note: The cities included in this figure have populations greater than 5 million. Hazard risk represents a cumulative score based on risk of cyclones, flooding, landslides and drought. *Source*: For cities: CIESIN (2006), *Global Rural-Urban Mapping Project* (GRUMP), alpha version. Data available from http://sedac.ciesin.columbia.edu/gpw/. For hazards: Dilley, Maxx, Robert S Chen, Uwe Deichmann, Arthur L Lerner-Lam and Margaret Arnold (2005), *Natural Disaster Hotspots: A Global Risk Analysis*, World Bank, Washington DC, 132 pages. Data available from http://www.ldeo.columbia.edu/chrr/research/hotspots/coredata.html.

II. FRAMING VULNERABILITY

Vulnerability is the degree to which a system or unit is likely to experience harm due to exposure to perturbations or stress. The concept of vulnerability originated in research communities examining risks and hazards, climate impacts, and resilience. The vulnerability concept emerged from the recognition by these research communities that a focus on perturbations alone (environmental, socioeconomic, technological) was insufficient for understanding the responses of, and impacts on, systems (social groups, ecosystems, places) exposed to such perturbations.[10] With the concept of vulnerability, it became clear that the ability of a system to attenuate stresses or cope with the consequences through various strategies or mechanisms constituted a key determinant of system response and, ultimately, of system impact. A clearer understanding of coping strategies or mechanisms can thus throw light on who and what are at risk from what, and how specific stresses and perturbations evolve into risks and impacts.

Vulnerability in the social sciences is typically identified in terms of three elements: system exposure to crises, stresses and shocks; inadequate system capacity to cope; and consequences and attendant risks of slow (or poor) system recovery. This perspective suggests that the most vulnerable individuals, groups, classes, and regions or places are those that: experience the most exposure to perturbations or stresses; are the most sensitive to perturbations or stresses (i.e. most likely to suffer from exposure); and have the weakest capacity to respond and ability to recover. In this paper, we apply a vulnerability framework, described elsewhere,[11] to better understand the vulnerabilities of three megacities to hazards resulting from climate change and variability. The framework addresses the vulnerability of interacting human–environment systems to multiple and synergistic stresses that emanate from within as well as from outside the system.

Within this extended vulnerability framework, there is formal recognition that macroforces – broad-scale environmental and human systems within which the local system resides – come together to affect the local system and, simultaneously, influence the pressures that act upon it. Different pressures across scales come together in various sequences to create unique “bundles” of stress that affect local systems. A major hypothesis holds that when stresses or perturbations emanating from the environment coalesce with those arising from society, significant consequences can result. For example, economic depression reduces society’s capability to develop or maintain pre-emptive coping measures to reduce the impacts of drought, such that the co-occurrence of drought and economic depression synergistically enlarges the vulnerability of the system. The risks resulting from such vulnerabilities emerge from multiple sources, and at different scales. These risks cascade through interacting human and environmental systems to create adverse consequences.

We find that the framework provides new insights into vulnerabilities because it considers multiple, synergistic stresses and perturbations on one side of the equation, and multiple, synergistic physical and social characteristics of the exposed system on the other. This enables us to conduct a “gap analysis” that identifies areas of exposure and vulnerability, and points to areas of greatest need for strengthened adaptive capacity and risk management.

III. THE CASE STUDIES

We examine here three case studies of global coastal cities in light of climate hazards: Mumbai (formerly Bombay) in India, Rio de Janeiro in Brazil and Shanghai in China. Each of these cities has urban agglomerations in excess of 10 million people, the threshold that the United Nations applies to designate a “megacity”, and they each represent important national and regional engines of economic development and innovation.

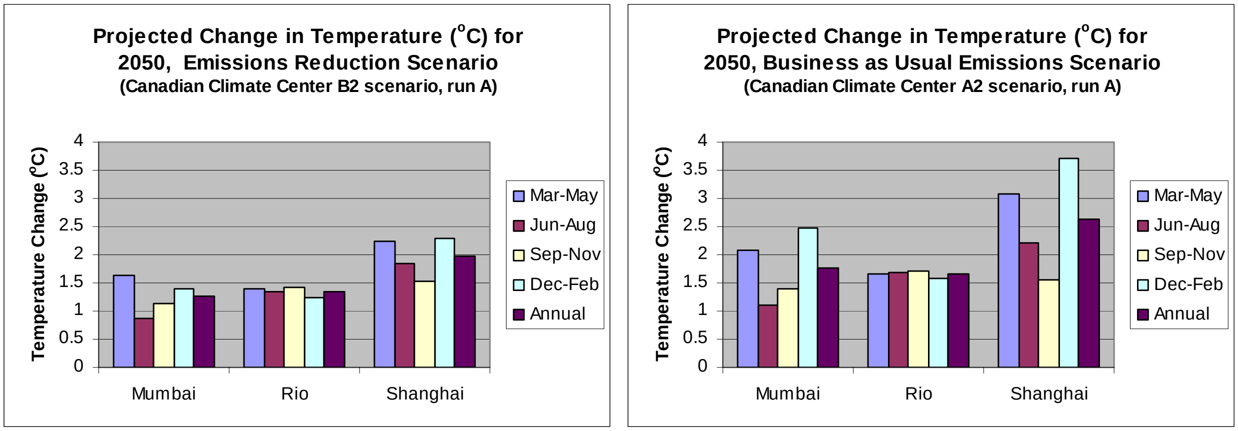
This paper addresses current and future vulnerability to climate hazards. The respective sections provide baseline information on climate in each of the cities. To assess future vulnerability, we use standard sets of climate change and sea-level rise scenarios. Figure 2 provides projected temperature changes by season for reduced emissions (“sustainable path”) and increased emissions (“business as usual”) scenarios.[12] Compared to temperature changes, precipitation changes are considered to be more difficult to accurately model, and therefore are not included here. Projections of sea-level rise due to melting land-based glaciers and polar ice caps range from 0.2 to 0.9 metres by 2100,[13] though recent rapid melting in Greenland and Antarctica suggest that these estimates could be superseded.[14] We adopt a common projected sea-level rise of 50 centimetres by 2050, although local variations in land subsidence will affect the relative sea-level rise in each location.[15]

These global cities are located in very different physical environments, which makes for interesting comparisons. The climate of Mumbai is tropical moist, Rio is sub-tropical wet and dry, and Shanghai is on the border between sub-tropical and warm–temperate. Shanghai is located at the mouth of a major river (the

Yangtze), and all are coastal cities with significant areas just above sea level. Two of the cities, Mumbai and Shanghai, are subject to hurricane (tropical cyclone) landfalls at least once a year.

We focused on collecting data in the categories shown in Table 1 to explore climate hazard vulnerability for these three global cities. Note that data on stresses and perturbations include both climate and social components, some of which arise endogenously to the system. Likewise, system characteristics include elements of physical geography and built infrastructure, coupled with socioeconomic conditions that include what we term endowments, and coping abilities (both direct and indirect).

Figure 2. Projected changes in temperature by city and season



Source: Goldberg, Richard (2001), Goddard Institute for Space Studies, New York, NY

Table 1. Data collected to test the expanded vulnerability framework

Stresses/perturbations		System characteristics		
Climate-related	Temperature increases	Physical environment		Topography/bathymetry
	Extreme rainfall/flood			Geology
	Drought frequency			Current/recent climate
	Wind speeds			Wetlands/low-lying areas
	Sea-level rise	Infrastructure		Domestic water needs
Socioeconomic	Population growth			Industrial water needs
	Economic downturn			Sanitation/waste disposal
	Globalization	Socioeconomic conditions	Endowments	Income/poverty rates
				Education
				Health care
			Direct coping abilities	Early warning system
				Evacuation plan
				Disaster management plan
				Appropriate zoning
				Dykes or other armaments
				Building codes
			Indirect coping (social capital)	Percent migrants
				Crime rate
				Single-parent households
				Voter turnout

		Households with secure tenure

a. Mumbai

Mumbai is the largest and most economically important city in India. Its 17 million people (1.7 per cent of India's total) contribute roughly 17 per cent of India's income tax and 37 per cent of India's corporate tax annually.(16) Mumbai hosts India's largest stock exchange, its largest high-tech centre, the world's most prolific film industry, the world's largest metro-suburban rail system and Asia's largest squatter community. Across the bay from the old city, Navi Mumbai (New Mumbai) is taking shape as the world's largest totally planned city. Unfortunately, with its downtown located on a flood-prone, poorly drained peninsula composed largely of landfill, Mumbai is highly vulnerable to climate hazards, as demonstrated by the extensive monsoon flooding of July 2005 that killed more than 1,000 residents. Among the most vulnerable are the approximately one-half of the city's residents who live in squatter communities, many of which are located in low-lying areas without adequate sanitation or water supplies. Finally, these vulnerabilities are compounded by Mumbai's location on several seismic faults, as well as its unsanitary methods for raw sewage and industrial waste disposal into the waters and air surrounding Mumbai.

i. Physical environment

The Portuguese were first attracted to Mumbai, known then as Bom Bahia ("good bay" in Portuguese), for its excellent harbour and the opportunities for trade with several communities on islands within the harbour. The British gained control of Mumbai (then Bombay) from the Portuguese in 1661 and, as trade and population increased, the need for additional land led to the filling in, between 1784 and 1845, of the shallow waters and tidal mudflats connecting the original seven islands with rock and dirt from the island's own hilltops. Today, most of Mumbai city centre, which includes the stock exchange, the main train stations and train lines, and numerous high rises, is located on landfill. The inland suburbs, where most of the population now lives, are located at higher elevations. However, much new settlement (industrial, residential and commercial) has occurred along the coastal areas of Greater Mumbai, which are low lying and flood prone.(17)

Mumbai's climate is tropical, with temperatures ranging between 16 and 33°C. Temperature and rainfall are strongly affected by the Indian monsoon, which normally starts in June and ends around the middle of September. Approximately 2,500 millimetres of Mumbai's 2,700 millimetres of annual rainfall comes at this time, with flooding common when spells of heavy rainfall coincide with high tides or storm surges. On 26 July 2005, the city received an unprecedented 944 millimetres of rainfall in a 24-hour period, resulting in the most devastating floods in recent history.

ii. Built environment

Mumbai has a diverse built environment with unique combinations of urban problems associated with its drainage system and its squatter communities, including building collapses, likely future water shortages and poor sewage disposal.

Drainage. Most landfill areas (i.e. most of the old city) are prone to flooding during the monsoon, especially when heavy rains combine with high tides or storm surges. Even in wealthy areas, drains are often blocked by trash and debris, and monsoon flooding often shuts down Mumbai's commuter rail lines, which are among the most heavily used in the world.(18) Flooding of this type would likely increase with sea-level rise, necessitating major upgrades in the drainage systems and possibly an elevation of major rail lines. Projects are already underway to upgrade the drains that run alongside the rail lines and to demolish squatter communities also situated alongside rail lines that contribute to clogged drains. However, this work was not designed with sea-level rise in mind. A national study ranking India's coastal zones according to their vulnerability to sea-level rise found Mumbai to be the most likely to experience damage.(19)

Squatter communities. It is estimated that 55 per cent of Mumbai's population lives in squatter communities, locally referred to as slums, roughly half of which are severely dilapidated. Many squatter structures are single storey and built of salvaged materials. Nevertheless, population densities for roughly one-half of Mumbai's squatter communities are estimated to be as high as 94,000 people per square kilometre, making it one of the most densely settled districts in the world. Mumbai's squatter communities suffer from inadequate access to potable water and sanitation, with the World Bank estimating that 170 persons depend on each public latrine in these areas, and that one-third of the 35,000 latrines in Mumbai are out of service.[20] As demonstrated in July 2005, even without sea-level rise, many squatter communities in Mumbai are already frequently flooded, as they are often located in low-lying coastal areas and along stream banks. Flooding is common even on the higher ground in Mumbai's squatter communities, as the large amount of refuse and debris in these areas tends to clog storm sewers, causing a backup of water that would otherwise run off or find its way into storm drains.[21] Landslides are another threat to squatter communities that are near or on the few hillsides in the city.

Historically, Mumbai authorities have dealt with the problems caused by squatter communities by demolishing them and forcibly relocating the inhabitants to new areas in the suburban fringe. Increasingly, non-governmental organizations (NGOs) are organizing to meet the needs of squatter dwellers for better access to sanitation and water, but their efforts are still limited in scope and their impact is quite small, especially with regard to some of the squatter communities most vulnerable to sea-level rise and flooding. This is because funding from the Indian government cannot be used in violation of zoning regulations that prohibit residential development in coastal areas.[22] While, in theory, restricting coastal zone settlements reduces settlement in vulnerable areas, in practice this has not deterred such settlement and has merely stalled efforts to make these areas less susceptible to damage and loss of life.

Drinking water/potable water capacity. Mumbai's water supply consists of several artificial rain-fed lakes located in the suburbs to the north of the old city. Their location on hills makes them less susceptible to impacts from sea-level rise, although their dependence on local rainfall (as opposed to canal systems or piping from other regions) means that increasing rainfall variability could threaten local supply. The World Bank's Bombay (Mumbai) Water Supply and Sewage Disposal projects, which were implemented between 1975 and 1995, increased the city's water supply from 984 to 2,460 million litres per day.[23] Yet, according to the Mumbai Metropolitan Region Development Authority, as of 1995 demand still outstripped supply by 23 per cent, and they have projected that total demand will exceed 7,940 million litres per day by 2011.[24] Antiquation, leaking and partially unmetered water delivery are cited by the World Bank as major problems holding back improvement of the city's water system.

Pollution. Both air and water pollution have been identified as major problems in Mumbai. The World Bank describes Mumbai's air pollution as "severe" and, with regard to Mumbai's water pollution, states that "…*about 75 per cent of all sewage is untreated and discharged to local waterways and coastal waters, causing extensive environmental hazard*."[25]

iii. Socioeconomic conditions

Endowments. While Mumbai has by far the largest concentration of wealth in India, it is unevenly distributed within the city. Per capita income, adjusted for purchasing power parity, is estimated to be three times the Indian average, or equal to US$ 6,600,[26] yet income distribution in the city is a major problem. In 1989, 62 per cent of households in the Mumbai Municipal Region (MMR) earned less than US$ 120 per month, and one-quarter of all households in the area were below the US$ 48 per month poverty line.[27] The unemployment rate is close to 15 per cent.[28] In 2001, the urban agglomeration's population was 16.4 million, and it is now estimated to be 17.7 million. By 2011, these figures are projected to rise to 22.4 million, with 12.9 million in the old city and its immediate suburbs, and 9.5 million in the rest of the MMR.

Direct coping. Mumbai is the headquarters for the State of Maharashtra Disaster Management Plan. An emergency operations centre (central control room) in Mumbai is the main hub for a network connected to a variety of sophisticated technologies aimed at emergency planning and disaster management. Multi-hazard response plans, financed by the UK's Department for International Development, are also in place in Mumbai as well as in six other centres across the state. There are multi-hazard response plans in place for each district, including risk assessment and vulnerability analysis with reference to earthquakes, floods and cyclones, epidemics, road accidents, fires, and chemical and industrial disasters. These systems also contain a multi-hazard response structure, capability analysis, inventory of resources, mitigation strategies, and a directory of personnel and institutions in the districts with their contact addresses, telephone and fax numbers.[29] Revi laments, however, that despite identifying flood risks and pinpointing vulnerable slums, no systematic action has been taken in the five years since the plan's development to mitigate the risk.[30] Moreover, the ongoing landfill projects of various Mumbai development authorities suggest that a prevention-oriented approach to disaster avoidance and reduction is lacking.

Regulations are in place that prohibit the location of new industries in the old centre city. This has been done in order to reduce congestion and pollution, and to discourage further dense settlement in this old portion of the city that has an antiquated built environment. These regulations have an added and, as yet, unappreciated benefit of decreasing settlement on landfill areas that are susceptible to flooding and potential shifting due to sea-level rise and increased storm frequency. However, some of the new settlements to which industries and people are being relocated are also in low-lying coastal areas that may be similarly susceptible to sea-level rise and storm surges.

Indirect coping. Despite its many chaotic qualities, Mumbai is socially highly organized, a quality that mitigates some of the city's vulnerability to natural hazards. The internationally known squatter organization, the National Slum Dwellers Federation (NSDF), is based in Mumbai. The NSDF received the prestigious Scroll of Honour from the United Nations Human Settlements Programme for its work in the collective design and construction of low-cost houses and toilets, improving environmental sanitation in ways that can help mitigate the disease impact during and after flooding.[31] The NSDF has more than 90 housing projects that are either built or underway, providing housing for more than 35,000 households.[32] The NSDF and similar organizations in Mumbai have built strong partnerships between poor communities, NGOs and various levels of government.[33]

Despite the existence of slum federations, Revi decries the "institutionalization of disparity" in Mumbai, citing a decline in the quality of law enforcement and justice institutions and a rise in organized crime and terror networks. He cites the income disparity, one manifestation of which is the over-priced land market that contributes to the spread of informal settlements, as a significant vulnerability.[34]

Another important aspect of Mumbai's social support system is the city's ability to garner resources from abroad. As the wealthiest and most cosmopolitan city in India, and as the centre of India's film industry (the world's largest in terms of output), Mumbai looms large in the minds of Indians living abroad. This community is recognized throughout India as a key to the country's overall development, and Mumbai's unique ability to broadcast its problems and needs to this community abroad may prove an important factor in reducing the impacts of climate hazards on the city. This may be especially true in the case of dramatic perturbations, such as sea-level rise and associated flooding, which could threaten Mumbai's status as the leading city of India.

iv. Likely future climate hazards and overall vulnerability assessment

The Canadian Climate Centre's A2 (business as usual) and B2 (sustainable path) scenarios predict an average annual temperature increase of 1.75°C and 1.25 °C, respectively, by 2050 (Figure 2). This increase is similar to that predicted for Rio but lower than the increases in New York or Shanghai. Mumbai is predicted to have an average annual decrease in precipitation of two per cent for the A2 scenario and an increase of two per cent for the B2 scenario. The predicted sea-level rise of 50 centimetres by 2050 could prove seriously damaging for Mumbai.

Potential impacts of precipitation extremes. The A2 (business as usual) scenario may engender water shortages in Mumbai, given the city's complete dependence on locally stored rainfall for its water supply. The fact that both scenarios predict a decrease in rainfall during the first part of the year (January–August) suggests that droughts will become more common in the MMR, although predicted reductions during the monsoon season are less dramatic. Furthermore, both scenarios show an increase in rainfall from September to November, which may mitigate water shortages from reduced monsoons. If droughts do increase in severity, this could trigger migrations from surrounding agricultural areas (a common occurrence during drought years), which could tax the city's resources in the context of multiple climate change impacts.

Coastal/marine issues. A 1996 TERI study put the cost to Mumbai of a one-metre sea-level rise at US$ 71 billion.[(35)] The study concluded that US$ 24 million invested in protection against sea-level rise would reduce the economic impact by about US$ 33 billion dollars. The predicted rise in sea level of 50 centimetres, together with storm surges, would render uninhabitable the coastal and low-lying areas where many squatter communities are located. Moreover, shifting would likely occur in the sub-surface of the landfill areas, resulting in many buildings becoming uninhabitable due to structural instability. Mumbai's landfill areas contain a mixture of high value commercial properties, such as the stock exchange, important public facilities, such as the main train stations and train lines, numerous high value residential high-rises and a number of squatter communities. The few hills, formerly islands, that were not levelled to create the landfill that the majority of the city was built on, comprise mostly upscale residential areas long-prized for their relative immunity to flooding. These areas lack the commercial potential to take up slack should the landfill areas go into decline. However, provided that sea-level rise occurs gradually, and is recognized early enough, Mumbai might be able to mitigate damage, perhaps by shifting much of the old city to the adjacent suburbs or to Navi Mumbai.

Overall vulnerability. What emerges from using the extended vulnerability framework is the identification of a set of stresses and perturbations that collectively converge to create great "stress bundles" for Mumbai. An example is the convergence of extreme rainfall and floods. Mumbai's various characteristics of topography (flat), geology (unconsolidated fill material), numerous wetlands and flood-prone areas, the city's building conditions (not meeting building codes, squatter dwellings, previously flood-damaged buildings), poor sanitation and poor waste treatment and removal capabilities together create a particular "bundle" of stresses that "collides" with the set of socio-environmental conditions of Mumbai, such that vulnerabilities emerge for the system.

In addition, a "stress bundle" composed of population (large and growing), projected sea-level rise, and economic stresses converge to create some particularly problematic issues for Mumbai. This is because of a set of characteristics for Mumbai that include the lack of dykes and other coastal armaments for dealing with sea-level rise, weak disaster preparedness at the scale of sea-level rise, building conditions (not meeting building codes, squatter dwellings, previously flood-damaged buildings), and low incomes that do not allow the city to improve building conditions to the level required, nor to better develop and fund disaster preparedness. Mumbai is thus facing threats that local authorities have very little ability to control, dampen or mitigate. This suggests that a reinforcing spiral could emerge for this set of issues, where increasing population comes together with sea-level rise and a stressed economy to further damage already weak buildings, undermine efforts to improve disaster preparedness and build coastal armaments; and these, in turn, further erode the economy while sea-level rise marches on. Mumbai's informal coping capacities, as a result of notably strong social networks and cooperation, emerge as important parts of Mumbai's resistance and resilience in the face of stresses. These informal coping systems are expected to help reduce vulnerabilities to some degree for both sets of issues that emerge from this preliminary analysis. Yet, by themselves, these informal coping capacities appear quite inadequate to meet the challenges from climate hazards and population size and growth that now face Mumbai.

Mumbai's overall vulnerability appears to be high. While the city is relatively prosperous compared to the rest of India, and it does have an elaborate disaster management plan in place, the challenges posed by climate change, especially flooding and sub-surface shifting in landfill areas, are unlikely to be met effectively. In particular, sub-surface shifting of the type that Mumbai might face could well overwhelm the adaptive abilities of any city, and particularly one with some of the other critical issues that Mumbai now faces.

b. Rio de Janeiro

Rio de Janeiro is a city of just over 10 million people located on the southeastern coast of Brazil, and covers an area of 1,171 square kilometres. Guanabara Bay, where Rio is situated, faces almost due south. Rio is the second most populous city in Brazil, after São Paulo, and ranks second only to São Paulo in industrial production. This erstwhile capital of Brazil is known for its beautiful beaches and the granite hills that rise dramatically from sea level to more than 1,000 metres. Yet Rio faces significant environmental sustainability challenges stemming from unregulated settlement in hazardous areas, sewage disposal and industrial wastes. These will be exacerbated by potential climate changes.

i. Physical environment

Rio's dramatic topography has made it more prone to certain types of hazard. When the Portuguese discovered Guanabara Bay in 1501, the coastal mountains were carpeted in thick Atlantic rainforest. As this protective covering has been progressively stripped away to make room for settlements, the thin soils have become prone to landslides, and the granite and gneiss bedrock has been left exposed to weathering, making it more prone to decomposition and erosion.

The coastline in this area was characterized by lagoons, estuaries and low-lying coastal marshes, many of which have been filled in. The flat topography of low-lying areas, combined with a lack of drainage, has continued to result in flooding during the summer rainy season (January–March). The few remaining lagoons, mangroves and marshes have been affected by sedimentation, reducing their absorptive capacity during extreme rainfall events. Ninety per cent of mangroves surrounding Guanabara Bay have been removed, and intense sedimentation has resulted in the need for dredging to maintain shipping lanes. Rio's beaches, a major tourist asset, are subject to intense erosion during storms (with up to five metres recession), but usually recover quickly through the deposition of sand laterally along the coast.[36] Significant resources are also expended on beach nourishment following intense erosion.

The climate in Rio is moderated by the coastal effect, its southern exposure, and the mountain ranges to the north. The mountain ranges block cooler northeasterly winds during the winter months and enhance orographic precipitation during the summer months, when winds are predominantly southwesterly. Rio experiences wet summers (December–March), with an average temperature range of 24–26^{o}C, and dry winters (June–September), with an average temperature range of 20–22^{o}C (Figure 3). Maximum temperatures rarely exceed 42^{o}C. From year to year, precipitation ranges between 1,200 and 1,500 millimetres, and evaporation between 800 and 1,200 millimetres.

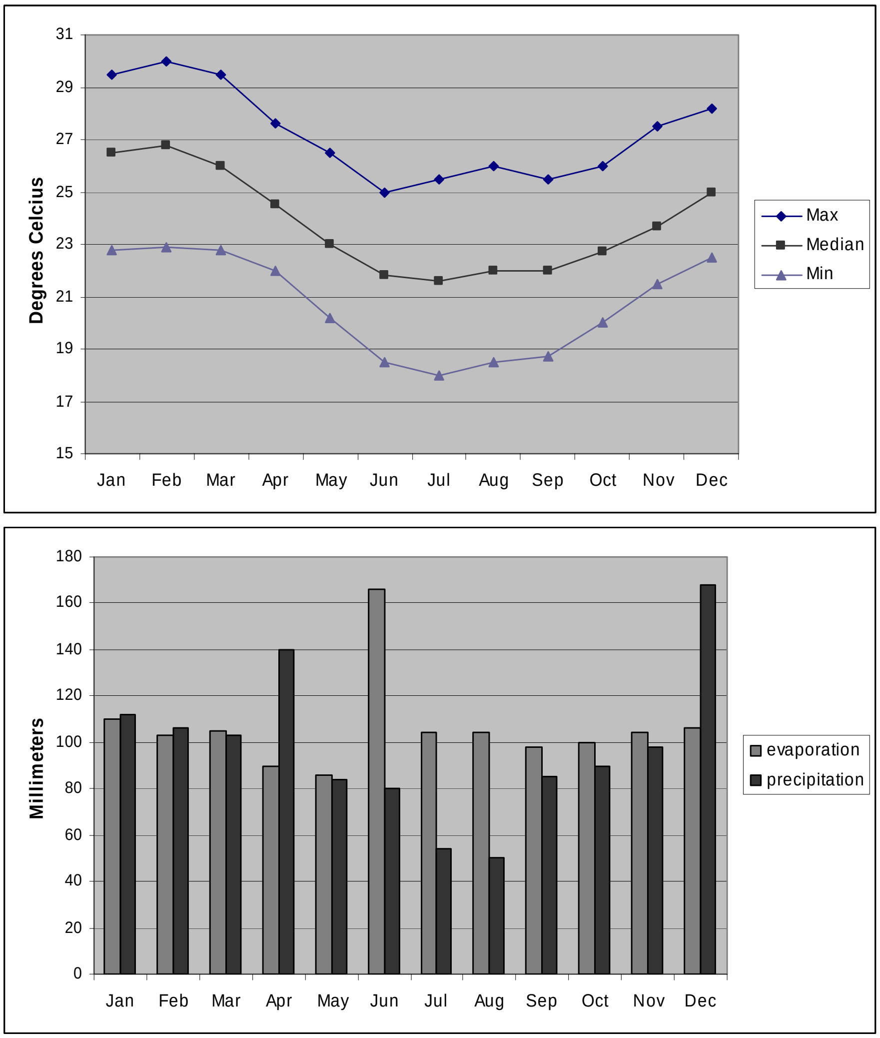
Rio has never been impacted by tropical cyclones, although this may change. The first recorded South Atlantic hurricane reached land in the state of Santa Catarina in March 2004, suggesting that what was once thought to be a meteorological impossibility is no longer so, with global warming-induced increases in regional sea surface temperatures.[37] The city receives a strong El Niño–Southern Oscillation (ENSO) signal, and during El Niño years the city receives higher then normal precipitation during the summer months. During one recent El Niño year, 1988, the city was affected by severe floods as a result of two intense periods of rainfall in early February that produced a total of 480 millimetres of rain, one-third the annual total rainfall.

ii. Built environment

Rio's peculiar geography, and the circumscribed nature of suitable building sites, has spawned two kinds of response. One is the construction of high-rise apartments close to the coastline (e.g. Copacabana, Ipanema and Leblon) and in flood-prone areas further inland; the other is unregulated construction on steep slopes, particularly on the Tijuca mountain range. The unregulated construction of *favelas* (shanty towns) has a long history, and stems from the invasion of both private and public urban lands by poor urban squatters who become de facto (and in some cases de jure) owners of plots of land.[38] Many *favelas* have evolved over time from ramshackle collections of wooden shacks lacking even the most basic amenities to organized communities of largely concrete housing with cemented walkways, electricity, plumbing, sewerage and other services.

Although *favelas* have always suffered during rainy seasons, the paving of walkways has had the effect of increasing runoff to the point where water is often ankle or knee deep between the houses. Runoff from communities on steep hillsides, including Petropolis and *favelas* on the Maciço da Tijuca massif, are channeled down cemented and quasi-natural watercourses to the narrow coastal lowlands, where they join canals whose limited flow capacity causes frequent flooding. By contrast, the Baixada Fluminense, a large marshy lowland somewhat removed from the steeper parts of the city, has had reasonably adequate drainage since the 1930s.[39]

Figure 3. Temperature (top) and hydrographs (bottom) for Rio de Janeiro



Temperature does not vary significantly through the year. In contrast, the hydrograph shows that precipitation is greatest in April and December, whereas potential evapo-transpiration greatly exceeds rainfall from June through August (the southern hemisphere winter months).

Source: Instituto Nacional de Meteorologia (INMET)

In terms of services, the city has a reasonably clean and reliable water supply that is piped in from rivers in the state of Minas Gerais to the north. Over 84 per cent of the population is supplied with water. Eighty-three per cent have their own sanitary installations. Ninety-four per cent of the population has access to electricity supply at home. Electricity is largely generated by Brazil's major hydroelectric facilities, which supply 92 per cent of the country's electricity needs. A drought in 2001 led to electricity shortages throughout the country, and consumers in Rio de Janeiro were ordered to cut consumption by 20–25 per cent.

Waste disposal is a significant problem. Trash disposal for *favelas* remains haphazard, with some estimates that 5,400 tons per day or more end up in rivers and drainage channels, blocking channels during peak flow.[40] This compares with 7,000 tons per day that end up in city dumps, mostly on the margins of Guanabara Bay. Daily discharges into the bay include 465 tons of organic matter, 68 tons of which receive adequate treatment, and 9.5 tons of oil. The Iguacu and Estrela rivers, which drain the bay's watershed, are often anoxic and produce a strong hydrogen sulfide smell.[41]

Guanabara Bay is surrounded by a mix of industrial and residential land uses. As the second largest industrial zone in the country, it has 10,000 industries, 10 oil terminals, 12 shipyards and two oil refineries. Petrobras, the Brazilian oil company, has numerous off-shore drilling platforms near Rio, and uses Rio as its primary distribution point. A giant causeway crosses the bay, leading to Niteroi, and two airports are located just above sea level on the margins of the bay.

iii. Socioeconomic conditions

Endowments. Although Rio's product per capita is roughly double the national average, its income distribution is highly skewed. The existence of pockets of extreme poverty side-by-side with some of the most affluent neighbourhoods is characteristic of the city. Rocinhas, among the oldest and largest of Rio's *favelas*, clings precariously to the steep slopes of the Tijuca mountain range just above Gavea, one of the city's wealthiest neighbourhoods. It is estimated that 1.1 million people live in *favelas*, or 20 per cent of the municipality's population.

According to the 2000 census, the population of Rio metropolitan area is 10.9 million, with 5.8 million residing in the municipality.[42] Population density in the latter is 4,640 persons per square kilometre, but densities in the smaller administrative units of the metro area are between 8,000 and 12,000 persons per square kilometre, indicating that some parts of the city have significant population concentrations. Although rapid population growth of 3.8 per cent was predicted for the 1990s, the recent census figures suggest that the rate may have been slower. Corrêa do Lago notes that the metro area received 758,000 migrants between 1970 and 1980, but that between 1980 and 1991 the number had decreased by 24 per cent to 573,000.[43] It is possible that continued declines in migration account for the somewhat lower than expected overall population growth. The 2005 estimated population of the municipality was 6.1 million, a one per cent growth rate between 2000 and 2005.

Direct coping. The state of Rio de Janeiro has a 15,000 member Civil Defense, which includes the fire department, emergency medical services, sea rescue services and the community relief department. Brazil's State Environmental Engineering Foundation (FEEMA) is responsible for coastal monitoring and land use zoning in the state. Baptista de Araújo urges more micro-planning for disaster management such as occurred under the Rio Reconstruction Project, which was implemented in the wake of the 1988 floods.
In terms of zoning, until recently there was little effort to segregate industrial or waste disposal activities from residential areas. This could result in potential vulnerabilities, particularly should flooding lead to the dispersion of pollutants to surrounding areas. New regulations have been put in place that restrict building in hazard-prone areas and, according to Kreimer et al., "…*major emphasis has been placed … on command and control mechanisms to regulate urban growth*." Efforts to "regularize" *favelas* have also been underway for several years, with various government programmes to undertake cadastral surveys, grant deeds to de facto owners and provide basic infrastructure. These same plans limit the further expansion of *favelas* in flood-prone or steeply sloped areas.

Indirect coping. There are several issues that weaken Rio's indirect coping capacity. These include official corruption and political tensions between federal, state and municipal governments; and large migrant communities with low security of tenure, decreasing levels of social cohesion and low levels of education.

Geddes and Ribero Neto write of the widespread corruption during the Collor administration.[44] According to them, the weakening of the executive branch's ability to build coalitions and assure the loyalty of supporters in Congress created strong incentives to exchange material benefits (in the form of public works projects) for congressional support. Unfortunately, for those jurisdictions (such as Rio de Janeiro) that had leaders in rival political parties, this led to the denial of federal financing for public works projects and even problems in the implementation of disaster relief programmes. Allen describes how political wrangling between federal, state and municipal authorities negatively affected relief and reconstruction efforts after the floods of 1988.(45) She writes:

> "…political rivalry between state and municipal government, between both of them and the federal government, and even at managerial level within the Caixa Economica Federal, exacerbated problems of project implementation, involving an 18-month delay in starting the reconstruction plan."

However, clearly the political landscape has changed significantly since then, and recent evidence suggests a more cooperative atmosphere.

Rio has a large migrant population from the poorest parts of Brazil's arid northeast region. The fact that many of them do not have personal experience with mudslides or mass wasting may account for their building practices. Migrants move up hillsides in search of new land, consistently eating away at the vegetation cover on the slopes above the *favelas,* despite government efforts to cordon off such areas to prevent further development. Improved local environmental knowledge and an understanding of slope dynamics might cause *favela* dwellers to reconsider such activities.

Rio de Janeiro has invested more than US$ 600 million in its Programa Favela Bairro to improve access to basic infrastructure, health and education for half a million of its poorest residents.(46) In terms of social cohesion, the *favelas* do have some rudimentary organization, including neighbourhood watches and self-improvement societies. However, the level of cohesion has apparently declined over time as the levels of drug-related crime and violence have increased. One observer speaks of the prevalence of young, predatory gangs, which contrasts with the kinds of gangs that, at one time, had a sense of allegiance to *favela* residents, and would even provide protection for their own.(47)

iv. Likely future climate hazards and overall vulnerability assessment

The Canadian Climate Centre's A2 (business as usual) and B2 (sustainable path) scenarios predict roughly equal average annual temperature increases of 1.5^{o}C by 2050 (Figure 2). This increase is about the same as that predicted for Mumbai, but is lower than that for Shanghai. Unlike the other cities, the same approximate 1.5 ^{o}C increase is predicted across all four seasons. As mentioned earlier, projected precipitation changes are less reliable, although Canadian A2 and B2 scenarios suggest declines of 7 per cent and 2.5 per cent, respectively. Sea-level rise, as mentioned earlier, is predicted to be in the order of 50 centimetres by 2050.

Potential impacts of precipitation extremes. Given the potential decreases in precipitation during winter and/or spring, it is likely that these seasons will suffer from increased drought. Summer months may also experience drought, as evapo-transpiration increases due to increased temperatures with no offsetting increases in precipitation. Drought conditions could precipitate two kinds of problem. One is water scarcity, particularly if the droughts extend into the Paraíba River basin in Minas Gerais, from where Rio obtains the majority of its water. The other is electricity shortages, as were recently experienced throughout the country in 2001.

Although average precipitation during the summer rainy season may decline, increases in sea surface temperature and in the severity of El–Niño/Southern Oscillation (ENSO) events could result in periodic flooding of the kind encountered during February 1967, and again in February 1988. The 1967 floods were even more extreme than those in 1988 – 1,985 millimetres fell over two days (83 per cent higher than average annual rainfall).(48) Generally, precipitation extremes are expected to increase in severity with climatic change, and these will have adverse impacts on Rio, given that the city already experiences extreme flooding on a 15–20 year basis. Poor neighbourhoods are particularly vulnerable to this kind of flooding; roughly 300 people died and more than 20,000 people were made homeless during each of the floods in 1967 and 1988.

Coastal/marine issues. Rio does not suffer from subsidence, so this will not exacerbate sea-level rise. However, should sea-level rise be coupled with more extreme coastal storms, there is significant likelihood of increased beach erosion, which will affect nourishment costs and could ultimately impact the tourism sector of the economy.[49] However, Muehe indicates that it is unlikely that high-rise apartment buildings in Copacabana and Ipanema will be directly impacted by a rise in sea level of 50 centimetres, even in the event of storm surges.[50]

As mentioned above, Guanabara Bay has lost most of its coastal mangroves, and significant portions of coastal marshes have been filled in. The potential for mangroves or marshes to retreat inland with rising sea level is impeded by the concentrated development along the coast. This will reduce the capacity of the few remaining wetlands to act as buffers during storm surges.

Rising water temperatures may precipitate algae blooms in Guanabara Bay, especially if no effort is made to treat discharges into the bay.

Overall vulnerability. We find that there are three stress bundles that are particularly troublesome for Rio de Janeiro. Each converges with a particular set of system characteristics to produce vulnerabilities that result from gaps in Rio's socio-ecological system and which do not allow it to withstand, respond or cope effectively with these predicted stress bundles.

Temperature increases come together with drought to put stress on Rio's drinking water supply. In addition, problems with governance exist that could further hinder the city in developing more robust potable water storage and delivery systems. Extreme and unpredictable rainfalls and floods converge with projected sea-level rise to increase stresses which will be difficult for Rio to handle owing to the city's topography (narrow coastal shelf backed by steep mountains subject to mass erosion), poor building conditions, the lack of secure land tenure for a notable portion of the city's population, poverty coupled with large income inequalities, high rates of crime that reduce social trust, and large problems with sanitation systems and sewage disposal.

Lastly, sea-level rise converges with the tourism-based economy of a beach city to create a third stress bundle of great importance to Rio de Janeiro. Because of Rio's characteristically narrow beach, which is backed by steep slopes and mountains, modest increases in sea level will likely magnify sand erosion. In addition, Rio has no dykes or other armaments that could protect the beach from modest sea-level rise, or even from great storm surges. This situation illuminates a gap between the stress bundle and Rio's ability to resist or cope with it. Because of Rio's economic dependence on beach tourism, such damage will likely have reciprocal effects on the economy, thus creating additional stress on the city.

Based on this preliminary assessment, we conclude that Rio suffers from a significant ongoing vulnerability to climate hazards, particularly flooding and landslides. Although civil defense institutions have been set up to cope with natural disasters, underlying structural problems, including political clientelism and spatial segregation based on income, render the city vulnerable to climate hazards. Little in the way of concrete flood protection infrastructure has been set up in the wake of the 1988 floods. It is possible to speak of highly vulnerable sub-populations living in *favelas* and near waterways, and relatively less vulnerable upper classes living in high-rise apartments in locations less susceptible to inundation. At the same time, climatic changes are predicted that will likely increase the severity of intense rainfall events and raise sea level. Although the economy of Rio de Janeiro is relatively robust, significant portions of GDP will be required for relief and reconstruction if floods of the magnitude of 1967 and 1988 are repeated. Unless more concerted efforts are made to prepare for climate hazards, the city will remain vulnerable.

c. Shanghai

Shanghai ("on the sea" in Chinese) is one of the world's largest seaports and a major industrial and commercial centre of the People's Republic of China. It is located at 31^{o}41' latitude north and 121^{o}29' longitude east. Bordering Jiangsu and Zhejiang provinces to the west, Shanghai is washed by the East China Sea to the east and Hangzhou Bay to the south. North of the city, the Yangtze River (or Changjiang) pours into the East China Sea. The municipality covers 6,185 square kilometres, which includes the city itself, surrounding suburbs and an agricultural hinterland. It is also China's most populous urban area, with a 2000 population of more than 16.5 million inhabitants in the municipality and almost 10 million in the city proper.

i. Physical environment

With the exception of a few hills in the southwest corner, most of the Shanghai area is flat and is situated on the alluvial plain of the Yangtze River delta. Shanghai's elevation is only 3–5 metres above sea level and averages four metres. There are no high mountains in the surrounding area, and the Jiangshuai and Huabei plains extend northwards. Cold air masses from the north and moist, warm air from the south meet and mix above Shanghai with no topographical hindrance.[(51)]

Geologically, the Shanghai area lies in the northeast section of the southern Changjiang land mass. Since the beginning of the quaternary era, this area has undergone tectonic subsidence and global marine transgressions and regressions. With the exception of the west, where there are several scattered stripped kops (igneous Mesozoic rocks), most of the area is covered by unconsolidated sediments, including fluvial, lacustrine and littoral facies that range in thickness from 100–150 metres in the west to 350–400 metres in the east.[(52)]

Being located at the mouth of the Yangtze River, the Shanghai region is very much the product of riverine and marine processes. The evolution of the landscape has been deeply influenced by local hydrodynamics, especially tidal flows and runoff. The Yangtze is a major river, with a yearly discharge of 9.24×10^{11} cubic metres, and carries an annual sediment load of 4.86×10^{8} tons. These sediments feed the delta's continued seaward expansion. The basin drains a humid region, with an average annual precipitation greater than 1,000 millimetres, rising to 2,000 millimetres in certain localities.[(53)]

The Shanghai area experiences a sub-tropical monsoon climate. Frequent summer and autumn typhoons bring not only rainstorms that greatly increase surface runoff, but also cause storm surges in coastal areas. Both significantly modify the geomorphic evolution of the coastal area, as illustrated by typhoon Number 14 that occurred in 1981. This typhoon created high tidal flats while simultaneously strongly scouring middle and low tidal flats along the local coast. Waves produced by strong northeast river mouth winds can also cause significant coastal erosion, which lowers the surface of the tidal flats and promotes shoreline recession.

ii. Built environment

Shanghai utilizes the uniform system of classifying urban land use and codes, created by the Construction Ministry, to structure different land uses. Typically, the centres of large cities have high population densities. In the central districts of Shanghai, residential land use occupies 30.1 per cent of the area. Good and normal residential quarters (codes R2 and R3) account for 82.4 per cent of this residential land, while high-quality residential quarters (code R1) and poor-quality residential quarters (code R4) represent only 2.7 and 12.6 per cent, respectively.

In the central urban area, there are 13.4 square metres of residential land per person, which equates to a housing density of 74,600 persons per square kilometre. The proportion of land devoted to industrial and warehouse use is 22 per cent.

The Huangpu River is Shanghai's main source of water. There are over 30 waterworks in Shanghai, 11 of which are located in the urban district along the Huangpu River. Five million tons of tap water are supplied to the urban district every day. Each suburban county also has one or two waterworks. Water resources are used in three significant ways in Shanghai, namely industry, agriculture and public water use, in a ratio of 3:6:1. Even in a dry year, such as 1988, consumption was only 12 billion cubic metres, that is, about 19 to 22 per cent of the available water.

One of the serious water resource problems is the over-exploitation of groundwater resources in the surrounding agricultural lands, which has caused significant subsidence.[(54)] Since 1921, groundwater has been exploited on a large scale. Because recharge is slow, the water table has fallen and soil moisture has dropped, leading to compression. During the period 1921–1965, mean subsidence in the city of Shanghai was 1.76 metres, and the highest recorded figure was 2.63 metres. This process of subsidence has encouraged greater intrusion of seawater into Shanghai's waterways, thus decreasing their quality. Since 1965, the level of groundwater exploitation has been reduced, and aquifer-recharging projects have been carried out. As a result, subsidence was reduced to as little as a few millimetres a year; however, since 1984, with the development of new industry in suburban counties, the exploitation of groundwater has increased again, with no adequate control.

iii. Socioeconomic conditions

Endowments. Shanghai has 9.8 million residents in the city proper and an average residential density of 74,600 persons per square kilometre. Owing to stringent application of the "one child" family planning policy, in 1993 Shanghai was the first area in China to report a negative natural growth rate (births minus deaths). The city registered a negative population growth rate of -1.9 per thousand in 2000, based on a birth rate of 5.3 per thousand and a mortality rate of 7.2 per thousand. However, rapid rates of in-migration more than make up for declining fertility.

Perhaps the biggest single endowment is the city's burgeoning economy, coupled with its pre-eminent status as China's financial capital. Thus, whatever the threats that may exist in the way of subsidence and sea-level rise, the government of China and the local authorities are likely to make whatever investments are required in order to build coastal defenses.

Direct coping. In August 1998, China experienced devastating floods when the Yangtze River overflowed, causing more than 3,000 deaths, affecting 223 million people, displacing 16 million people, flooding 25 million hectares of crop land and causing US$ 36 billion worth of damage.(55) Heavy rainfall in 1999 also caused flooding, although less extensive. This put disaster management institutions to the test.

Shanghai has a Municipal Civil Defense Office, which cooperates with the Public Security and Fire Protection agencies. In addition, 284 streets and counties have civil defense organizations which, in turn, organize communities into volunteer civil defense teams.(56) According to UN Secretary-General Kofi Annan:

> "In China, where extensive disaster control policies have been introduced over the years, the death toll from floods has fallen dramatically. Flooding cost more than 3,000 lives in China in 1998, but similar floods in 1931 and 1954 cost 140,000 and 33,000, respectively. Prevention strategies saved tens of thousands of lives."(57)

Among the prevention strategies employed are massive afforestation and reforestation campaigns in the Yangtze River basin to reduce runoff and prevent flooding and landslides, as well as dyke construction.

Although such responses have demonstrated a commitment by national, provincial and municipal authorities to disaster mitigation and preparedness, there are underlying structural impediments to disaster management that are very similar to those found in Mumbai and Rio. These include fragmentation of political authority at central government, provincial and municipal level, and lack of coordination in the areas of environmental policy.(58)

Indirect coping. Shanghai's population, at close to 17 million, is largely poor, and is composed of an increasing number of migrants from rural hinterlands. Official statistics do not provide a clear picture of income and wealth distribution, or measures of social cohesion in Shanghai. However, broader trends in China suggest that disparities are increasing in urban areas, that urban unemployment is rising, and that the *hukou* system of household registration is limiting access to benefits.(59) While inequalities may be rising and social cohesion may be low in areas settled predominantly by migrants, official efforts have been made to involve citizens in disaster response.

Since 1993, Shanghai's natural population growth has reversed from positive to negative, making it the first provincial region in China to experience this phenomenon. Low birth rates could engender population aging, and a growing elderly population could imply vulnerability to heat stress. High immigration means that the base of the population pyramid is continuously being replenished. As of the 2000 census, 3.8 million migrants resided in the city.

iv. Likely future climate hazards and overall vulnerability assessment

Temperature changes for Shanghai suggest that the city will be the most severely affected of the three cities considered here, with average annual temperature increases of between 2 and 2.5^{o}C. This will have an impact on evapo-transpiration and, consequently, on the moisture balance. Temperature changes will also likely lead to more severe extra-tropical storms and consequent flooding. However, the greatest issue of immediate concern for Shanghai is flood defenses in response to subsidence, sea-level rise and the likelihood that future extreme precipitation will cause flooding from the Yangtze.

Overall vulnerability. As in Mumbai and Rio, recent and severe flooding has tested Shanghai. Perhaps given the magnitude of the city's losses (3,000 dead and 16 million displaced in the Yangtze basin, against 300 dead in Rio), the government appears to be taking a genuine interest in long-term disaster planning. The municipality has also engaged citizens in "volunteer" civil defense networks, which presumably means that citizens know what to do in the event of disaster and are prepared to take action.

Nonetheless, several key bundles of stress converge to create specific vulnerabilities for Shanghai that emerge out of gaps in the city's ability to resist and cope with these stresses. First, sea-level rise along with increasing severity and frequency of heavy rains and floods come together with Shanghai's topography (level and low lying), geology (unconsolidated), land subsidence due to groundwater withdrawal, many wetlands and flood-prone areas, the inability of many buildings to withstand shifting land and water damage due to their poor condition, sanitation and waste disposal systems that are near capacity, and relatively modest income levels. This mix is likely to produce significant vulnerabilities for a large proportion of the city's residents, the city's built infrastructure and the Shanghai region's economy. Second, Shanghai's population is already large and continues to grow rapidly. When this massive trajectory comes together with projected sea-level rise and increasing water use by the city, this exacerbates land subsidence, probably puts greater numbers of people in harm's way from climate hazards and coastal erosion, and places people in greater concentration within areas that are likely increasingly flood prone. This set of circumstances may lead to a diminishing capacity for Shanghai to cope with such stresses because of its burgeoning population on already vulnerable lands, and a greater draw down of groundwater, causing densely populated lands to subside while sea level continues to rise. This could lead to increases in direct mortality, economic downturn and, potentially, large-scale disease outbreaks. On the other hand, as noted above, Shanghai's wealth means the city has a high adaptive capacity. Resources will likely be invested in technological solutions even if such solutions fail to address root causes of vulnerability.

IV. DISCUSSION AND CONCLUSION

The foregoing sections provide a snapshot of vulnerabilities to climate-related hazards in three global cities. Our aim here was not to assess definitively the vulnerability of each of these cities but instead, to apply a selection of data identified by the vulnerability framework in order to better understand multiple, synergistic stresses and perturbations on one side of the equation, and multiple, interacting physical and social characteristics of the exposed human–environment system on the other side. Vulnerabilities that may have been hidden with simple "summations" of stresses when compared with "summations" of vulnerabilities, were instead highlighted with this process.[60] A novelty of this paper is that we apply a more traditional approach to vulnerability assessment – using scenario-based models to assess likely climate impacts, or a "top-down" approach – and couple this with more recent advances in vulnerability mapping through "bottom-up" assessments.[61] The result is something of a hybrid, which facilitates an understanding of likely future climate impacts while assessing the resilience of the current socio-ecological system in the face of bundles of stresses that are partly related to climate impacts and partly related to fragilities in the system itself.

From a policy perspective, there are few easy prescriptions for reducing vulnerability and better preparing for future climate hazards, at least in the case of the low-income country cities we describe above. Among other things, this may be attributed to the following factors:[62]

- Disasters are an unequally distributed public "bad" that is more likely to affect poorer, more vulnerable sub-populations with the least political influence. Mitigation measures, by contrast, are a public "good" that require substantial investment and adequately functioning institutions.

- Low tax collection capacity and low incomes constrain the resources available to government to make necessary infrastructural or institutional investments. Government resources themselves may become highly contested through political manoeuvering (as in the case of Brazil).
- The wealthy and more influential classes may simply choose to "exit" from political decision-making processes rather than voice their concern over the lack of disaster preparedness. "Exit" means that they opt out of public resources and, instead, choose to invest in their own capability set (e.g. purchasing a well-built home in a safe location, insurance policies, or private education and health care).
- Adaptation measures are difficult to implement because they require long time horizons, whereas politicians typically operate on short-term horizons. Incentives need to be intelligently designed so that politicians, officials and the private sector find it in their interest to build less risk-prone equitable cities.[(63)]
- If vulnerability mitigation/prevention measures are expensive, there may exist a "moral hazard" on the part of state decision makers, as they may assume that the international relief community will come to their assistance in the event of a significant natural disaster. Thus, to act means committing scarce public resources for a medium- or even low-probability future event, whereas to "wait and see" if disaster strikes, and later claim that the disaster could not be foreseen, shifts the financial burden onto international agencies.

The authors do not underestimate in any way the difficulties entailed in preparing adequately for future climate change-related vulnerabilities. Given these political and institutional issues, it is worth considering how communities themselves, through micro-planning or other efforts at collective organization, might develop plans and infrastructure necessary to reduce their vulnerability to natural disasters in contexts in which governments either lack the resources or are unwilling to consider investments in preparedness.[(64)] Many efforts to improve local environments, such as enhanced drainage and improved waste disposal, also reduce vulnerabilities to disasters and their consequences (such as the spread of disease).

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[59] A *hukou*, or household registration record, officially identifies a person as a resident of an area, and includes identifying information such the name of the person, date of birth, the names of parents, and name of spouse, if married. See McGranahan, Gordon and Cecilia Tacoli (2006), "Rural-urban migration in China: policy options for economic growth, environmental sustainability and equity", Working Paper No 12, Rural–Urban Interactions and Livelihoods Strategies Series, IIED, London.

[60] We found some parts of the extended framework currently beyond our ability to gather appropriate data. This was particularly true when we tried to identify data on informal coping abilities for Shanghai. Informal coping, as we defined it, relies on surrogate measures of social cohesion, cooperation and social safety net. Such data, even though they are surrogate measures for such characteristics, were impossible to collect for Shanghai, and difficult to collect for Mumbai and Rio de Janeiro. While the extended framework includes much richness, it simultaneously begs for better data for the framework to be used to its full potential.

[61] For an example of the latter, see Adger, N (1999), "Social vulnerability to climate change and extremes in coastal Vietnam", *World Development* Vol 27, No 2, pages 249–269.

[62] Selected elements of this list are derived from Di John, J (2001), "An institutionalist political economy perspective of risk and vulnerability", presentation at a joint World Bank/Columbia University Workshop on Assessment of High Risk Disaster Hotspots, 6–7 September 2001, Palisades, NY.

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[64] Goethert, R and N Hamdi (1988), *Making Microplans. A Community-based Process in Design and Development*, Intermediate Technology Publications, London. In some instances, community preparedness is directly supported by the government, as in the case of Cochin in the state of Kerala, India. See Alungal, N B (2006), "Management strategies for urban coastal zones: integrating DPSIR concepts with GIS tools in people's participatory programmes", Paper presented at the Earth Systems Science Programme Open Conference, 9–12 November 2006, Beijing, China.