A Perfect Storm?
Climate, Weather and Demographic Changes in the Cities

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Summary. Global population projections indicate that cities will continue to grow rapidly at the expense of rural areas, much in the way that population patterns have already changed since the mid-1980s. Urban growth will be especially pronounced in the developing regions. At the same time, there is compelling evidence that Earth's climate is changing – in large part as a consequence of anthropogenic emissions of radiatively important trace gases. Computer model projections indicate these changes will continue for the foreseeable future, pending significant reductions in human-produced emissions. The recent report of the Intergovernmental Panel on Climate Change reinforces the sense that climate changes will be accompanied by changes in weather, and that there are indications that some climate-induced weather changes may already be happening. In the face of these pronounced changes in population, climate and weather, the importance of short-range weather forecasts and predictions will be even greater in the future. Especially vulnerable are the low-lying coastal regions where fully ten percent of the world population – 634 million people -- lives on just two percent of the world's land with elevation less than 10m msl. In the face of these ominous trends, urban forecasts and warnings still depend on observations and data from a surface-based observing system that is synoptic in design and is not well matched to the needs of accurate and precise, high-resolution weather predictions in the cities of today and tomorrow. This impending "perfect storm" – urban population growth and climate and weather changes – and the implications for public safety must be met in the future by the national meteorological services in partnership with non-governmental organizations, academia and private industry. Together they must implement advanced regional atmospheric observing systems that facilitate markedly improved warnings, forecasts and predictions of weather-related hazards of all types – severe weather, flooding, heat stress, poor air quality, wildfires and disease.

The Population Challenge.

The United Nations Population Division (UNPD, 2002) has prepared estimates and projections of urban and rural populations for major areas, regions and countries of the world for the period 1950-2030. Some say that a tipping point was reached in 2007 when the number of the world's urban dwellers was estimated to have equaled the number of rural dwellers. In 1950, only 30 per cent of the world's population lived in urban areas, but this had increased to 47 per cent by 2000. According to the UNDP report, the world's urban population reached 2.9 billion in 2000 and is expected to rise to 5 billion by 2030 when the urban proportion will reach 60 per cent. Virtually all the world's population growth during 2000-2030 is expected to be concentrated in urban areas. And almost all of the expected urban population increase will occur in the urban areas of the less developed regions whose population will likely rise from approximately 2 billion in 2000 to just under 4 billion in 2030. In the more developed regions, the urban population is expected to increase slowly, passing from 0.9 billion in 2000 to 1 billion in 2030. But, urbanization is already very advanced in the more developed regions where an estimated 75 per cent of the population lived in urban areas in 2000. Even so, the concentration of population in the cities of the more developed countries is expected to increase further so that 83 per cent of the inhabitants will be urban dwellers by 2030, as illustrated in Figure 1. By 2030, the urban percentage in less developed regions is expected to rise substantially to 56 per cent. By comparison, the less developed regions will reach a level of urbanization in 2030 that is similar to that of the more developed regions in 1950. Table 1 summarizes various indicators of urbanization for the more- and the less-developed regions of the world. Compared to 1950, the percentage of the world's total urban population is projected to double by 2030, and it will more than triple in the less developed regions. But perhaps the most profound urban statistic is that of the so-called squatter cities[1] -- residential areas in an urban locality inhabited by the very poor who have no access to tenured land of their own, and hence they "squat" on vacant land, either private or public. It is estimated today that one person in six in the world lives in a squatter city!

Earth's Changing Climate and Urban Weather.

Over the past decade or so, the climate change debate has shifted dramatically. In the early 1990's, the questions being asked were: "Is the climate really changing?" and "Is there a perceptible contribution from human activities?" Today, the questions are very different: "Will climate change gradually or abruptly?"; "How can anthropogenic impacts on climate be diminished or reversed?"; and "Will the frequency and intensity of severe weather episodes change, and what will be the socioeconomic impacts?"

The World Meteorological Organization and the United Nations Environment Programme established in 1988 the Intergovernmental Panel on Climate Change. The role of the IPCC is to assess the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts, and options for adaptation and mitigation. The IPCC's assessments are undertaken by hundreds of global experts who base their analyses on peer reviewed, published scientific and technical literature. The fourth and most recent IPCC assessment report was completed in 2007 (IPCC, 2007a). The significance of the Fourth IPCC report was highlighted in Oslo on December 10, 2007, when the Intergovernmental Panel on Climate Change and Albert Arnold (Al) Gore Jr. were awarded the Nobel Peace Prize "for their efforts to build up and disseminate greater

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[1] Hari Srinivas, from "Defining Squatter Settlements," see http://www.gdrc.org/uem/squatters/define-squatter.html

knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change." Table 2 summarizes the IPCC's synthesis of past climate changes, the contributions from human activities, and projected changes in the climate of the 21st century. These changes in Earth's climate portend profound physical and socioeconomic implications as a consequence of higher temperatures, increased heat indices, sea level rise, more intense precipitation events, increased risk of drought and increased severity of tropical cyclones, among the many weather impacts.

Low Elevation Coastal Zones (LECZ)[2] are especially vulnerable to severe weather and their vulnerability will be exacerbated in the face of global warming. According to a recent global analysis by McGranahan, Balk and Anderson (2007), the LECZ encompasses two percent of Earth's land area but ten percent of Earth's population and 13 percent of its urban population. The less developed nations have 14 percent of their population and 21 percent of their urban population living in the LECZ, while for the more developed nations the respective percentages are 10 and 11. Moreover, the very large cities of the world are largely located in the LECZ as nearly two-thirds of urban settlements with populations more than five million are situated in the low-lying coastal zone. Low-lying coastal populations – urban and rural alike – are vulnerable to flooding from storm surges. But the coastal cities are especially susceptible to flooding. Paved-over and built-up areas increase the amount and intensity of runoff and river flows, putting the cities at greater risk of flooding, while the destruction of wetlands leads to a reduced buffering of tidal floods. These problems are likely to become more acute as the global climate warms and sea levels rise. The 2007 IPCC report estimates that sea level will rise 22-34cm in the coming 70-80 years in the absence of accelerated melting of the Greenland and West Antarctic ice sheets. It is further estimated that a sea level rise of 38cm would increase by a factor of five the number of people impacted by storm surges (Nicholis, Hoozemans and Marchand (1999).

The impacts from climate change will be enhanced for many cities due to other well-known effects that cities have on weather and climate (see Dabberdt et al., 2000). The urban weather problem is multidimensional with unique and significant impacts on those who live in large urban areas. Conversely, large urban areas can impact local weather, air quality and hydrologic processes in many ways. And urban dwellers have different needs for weather information than do their rural counterparts. Urban needs for specialized weather information derive from the diversity of the user groups and population sectors found in urban areas, which include:

- the general public;
- air quality management agencies;
- water supply and sewage facilities;
- electric power industry;
- fuel suppliers—natural gas, fuel oil, coal, gasoline;

- transportation sectors—aviation, marine, and surface;
- emergency response agencies;
- public safety agencies;
- insurance companies and underwriters;
- health care providers; and
- recreation facilities.

Urban heat islands can result in urban temperatures that are typically up to 5C greater than those of their rural neighbors, but nighttime differences as large as 12C have been observed (Voogt, 2004). Heat islands result from the combined effects of the thermal and radiative properties of buildings and road surfaces, anthropogenic emissions of sensible heat, and changes in the air-land exchange of heat and water and the corresponding impact on the radiation budget. Changes in surface roughness in urban areas also affect the exchange of heat, mass, and momentum between the surface and the atmosphere, as well as the depth of the urban mixed layer. Hydrological processes are altered to a significant degree as a result of buildings and pavement that affect surface moisture, runoff and streamflow. There are also some indications (e.g., Bornstein and Lin 1999) that large urban areas may actually influence the genesis, intensity, and movement of convective storms and frontal boundaries.

Weather impacts urban areas and urban residents in many ways. Heavy rains can cause severe flooding, snow and freezing rain can disrupt transportation systems, severe storms and accompanying lightning and high winds can cause power failures, and so forth. The major *direct* impact on human mortality results from heat waves, and urban areas are particularly vulnerable because of their high population densities and because urban areas exacerbate conditions that lead to heat stress. Changnon et al. (1996) analyzed the numbers of deaths from various weather conditions in the twentieth century in the U.S. Their analysis clearly showed that heat waves caused more deaths, both on an annual average basis and from single events, than all other weather conditions combined. The temperature–mortality relationship has a strong latitudinal dependence: mortality rates in northern cities are more sensitive to high temperatures and southern cities are more sensitive to colder temperatures. This was nowhere more evident than in August of 2005 when a prolonged heat wave resulted in more than 30,000 excess deaths in northern and central Europe, including more than 15,000 in France alone.

As mesoscale prediction models increase their spatial resolution (today's research models have resolutions of a few kilometers while for some operational models it's about ten kilometers and improving steadily), it is increasingly important to properly represent urban influences on the radiation budget, surface moisture, sensible heat exchange processes, and anthropogenic heat and moisture fluxes. This also means that weather observing networks need to be enhanced in order to provide the three-dimensional

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[2] As defined by McGranahan, Balk and Anderson (2007), the LECZ is defined as land in the coastal zone less than 10m above mean sea level (msl).

observations required to properly initialize the models, but also to provide improved information on weather conditions in the cities and to support the observational needs of very short-range nowcasting engines.

Enhanced Urban Weather Observations and the Role of Testbeds.

As important as weather observations and forecasts are today, they will be even more critical in the future as urban areas and populations grow in the face of accompanying changes in global and regional climates. The importance of observing systems that are designed to match the weather requirements of tomorrow's cities is receiving international attention[3]. For example, the Global Earth Observing System of Systems (GEOSS) has included a new task in its GEO 2007-2009 work plan (http://www.earthobservations.org/progress/transverse_areas/capacity_building.html). Task US-07-01: Nowcasting and Forecasting User Applications seeks to "... facilitate the transfer of advanced nowcasting and forecasting capabilities from and to major cities in developed and developing countries [by building] upon the Helsinki Testbed experience to develop user applications related to precision weather forecasts, severe weather warnings, hydrology (including flood control), air-quality forecasting, chemical emergency response, transportation safety, and energy management..... The Helsinki Testbed[4] is a Finnish initiative aimed at developing enhanced three-dimensional mesoscale observing networks critical to the advancement of modeling systems and related user applications. It is a public-private-academic partnership. The program is open to all interested parties and the data is freely accessible through the Internet. Related stakeholder groups include homeland security, agriculture, insurance, urban management, coastal zone management, media, and public safety."

A recent community workshop (Dabberdt et al., 2005b) with international participation considered the requirements of effective mesoscale measurement networks and reached the following conclusion: "existing ... mesoscale measurement networks do not provide observations of the type, frequency, and density that are required to optimize mesoscale predictions and nowcasts. ... To be viable, three-dimensional mesoscale observing networks must serve multiple applications, and the public, private, and academic sectors must all actively participate in their design and implementation as well as in the creation and delivery of value-added products. The [urban] measurement challenge can best be met by an integrated approach that considers all elements of an end-to-end solution: identifying end users and their needs; designing an optimal mix of observations; defining the balance between static and dynamic (targeted or adaptive) sampling strategies; ensuring data standards and data quality, establishing long-term

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[3] The need for improved mesoscale observations is the subject of an upcoming report by a blue-ribbon panel of the Board on the Atmospheric Sciences and Climate (BASC) of the National Academy of Sciences. The report is scheduled for release in June 2008, and can be accessed through the BASC website: http://dels.nas.edu/basc/.

[4] More information on the Helsinki Testbed can be found at http://www.fmi.fi/testbed, in a paper by Dabberdt et al. (2005a), and in previous issues of Vaisala News (Vol. 170, pp.22-23, Vol. 173, p.26, Vol. 174, pp. 4-7, and Vol. 174., p.17).

testbeds (i.e. evaluation and demonstration programs); and developing effective implementation strategies."

The challenge is to determine the most effective mix(es) of observations, including alternative network configurations and sampling strategies. For example, it may be more cost effective to sample only the boundary layer with denser coverage than to similarly enhance observations in the upper troposphere for improving mesoscale analyses and predictions. It may be more cost effective to deploy intermittent, targeted observations at high resolution than to maintain dense arrays of sensors that report regularly. Regional testbeds are an intermediate step that is needed to provide a basis for answering these and other questions. Testbeds must carefully gauge the value of forecast products provided to the end-users.

Improved mesoscale observations must include many elements. For example, the top observational priority for operational *nowcasting* is to establish a dense mesoscale network of surface weather stations that measure winds and state variables and provide real-time sub-hourly reports. Minimum station spacing in urban areas should be 10-km or better; and the reporting frequency should be 5 min or less. Radar is an invaluable tool for nowcasting applications, yet the current operational systems have not kept pace with technological advancements. Dual-polarization capability should be implemented on existing radars, and private and academic radars (where available) should be integrated into operational networks. Along these lines, consideration should be given to deploying X-band polarimetric radars, as well as techniques for improving boundary-layer coverage through the use of closely spaced low-power X-band radars. Radar refractivity measurements should be evaluated as a possible operational tool for sensing moisture discontinuities that may lead to improved nowcasting. Products detailing near-surface water vapor fields should be provided in real time to forecasters and assimilated into models to demonstrate how high-resolution water vapor fields can improve nowcasting. There is also a pressing need to provide boundary-layer observations using RF wind profilers. Not only are additional observations and observing systems required – including *in situ* and remote sensors, both earth- and satellite-based -- there is a critical need to seamlessly integrate data from all of the disparate observing systems and to extract maximal information products that can be effectively used by end users.

Establishing testbeds such as the Helsinki Testbed is seen as a valuable intermediate step in designing networks and sampling strategies, evaluating new observing systems, setting data-quality standards, creating products that better meet user needs, and testing the ability of the public, private, and academic sectors to form effective partnerships to enable operational mesoscale networks. Successful testbeds should meet the following criteria:

- Address the detection, monitoring, and prediction of regional phenomena;
- Engage experts in the phenomena of interest;
- Define expected products and outcomes, and establish criteria for measuring success;

- Provide special observing networks needed for pilot studies and research;
- Define the strategies for achieving the expected outcomes; and
- Involve stakeholders in planning, operation, and evaluation of the testbeds.

The implementation of advanced 3D mesoscale measurement networks entails many practical issues in addition to the technical and scientific ones. A national collection of regional and urban networks will require a significant commitment and a major infusion of financial resources. In many countries, the most viable model for developing and supporting operational mesoscale networks leans toward a consortium of public, private and academic partners. In the old paradigm of synoptic-scale networks, government took responsibility for all aspects of the observational problem—design, testing, standard-setting, quality assurance, implementation, and operation. But with the reduction in scale size – especially in urban areas – and the corresponding demands for more and improved observations, coupled with improved sampling strategies and modeling systems, a partnership approach may offer the greatest likelihood of successful and timely implementation. Establishing one or more end-to-end mesoscale testbeds is viewed as a tangible first step in establishing the urban networks needed by the world's growing cities.

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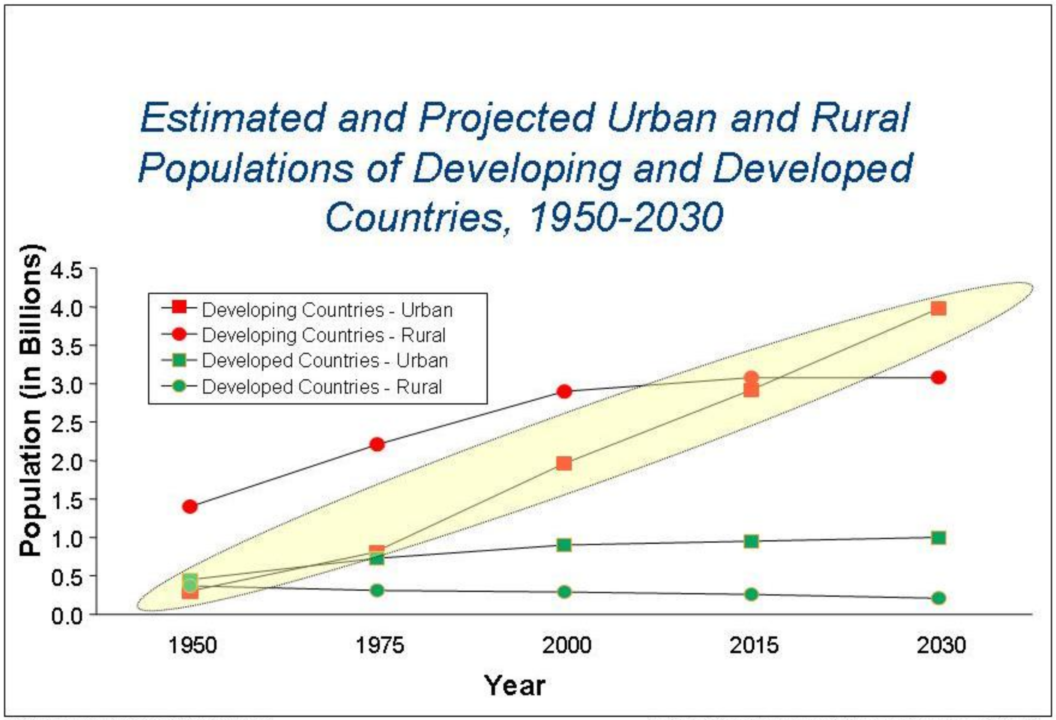

Original source: United Nations (2002)

Adapted from Hinrichsen, Salem and Blackburn (2002)

Figure 1. Urban and rural population of the more and less developed regions, 1950-2030 (adapted from: UNPD, 2002, and Hinrichsen, Salem and Blackburn, 2002)

Table 1.
Urban Indicators
(UNPD, 2001)

	Urban Percentage				**Urbanization Rate (%)**		**Doubling Time (yrs)**	
Region	**1950**	**1975**	**2000**	**2030**	**1950-2000**	**2000-2030**	**1950-2000**	**2000-2030**
World	29.8	37.9	47.2	60.2	0.92	0.81	75	86
MDR*	54.9	70	75.4	82.6	0.63	0.31	...	...
LDR	17.8	26.8	40	56.4	1.63	1.11	42	62

* MDR = more developed regions, * LDR = less developed regions

Table 2.

Climate Trends, Human Contribution and Projections

(Adapted from: IPCC, 2007b)

Phenomena and Trends	**Post-1960 Likelihood that Trend Occurred**	**Likelihood of Human Contri-bution to Trend**	**21st-Century Likelihood that Trend Will Occur**
Warmer & less frequent cold days & nights over most land areas	Very likely* (* 90-99% probability)	Likely$^+$	Virtually certain$^\#$ (>99% probability)
Warmer & more frequent hot days & nights over most land areas	Very likely*	Likely$^+$ (nights)	Virtually certain$^\#$
Warm spells/heat waves: frequency increases over most land areas	Likely$^+$ ($^+$ 66-90% probability)	More likely than not	Very likely*
Heavy precipitation events: Frequency (or % of total from heavy rainfalls) increases over most areas	Likely$^+$	More likely than not	Very likely*
Area affected by droughts increases	Likely$^+$ in many regions since 1970	More likely than not	Likely$^+$
Intense tropical cyclone activity increases	Likely$^+$ in some regions since 1970	More likely than not	Likely$^+$
Increased incidence of extreme high sea level (excludes tsunamis)	Likely$^+$	More likely than not	Likely$^+$

Table 3.

Population and Land Area in the LECZ[+] in the Year 2000

(source: McGranahan, Balk and Anderson, 2007)

	Population (10^6)		**Land Area (10^3 km^2)**	
Region	**Total**	**Urban**	**Total**	**Urban**
Africa	56	31	191	15
Asia	466	238	881	113
Europe	50	40	490	56
Latin America	29	23	397	33
Australia and N.Z.	3	3	131	6
North America	24	21	553	52
Small Island States	6	4	58	5
World	**634**	**360**	**2700**	**279**
World* (%)	**10**	**13**	**2**	**8**

[+] LECZ = low-elevation (<10m msl) coastal zone
* Est. world population = 6.34 billion.