Global Analysis of Urban Population Distributions and the Physical Environment

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Urbanization represents a significant recent change in the human habitat. The physical environment of modern urban areas is very different from the environments in which humans evolved and from those of the modern rural settlements that serve as population catchment areas for growing cities. In this sense, migration from rural to urban areas is a form of rapid environmental change that has affected a large fraction of the human population in the past century. This paper presents results of a global spatial analysis of modern urban population distribution with respect to several environmental parameters related to continental physiography and climate. Some of the differences between urban and rural population distributions can be illustrated by comparison of the areal extent of human population to spatial variations in local population density. The spatial distribution of population on Earth's potentially habitable landmass is extremely non-uniform. A large fraction of the current population lives in dense settlements occupying a very small fraction of the available land area. These dense populations span a wide range of climatic environments but are extremely localized with respect to continental physiography. The results of this analysis demonstrate the strong correspondence between continental physiography and settlement patterns and the extent to which humans have adapted to a wide range of climatic conditions. The implication is that adaptation to climate allows the expansion of the human habitat while the physical characteristics of the landscape induce a simultaneous spatial concentration of population within the expanding habitat. These factors have implications for impacts of climate change and natural hazards on urban sustainability.

Introduction

Human adaptation to the physical environment has resulted in habitation of almost every biome on Earth yet the current rate of urbanization represents a significant transition of the human habitat. Within the past 40,000 years the human habitat has expanded over almost all of Earth's ice-free land area. Within the past 4000 years humans have intensified settlement in areas conducive to agriculture and begun to localize in cities (*Hassan, 1981*). Within the past 40 years the growth rate of large cities has accelerated to the point where the majority of humans will soon live in urban environments (*United Nations, 1999*). This represents a significant recent change in the human habitat. Physical environments favorable to hunter-gatherers are fundamentally different from those favorable to pastoralists and agriculturists (*Reader, 1988*). Similarly, urban settlements often exist in areas unfavorable for agriculture. Throughout most of recorded history the majority of humans have engaged in agriculture so the recent large scale migration to urban centers represents an significant evolutionary transition for the human species. The purpose of this analysis is to quantify the extent to which modern human settlement patterns, specifically large urban areas, occupy different physical environments and to consider the implications of this migration for the sustainability of urban centers.

The environment of a large city is fundamentally different from the environment of smaller settlements in rural settings. The environments differ in terms of physical, biological, social and cultural factors (e.g. *Berry, 1990*). The focus of this discussion is on the physical factors. The other factors are at least as important as the physical factors but the physical factors are probably the most amenable to simple analysis at global scales. One significant difference between the urban environment and traditional human habitats is related to the energy balance. Solar energy flux is, by far, the largest and most persistent form of energetic exchange that most humans are exposed to on a daily basis (*Landsberg, 1981*). Interestingly, most of this energy is not exploited and an increasing number of humans expend significant amounts of resources in attempts to counteract the effects of solar energy flux. In most rural environments, humans live amidst moderately abundant vegetation but in most urban environments, vegetation is relatively sparse. Vegetation cover has a profound influence on solar energy flux (Figure 1). Vegetation absorbs radiation in the most energetic part of the solar spectrum to conduct photosynthesis. The unused fraction of the incoming solar energy is either transpired with water or reflected at Near Infrared wavelengths. Most building materials used in the urban mosaic absorb a significant fraction of this incoming solar energy and reradiate it as sensable heat resulting in the Urban Heat Island phenemenon (*Oke, 1982)*. An increasing percentage of the human population lives in urban areas where this heat induces physical stress and even loss of life during heatwaves. While the average temperature difference between urban and rural environments is small compared to the range of temperatures humans have adapted to, the nature of the physical space in urban areas tends to compound the effect of the heat island. The combination of higher temperature, restricted airflow and increased ozone and particulate concentrations creates a distinct physical environment associated with urban settlements at local scales (*Landsberg, 1981)*. On a regional scale, there is also evidence that areally extensive urban landcover may influence albedo and transpiration enough to influence local weather patterns near large cities (*Bornstein & Lin, 2000*).

Both deliberate and inadvertent human modification of the physical environment occur at different spatial scales. For the purposes of this discussion, micro refers to scales ranging from the individual to hundreds of meters while local scale covers the range from hundreds to tens of thousands of meters and regional refers to scales between tens and hundreds of kilometers. Although humans seem to be influencing the physical environment at all of these scales, deliberate manipulation of the physical environment is limited to micro and local scales. When available, significant resources are expended on "climate control" at the scale of residences and workspaces. Cities represent extensive habitat modification on scales of tens of kilometers but this modification rarely encompasses deliberate manipulation of physical conditions at these scales. Light levels and water flow are often controlled at local scales but human influence on air temperature and quality is largely inadvertent. At regional and global scales, human influence on these components of the physical environment is not well understood but it could not be considered direct intentional manipulation. Questions related to human modification the physical environment at regional and global scales have been the subject of extensive research within the global change research community for several years now (e.g. *Turner et al, 1990)*, but the the study of local scale urban environments is still a comparatively new field . A complementary, and equally important, form of global change is occurring with the expansion of these urban environments where much of the world's population now resides.

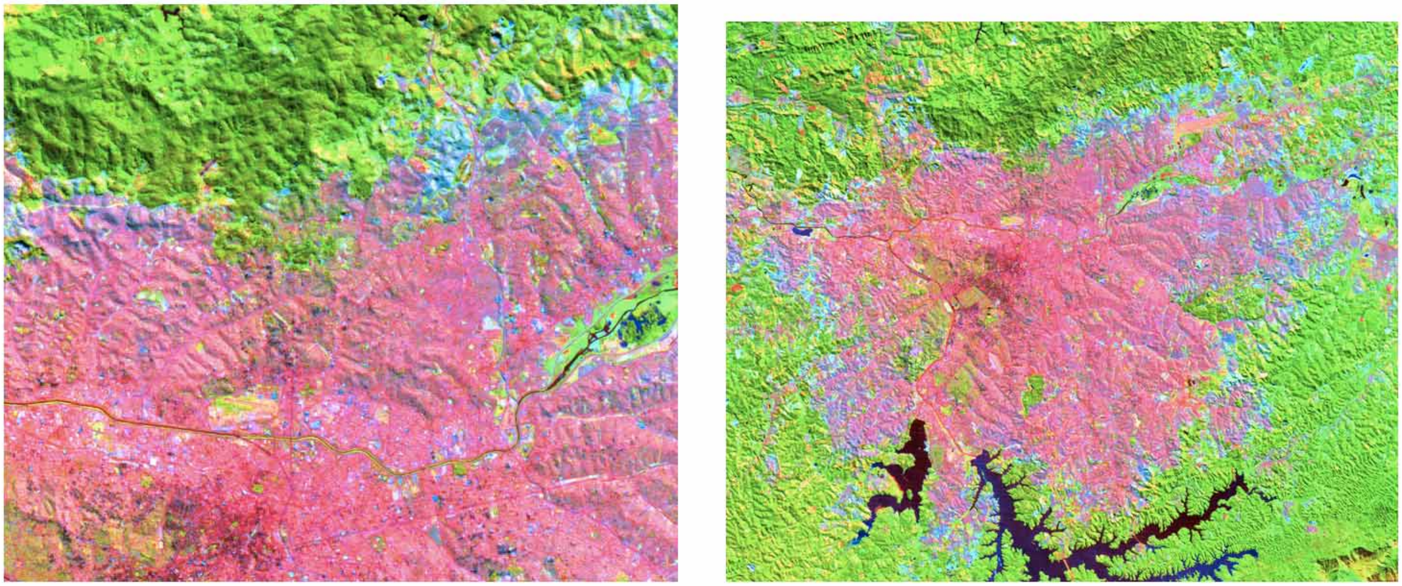

Figure 1 *Visible/Infrared/Thermal view of Sao Paulo, Brazil. This Landsat 7 image, acquired 17 June, 2000, shows higher surface temperature (red) in the built up area of Sao Paulo in contrast to the lower surface temperatures and higher Near Infrared reflectance of the vegetated areas(green) surrounding the city. The image on the left shows a more detailed view of the intraurban variations in surface temperature. Blue areas have higher albedo and lower surface temperature. The reservoirs south of the city appear black because the water transmits incoming radiation while maintaining a lower surface temperature. The horizontal dimensions of the images are 21 km and 61 km.*

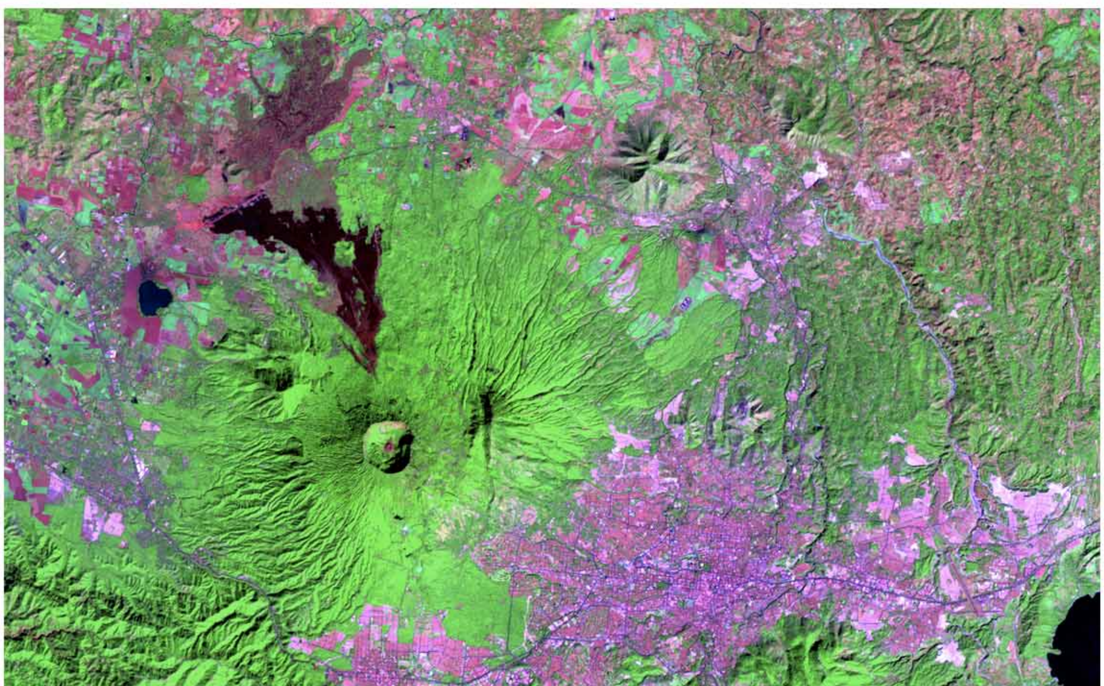

Figure 2. *Urban development in a potentially hazardous location. The city center of San Salvador is located 10 km from the vent of San Salvador volcano. This visible/infrared Landsat 7 image (RGB=7/4/2), acquired 31 December, 1999, shows the expansion of the built-up areas (purple) onto the southeast flanks of the volcano to within 4 km of the vent. The dark, lobate features on the northern flanks of the volcano are lava flows from eruptions in the17th century. This color figure is available from:* www.LDEO.columbia.edu/~small/Urban.html

The current demographic shift from sparsely populated rural to densely populated urban environments is a distinct form of global change. It is distinct from other types of global change in the sense that a rapidly increasing number of people are experiencing environmental change, not only as result of the environment of a particular location changing, but also as a result of growth centers shifting to different physical environments. The regional physical environment of urban areas is often different from the physical environments of its catchment areas in the rural hinterlands so the localization of populations in cities can result in the exposure of large numbers of people to different regional scale physical environments. On a smaller scale, locations where cities evolve are generally physiographically distinct from those of the nearby agricultural production regions. In some cases, this localization may result in dense habitation of hazard-prone sites (Figure 2). This is often a consequence of the physiography and climate of the city's location. The following analysis will quantify the extent of this localization and the relationship of the densely populated areas to physiographic and climatic characteristics of the physical environment.

Urban Population Distribution

In this global analysis, population distribution and density are determined from the latest Gridded Population of the World (GPW2) population dataset produced by CIESIN in 1999 (*CIESIN, 2000, Deichmann et al, 2001*). This compilation of 127,105 census estimates provides a median spatial resolution of 31 km, and allows 90% of the 1990 global population to be located to within 88 km (*Small and Cohen, 2002*). For the purposes of a global analysis, this dataset provides more than adequate spatial resolution relative to the regional environmental variables that will be considered. Each of the 127105 census estimates links a population count to an administrative area. Dividing the population count by the area provides an average population density for that area and allows the population to be distributed evenly over the area of the administrative unit (*Tobler et al, 1999*). The spatial resolution of the population data supports inference at scales of tens of kilometers. For the purposes of this analysis, urban areas and populations within the GPW2 dataset will be considered as those with a population density greater than 1000 people/sq.km. Justification for using this threshold density is provided by *Pozzi and Small, (2001)*.

In addition to dense populations, we will also consider the urban population living in large cities. In this case, large cities will be considered those with populations greater than 1,000,000 people. The United Nations (1998) provides an enumeration of 290 cities with populations greater than 1 million in 1990. The total population of these 290 cities is 795,009,000 people. By considering both administratively defined large urban areas and dense population two complementary measures of global urban population can be evaluated relative to different physical environmental factors.

The global spatial distribution of human population is extremely nonuniform. Figure 3a shows the spatial distribution of population density at a global scale. Figure 3c shows the corresponding distribution of people as a function of population density for the global dataset. It is immediately apparent that most of Earth’s land surface is sparsely populated at densities less than 10 people/km^2 while most of the people on Earth live at population densities greater than 100 people/km^2, The global map shows considerable spatial variation in population density but the range of densities is so large that it is difficult to appreciate the extent of clustering because so many people are concentrated in urban areas that are not visible at a global scale.

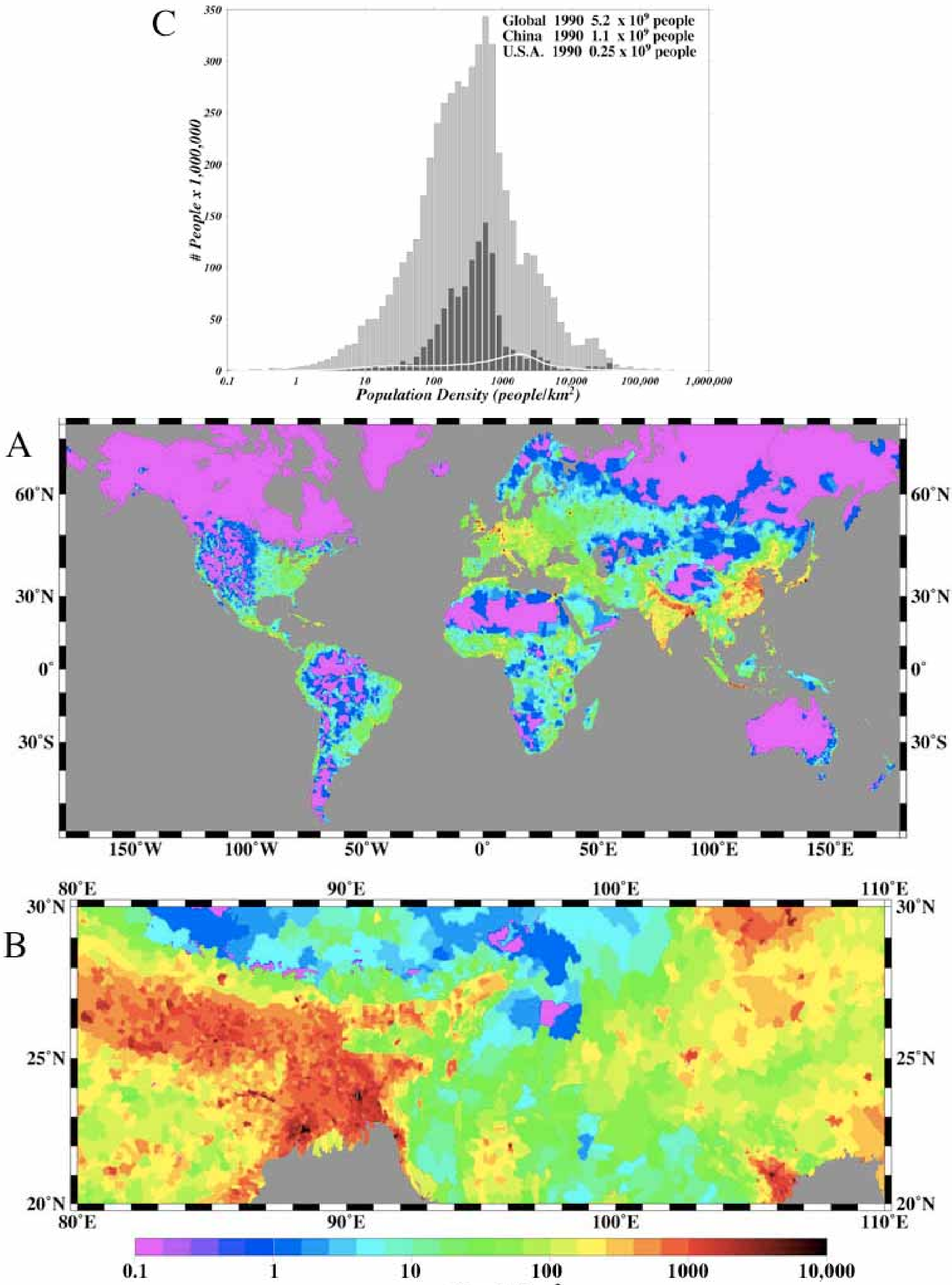

Figure 3. Human population distribution. A) Gridded Population of the World (GPW2) shows population density on a logarithmic scale. The global grid is derived from 127,105 census estimates of varying spatial resolution to produce a grid of population density estimates with a grid resolution of 2.5 arc minutes (about 4.6 km at the equator and 3.3 km at 45°N). B) Regional scale enlargement of GPW2 shows the variability in the spatial resolution of the administrative units on which the grid is based. The population count for each administrative unit is assumed to be uniformly distributed within the area of the polygon to yield a single population density (count/area) which is assigned to each grid cell within that polygon. C) Distribution of population as a function of density. The lighter histogram shows the global distribution for the 127,105 census estimates while the superimposed histogram and curve show distributions for China and for the U.S.A. (respectively). The GPW2 data are available from www.ciesin.columbia.edu. *A color version of this figure is available from* www.LDEO.columbia.edu/~small/population.html.

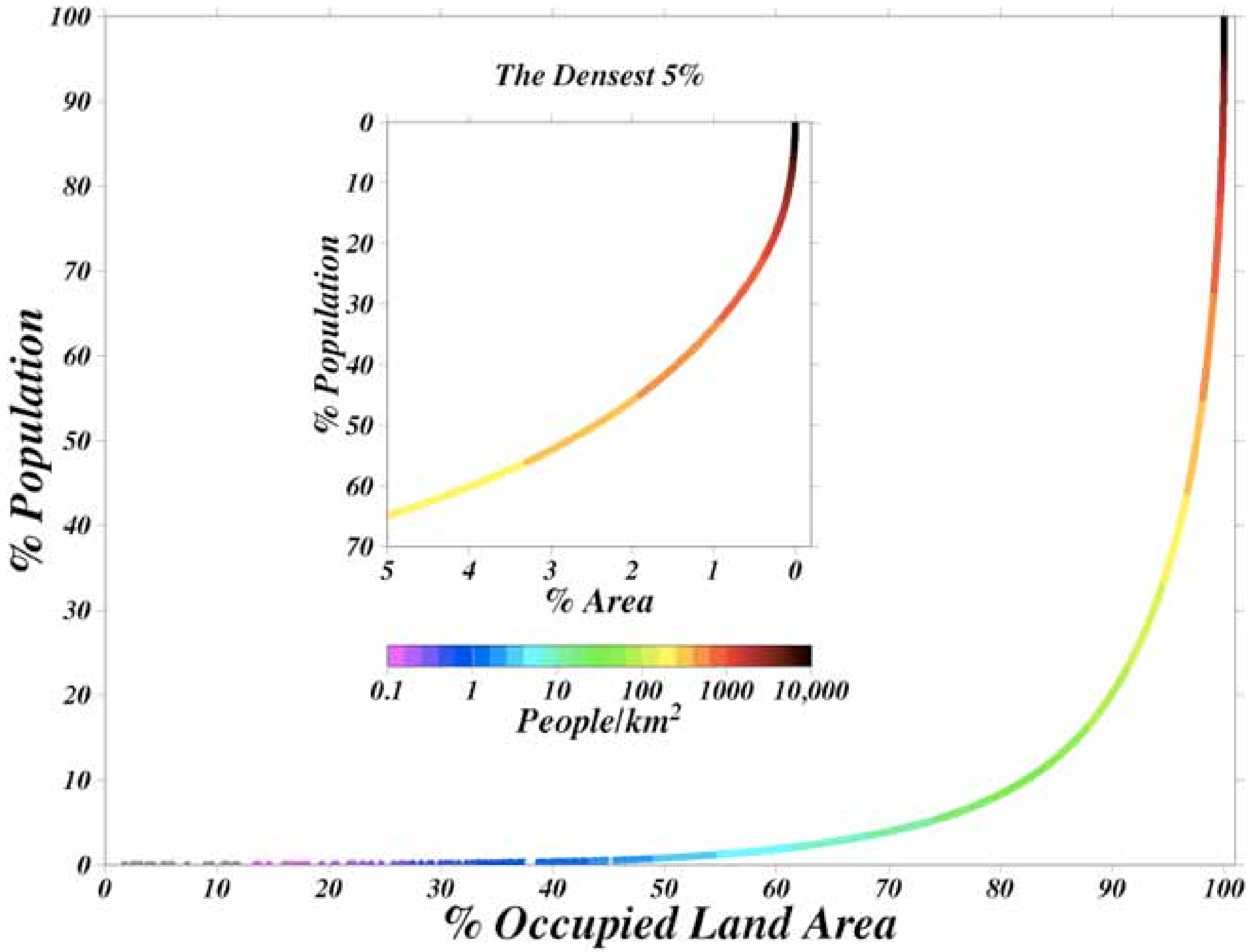

Figure 4. *Spatial Lorenz curve for the global human population in 1990. The curve shows the cumulative fraction of the population as a function of the cumulative fraction of land area (excluding Antarctica) for increasing population density. The curvature shows the spatial clustering of population that results in half of Earth's land area being effectively unpopulated. The inset shows the most densely populated 5% of land areas enlarged and inverted. The figure indicates that 50% of the world's population occupies less than 3% of the potentially habitable land area at densities greater than 300 people /sq.km. More details in: Small & Cohen (2002).*

The degree of spatial clustering of population can be summarized with a spatial Lorenz curve. Plotting the cumulative population as a function of cumulative land area for increasing population density shows the percentage of land area occupied by the corresponding percentage of population. Uniform spatial distribution of population would yield a linear relationship (30% of population on 30% of the land area, 80% on 80% etc.) and increasing curvature indicates increasing clustering. The spatial Lorenz curve in Figure 4 shows that the global population is strongly clustered with 50% of the world's population inhabiting less than 3% of available land area (excluding Antarctica) at average densities greater than 300 people/km^2, This clustering of population is significant because it emphasizes the simultaneous abundance of potentially habitable land area and preferential dense settlement of a small fraction of this land area. The next part of the analysis considers the physical environmental characteristics of the densely populated areas relative to those of the entire inhabited area of Earth's landmass.

Continental Physiography, Climate and Cities

Populations are not uniformly distributed on Earth's landmass and neither are physical environments. Quantifying the spatial coincidence of populations and environments can give some indication of the factors that may influence human settlement patterns. The spatial relationship between population and the physical environment can be quantified by calculating the distribution of people with respect to a particular parameter that characterizes the environment. Environments are often described in terms of climatic parameters related to temperature and precipitation. Both of these parameters vary appreciably at different temporal and spatial scales so averages are often used to summarize the climate of specific locations. Environments are also characterized by landscape or continental physiography. Physiographic parameters that might be expected to influence human habitation include elevation and proximity to coastlines and rivers. All of these quantities can be measured or estimated to different degrees of accuracy and resolution and used as a basis on which to calculate global distributions of land area and population. A more detailed discussion of this type of analysis is given by *Small and Cohen (1999, 2002)*. Global maps of these and other environmental parameters are available online at:
www.LDEO.columbia.edu/~small/population.html

The distribution of population with respect to continental physiographic parameters is extremely localized. In this context, localization refers to clustering of population within a range of parameter values (like temperature or elevation) that is significantly smaller than the total available range. Figure 5 shows global distributions of population and land area with respect to elevation, permanent rivers and sea coasts. It is immediately apparent that population decreases monotonically with elevation and distance from rivers and coasts. To some extent this is a consequence of the fact that the amount of available land area also diminishes. When the number of people at a given distance (or elevation) is divided by the total land area available at that distance (or elevation) the resulting Integrated Population Density (IPD) gives some indication of how densely a particular distance (or elevation) is populated relative to other distances (or elevations). The IPD curves shown on figure 5 indicate the extent to which the land areas at low elevations, near coasts and rivers is more densely populated than land areas farther away. These curves give an indication of the relative density but tend to de-emphasize the absolute numbers. For example, the spike in IPD at 2300 m elevation corresponds to the densely populated Mexican plateau. Although the integrated density of the plateau is comparable to the high integrated densities at sea level, the upper histogram indicates that there are many more people living near sea level than on the Mexican plateau.

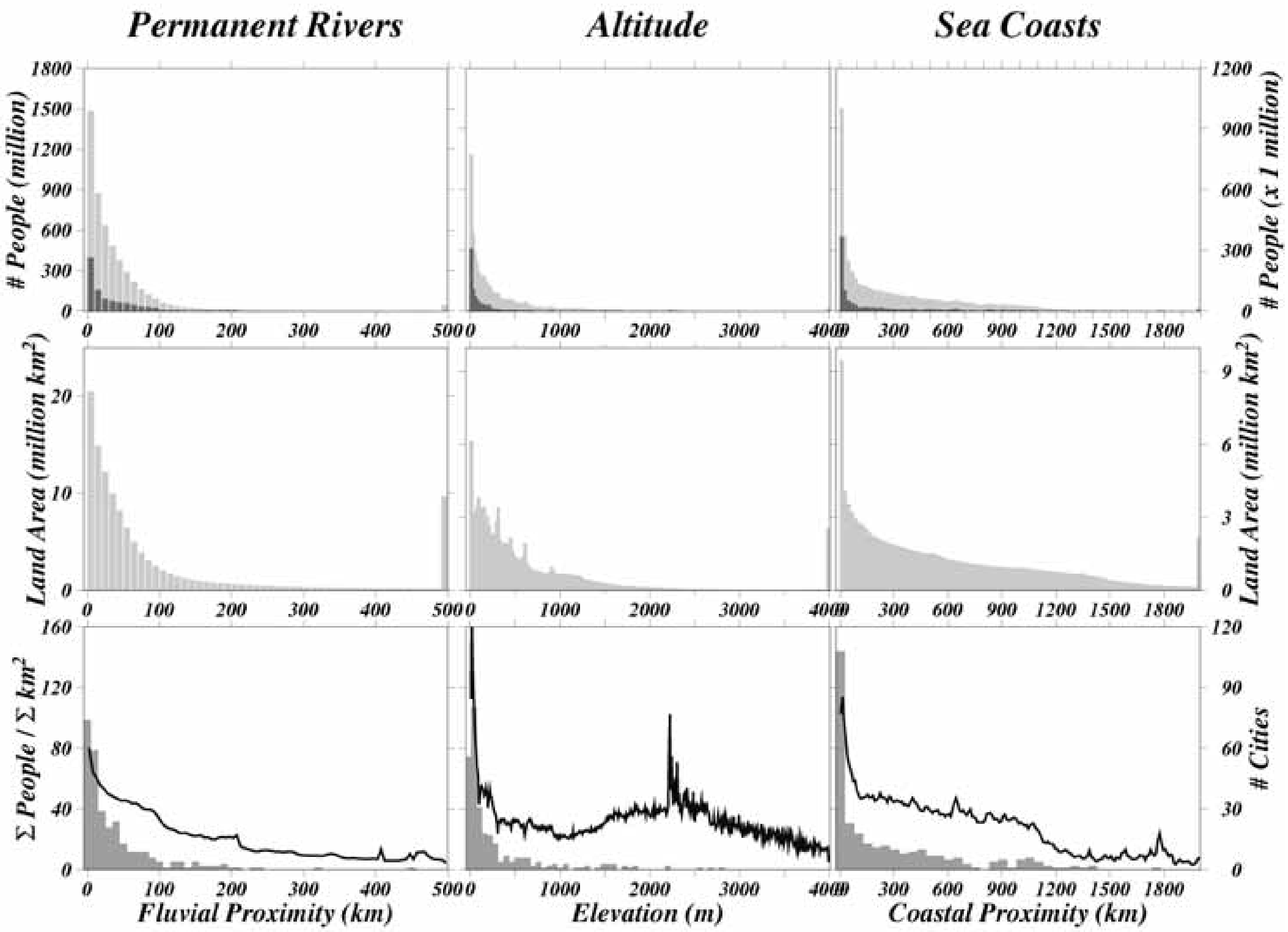

Figure 5. *Global distribution of population, land area and large cities relative to continental physiographic parameters. Population decreases rapidly with distance from coastlines, sea level and permanent rivers as does total land area. When population at a given elevation (or distance) is normalized by the land area available at that elevation (or distance), the lower curves show the Integrated Population Density (IPD) at that elevation (or distance) (Small & Cohen, 1999, 2002). The IPD indicates abundance of population relative to the abundance of land area at a particular elevation (or distance) but is distinct from local population densities. The distribution of large cities (lower histograms) and dense population (>1000 people/sq.km - darker upper histograms) is even more localized than global population overall.*

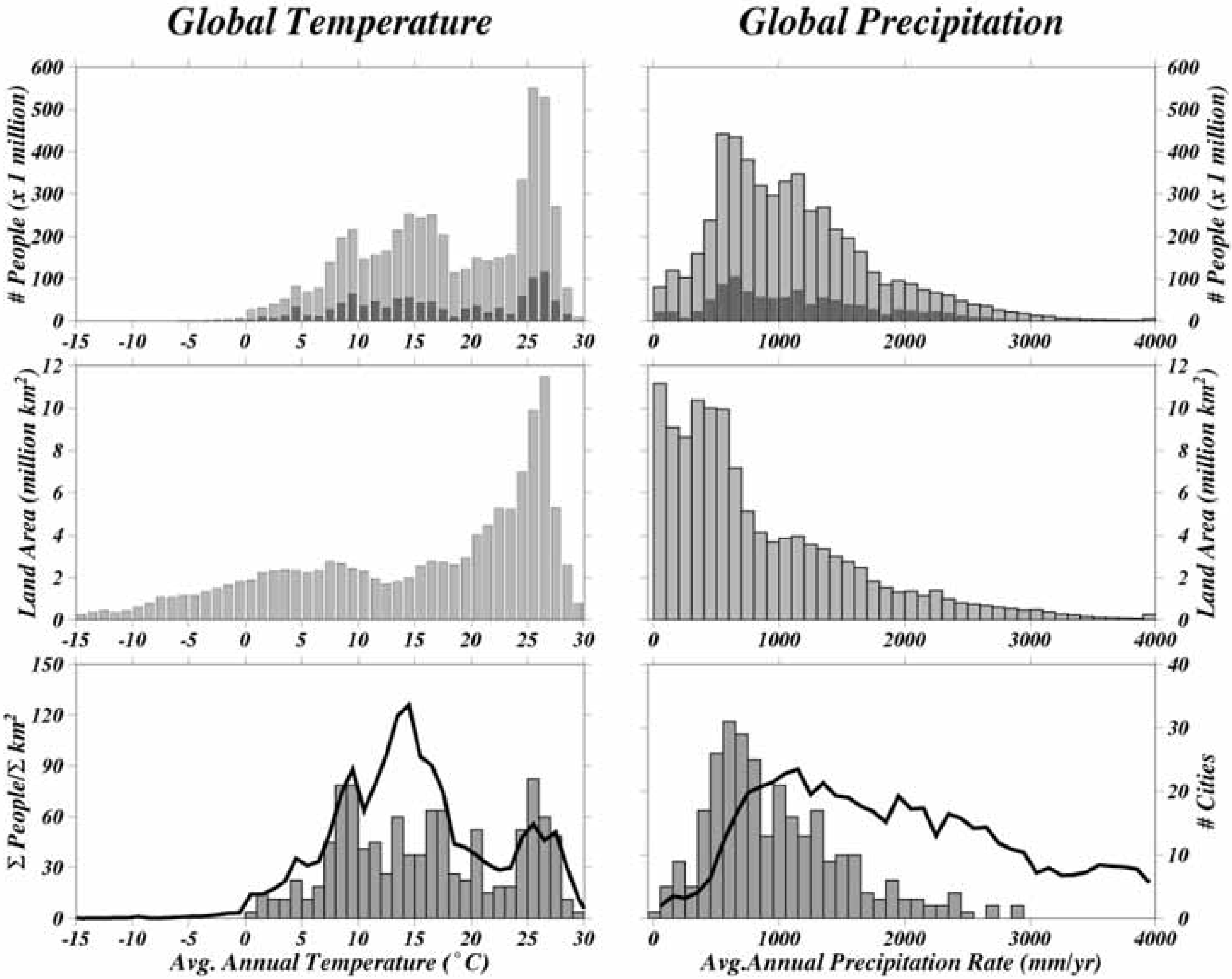

Figure 6. *Global distribution of population, land area and large cities relative to climatic parameters from (Small & Cohen, 1999, 2002). Population is more evenly distributed with respect to the range of temperatures and precipitation rates than with respect to the physiographic parameters in Figure 5. Integrated Population Density (IPD) also lacks the sharp peaks seen in Figure 5. The distribution of dense population (>1000 people/sq.km - darker upper histograms) resembles the global distribution but the distribution of large cities (lower histograms) is more skewed toward arid climates than the IPD.*

The distributions of dense population and large cities are also extremely localized with respect to physiographic environment The darker population histograms superimposed on the global histograms in Figure 5 show the distribution of people at high population densities with respect to these parameters. The peaked distributions of high density population are even more pronounced than the global distribution, particularly with respect to fluvial and coastal proximity. This emphasizes the preferential settlement of these physiographic environments at urban densities. The lower histograms superimposed on the IPD curves show the distribution of large cities with respect to these parameters. It is apparent that the large cities are even more strongly localized in these physiographic environments.

The global distribution of population with respect to climatic parameters is not strongly localized. Figure 6 shows distributions of people, land area and large cities with respect to 30 year averages of temperature and precipitation. While these distributions are hardly uniform, they are not dominated by sharp peaks and monotonic decreases as the physiographic parameters are. The distributions of dense populations and large cities are even less localized with respect to these climatic parameters. The distribution of dense population resembles the overall distribution in nearly even proportion for both parameters. The distribution of large cities is multimodal for temperature and somewhat skewed toward arid environments relative to global population as indicated by the IPD. The implication is that climate imposes less of a constraint on the locations of cities relative to sparser agrarian populations. A more detailed analysis of climatic parameters is provided by *Small and Cohen (1999, 2002)*.

Taken together, the distributions of global population, dense populations and large cities have implications for the comparative influence of physiographic and climatic components of the physical environment. This simple analysis does not account for microclimate or the temporal components of climatic environment and, as such, should not be over interpreted. The point is to demonstrate how strongly populations and cities are localized relative to physiographic parameters on a global scale. Climate is obviously a very important influence on human settlement but it is presumably less of a constraint on dense urban settlements than on sparse agrarian populations. This analysis quantifies the extent to which urban populations are environmentally localized compared to the overall global population. The implication is that adaptation to climate change allows the expansion of the human habitat while the physical characteristics of the landscape drive a simultaneous spatial concentration of population within the expanding habitat. This impacts the sustainability of urban settlements because the physiographic environments discussed here are often associated with natural hazards. Low elevation river basins and coastal zones are especially susceptible to the extreme weather events that some climate change scenarios show increases for. The tendency for cities to evolve in hazard prone physiographic environments combined with the increasing shift of populations from rural to urban environments implies that more people will be exposed to natural hazards as this transition progresses. Dense settlements in hazard prone locations expose large numbers of people to risk but at the same time the financial and organizational resources of some cities may allow for more effective hazard mitigation than would be possible for dispersed populations. In any case, the current growth rate of urban populations suggests that the impact of natural hazards on the global population may change.

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