Continental Physiography, Climate and the Global Distribution of Human Population

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Abstract: ***Human populations are not uniformly distributed on Earth's landmasses. The spatial distribution of the global human population at any time shows large variations over a wide range of spatial scales. Understanding this distribution is fundamental to understanding the relationships between humans and the environment. The recent availability of moderate resolution population data and higher resolution geophysical data now makes it possible to quantify the spatial relationships between population and basic geophysical parameters related to continental physiography and climate. Multivariate distributions of population and land area in geophysical parameter space reveal patterns that may not be obvious in geographic space. When population distributions are normalized by available land area as a function of a geophysical parameter, the most densely populated ranges of the parameter can be determined. When applied to multivariate distributions, the most densely populated combinations of the parameters are indicated. These integrated population densities are generally distinct from local population densities. We investigate the localization of human population with respect to elevation and coastal proximity and with respect to regional temperature and precipitation. Average population densities are far higher at low coastal elevations and diminish rapidly with increasing elevation and distance from coastlines. Inland population densities tend to be highest in topographic basins adjacent to mountain ranges. We also find that population is significantly more localized with respect to continental physiography than with respect to the climatic parameters we have analysed.***

Introduction

The spatial distribution of the global human population at a point in time shows large variations over a wide range of spatial scales and population densities (Figure 1 and ***Tobler, 1997***). Understanding what determines this distribution is fundamental to understanding the relationships between humans and the environment. The relationships can be considered from the standpoint of the system's influence on humans (e.g. ***King et. al., 1994***) as well as human influence on the rest of the system (***Vitousek et. al., 1997***). A necessary first step to understanding the spatial distribution of the population is to quantify its relationship to other factors that may influence it.

The immediate objective of this study is to quantify some of the geophysical factors that may influence the spatial distribution of the human population. A secondary objective is to investigate the application of hyperdimensional analysis to global and local distributions of population and basic geophysical variables. The ultimate objective is to understand the relationship between population and environment better than we do now**.**

Spatial Localization of Population

The extent to which a population is localized or dispersed is determined by the density distribution over the available land area (Figure 1). In a similar way, a population can be localized with respect to a particular range of a geophysical parameter independent of spatial localization. If the cumulative sum of population is plotted as a function of the cumulative land area that it occupies for monotonically increasing local density it is possible to quantify the localization of human population on Earth. This will be referred to here as a Spatial Localization Function (SLF) and is equivalent to a Lorenz curve for the spatial distribution of population.

The global localization function corresponding to the Gridded Population of the World (GPW) dataset is shown in Figure 2 with several regional localization functions for the more densely populated subregions of the world. Greater curvature of the function implies more spatial localization but provides no information on the number or distribution of local maxima of the density function. The limiting cases are represented by a linear localization function depicting uniform distribution over all available area and by an delta function depicting the entire population contained within the smallest possible land area.

The localization of human population apparent in Figure 1 reveals the extent to which Earth's landmasses are characterized by several populous regions with higher contiguous population density and by large regions with much lower average population densities. For comparison, we divided the populous areas into seven subregions of

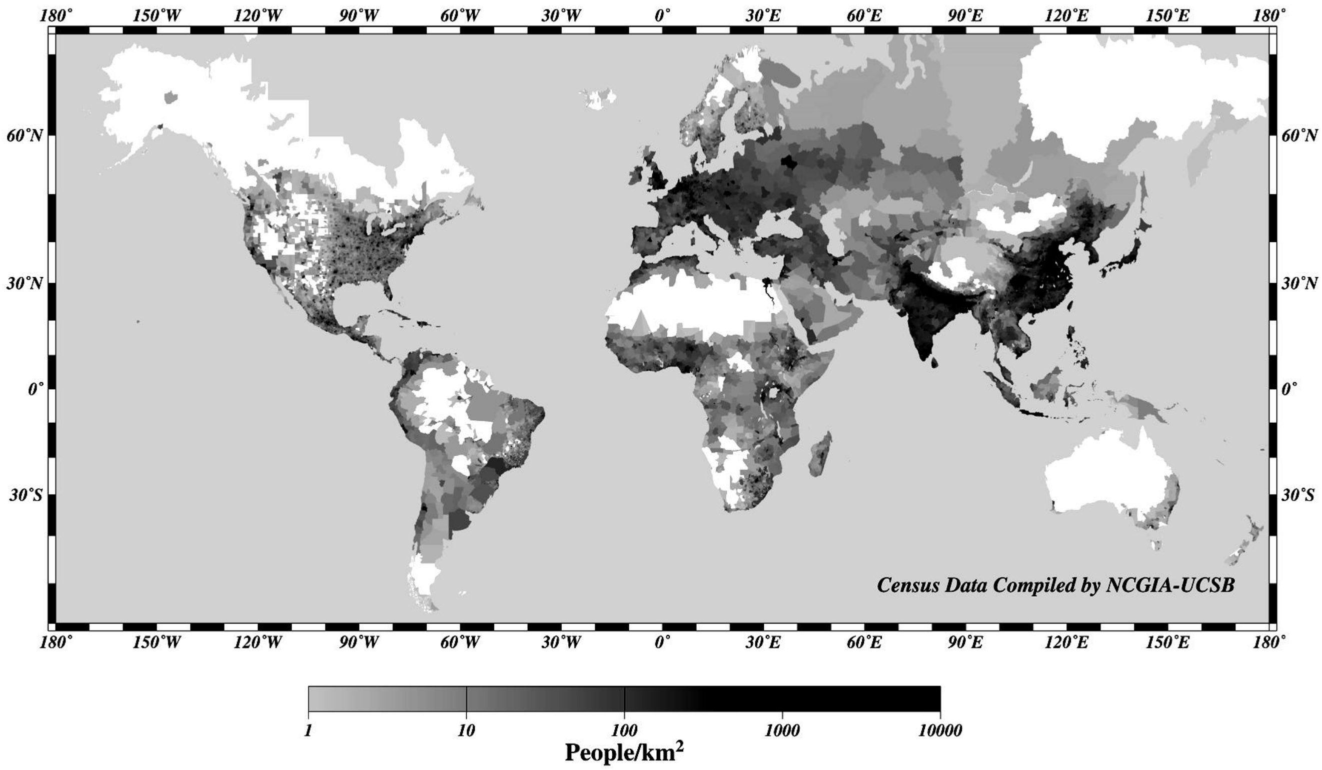

Figure 1 - Global population density map based on the Gridded Population of the World (GPW) dataset (Tobler et. al, 1997) . Gray shading shows Log_{10} population density gridded at 5 arc minute (~9 km at the equator) resolution from 19,032 census estimates compiled by the National Center for Geographic Information and Analysis at the University of California Santa Barbara. Data available from CIESIN (http://www.ciesin.org).

relatively contiguous population separated by regions of sparse population. Density constrained localization functions are plotted for these subregions to indicate population/area distribution for regions with local densities greater than 10 people/km^2 (Figure 2). The elimination of sparsely populated areas results in a more uniform distribution of the remaining population within the remaining land area indicated by the regional localization functions having less curvature than the global function. The regional localization functions indicate that while the south central and east Asian regions are, by far, the most densely populated, they are also the least spatially localized of the regions. North America, by comparison, is much less densely populated on average but is far more spatially localized.

Comparative Distributions of Land Area and Population

Long term habitation by human population is largely limited to Earth's continental landmasses. The habitable area of oceanic crust is limited to a modest number of volcanic islands. Most inhabited islands are composed of emergent subaerial continental crust around the submerged periphery of the larger continental landmasses. Characteristics of continental physiography such as elevation relative to sea level, proximity to nearest coastline and proximity to nearest drainage impose fundamental constraints on habitation. Other physical parameters, such as climate or ecological zone also impose constraints on, or influence, human habitation. Because these physical quantities are themselves limited by their distribution over Earth's available land area, it is necessary to consider both the distribution of population and the distribution of land area with respect to the parameter of interest. The distribution of population or land area can be considered within an arbitrarily high dimensional parameter space. In this discussion we limit ourselves to univariate and bivariate distributions of population and land area to emphasize specific patterns.

Some univariate relationships between global population and continental physiography are summarized in Figure 3. It is immediately apparent that population diminishes rapidly with elevation and with distance from coastlines and major rivers. The land area distributions show much the same pattern, thereby imposing a fundamental constraint on the land area available for human habitation. The population distribution can be normalized somewhat for the effect of land area distribution by dividing the number of people at a given elevation (or distance) by the land area available at that elevation (or distance) to give the total number of people per square kilometer of available land area at that elevation (or distance). We refer to this as the global Integrated Population Density (IPD) function for that parameter (***Cohen and Small, 1998***). The global IPD for elevation shows pronounced peaks at sea level and at 2300 m. The densities are comparable (> 100 people/km^2) but the peak near sea level represents many more people. To show the combined effect of the population distribution and the integrated density we multiply the IPD by the population at each elevation. Taking the square root of the product compresses the range and simplifies the units to people/km to give Normalized Population Distribution (NPD). The NPD for elevation shows the anomalous density at 2300 m while emphasizing the larger peak near sea level.

Global relationships between population, land area and some climatic parameters are shown for comparison in Figure 4. Because temperature and precipitation vary appreciably on annual and interannual time scales, we consider the temporal variability at both scales in addition to the annual averages. The direct interdependencies and time varying component of the climatic parameters require a higher dimensional analysis but some fundamental observations can be drawn from the univariate distributions shown in Figure 4.

Populations in Multidimensional Parameter Space

Every place on Earth is characterized by some combination of geophysical parameters as well as a population density and other non-geophysical parameters. A particular combination of two or more parameters can be considered a point in a multi-dimensional parameter space. A single point in parameter space is generally associated with a collection of points in geographic space corresponding to all the locations that are characterized by that combination of parameters. Each point in the parameter space is also associated with a distribution of other parameter values that are not included in the dimensions of the parameter space. For example, all the places on Earth that are 20 km from a coast and 10 m above sea level and have an annual average temperature of 25°C may receive different amounts of precipitation and have a range of population densities. The univariate distributions are therefore components of multivariate distributions which provide more information about the combinations of parameters for which land area or population are particularly abundant. Bivariate distributions for the physiographic and climatic parameters discussed above are shown in Figure 5.

Global bivariate distributions of population and land area are quite different for the physiographic and climatic parameters considered here. As with the univariate distributions, the bivariate population distributions are more localized for the physiographic parameters than for the climatic parameters. The bivariate distributions also reveal some patterns not apparent in the univariate distributions. The large number of people at low elevations (< 400 m) is not uniformly distributed with respect to coastal proximities but rather follows a specific upward curving trend with distance extending ~1000 km inland. The large number of people in close proximity (< 100 km) to coastlines appears to be distributed over a 1000 m range of elevations. This pattern is likely to be biased by the resolution of census data in some coastal areas. Many areas on the Pacific coast of South America are characterized by narrow coastal plains rising rapidly into the Andes mountains within the area of a single census district. The populations of those districts are often localized along the coastal plain rather than uniformly distributed over the full range of elevations.

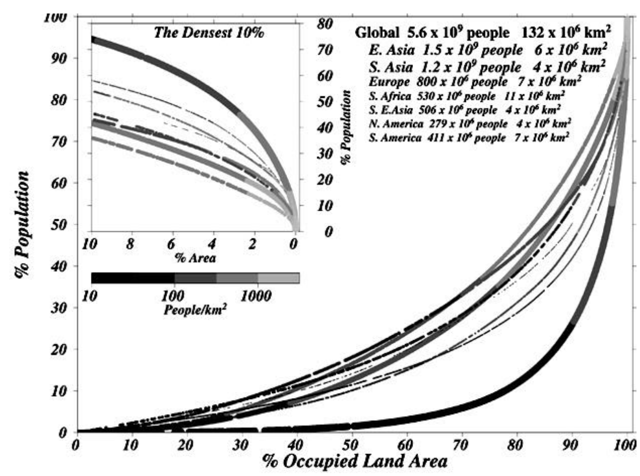

Figure 2. Spatial Localization Functions for the global human population and for seven populous subregions. Each curve shows the cumulative fraction of the population with cumulative fraction of land area for increasing population density. The thick global curve is the most concave because it covers all ice-free land area including many sparsely populated areas. Regional curves (thickness proportional to total population) include only areas that are populated at local densities greater than 10 people/km^2. The inset shows the most densely populated 10% of land areas enlarged and inverted. The figure indicates that 50% of the world's population occupies less than 4% of the ice-free land area at densities greater than 300 people /km^2 while in Eastern Asia 42% of the population occupies 10% of the populated land area at densities greater than 700 people/km^2.

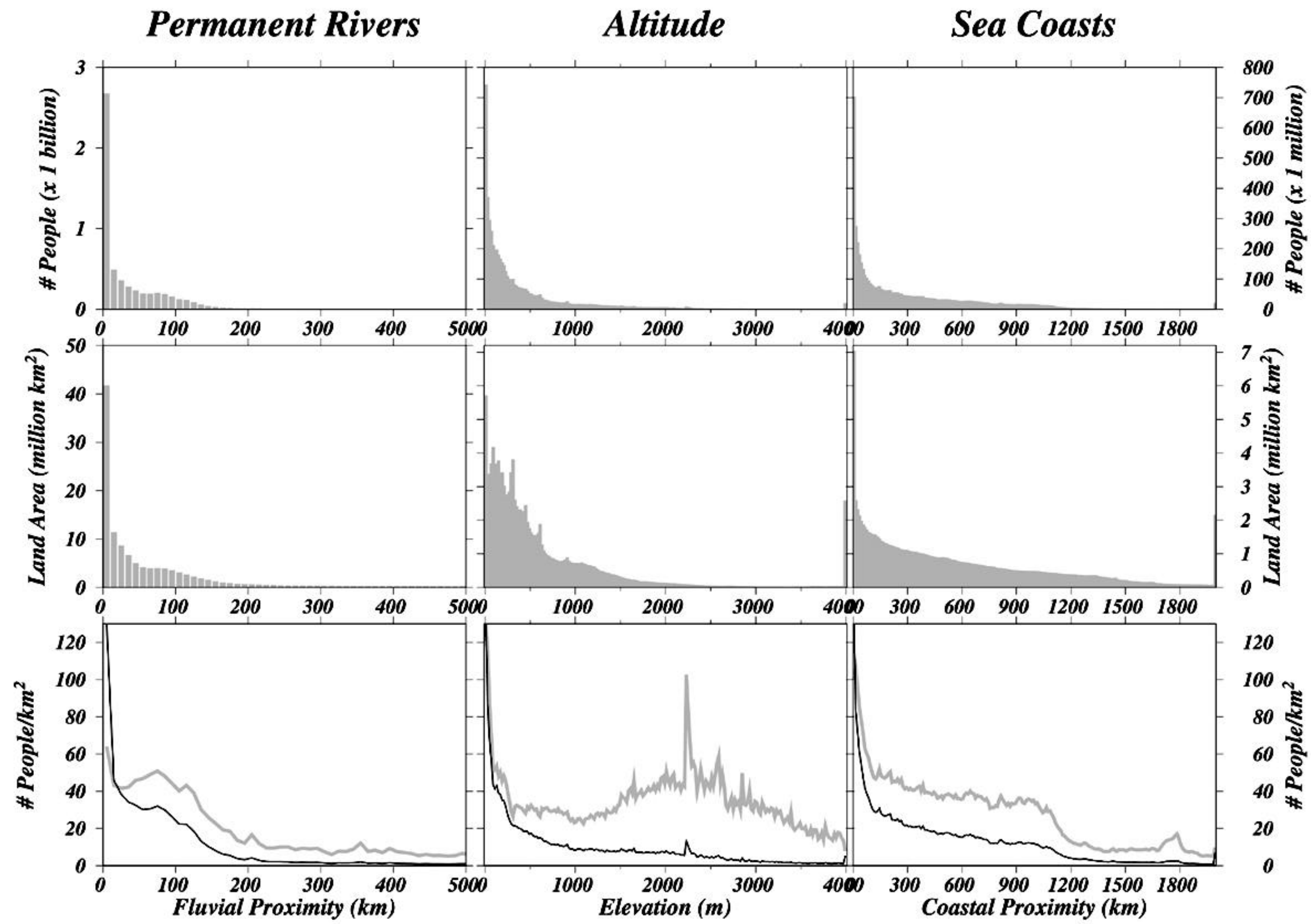

Figure 3** **Global distribution of population and land area relative to continental physiographic parameters. Population decreases rapidly with distance from coastlines, sea level and permanent rivers as does total land area. When population at a given elevation (or distance) is normalized by the land area available at that elevation (or distance), the lower curves show the Integrated Population Density (IPD, thick curve) at that elevation (or distance). The thinner curves rescale the IPD with the population ($(people^2/km^2)^{1/2}$ = people/km) to show large populations at high integrated densities. The peak around 2300 m corresponds to the densely populated Mexican Plateau.

Results and Implications

The primary observation that can be drawn from these simple analyses is that human population is more localized with respect to the physiographic parameters than with respect to the climatic parameters considered here. Even when the land area distribution is taken into account, there are far more people per available land area within 100 km of coastlines and within 200 m of sea level than further inland or at higher elevations. Regional analyses of bivariate distributions of population with respect to elevation and coastal proximity indicate that the lowest available elevations at each coastal proximity contain the greatest number of people. Localization along coastlines has commercial and strategic advantages as well as proximity to an abundant food source. Inland localization is consistent with agricultural development since the lowest elevations tend to be river valleys and deltas where sediments accumulate to form extensive flat areas of rich soil. This analysis provides quantitative estimates of the distribution of global population relative to coastlines but the resolution of the data is not sufficient to make meaningful statements about the number of people subject to coastal hazard or sea level rise worldwide (see ***Small, Gornitz and Cohen, 1999***).

At a global scale, no such sharp localization is apparent for the climatic parameters considered here. The most prominent climatic localization is the large population in southern and eastern Asia that experiences high annual variability in precipitation from the Indian and East Asian monsoons. It may be significant that the monsoons are relatively stable components of the climatic system in

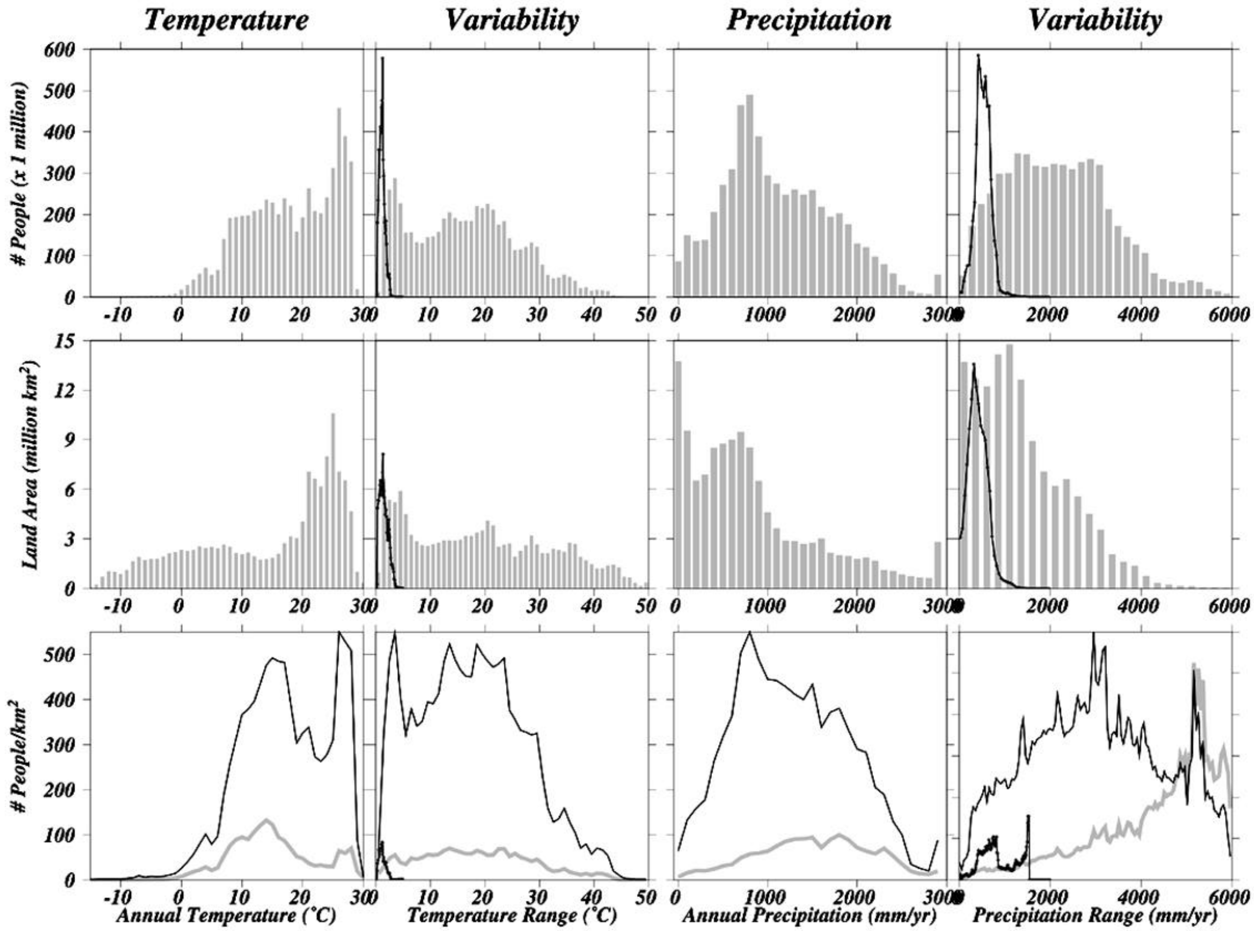

Figure 4. ***Global distribution of population and land area relative to climatic parameters. The 35 year mean and annual range of monthly temperature and precipitation estimates are derived from a regional (2° resolution) compilation of climate data (Kalnay, et. al., 1996). Thin variability curves show interannual RMS with respect to 35 year annual climatology. In comparison to continental physiographic parameters, population distribution is not strongly localized with respect to any of the climatic parameters. The most prominent features are the low population at average temperatures below 0°C and the pronounced peak in integrated density (thick gray curve) and normalized distribution for annual precipitation ranges around 5000 mm/yr. This peak corresponds to the Asian monsoons.***

the current continent/ocean configuration. A more detailed global/regional analysis of population distribution with respect to physiographic and climatic parameters is currently in progress.

It is important to remember that all of the quantities discussed here are estimates derived from spatial and temporal averages. A more detailed analysis should consider the spatial and temporal scaling of the distributions from which these estimates are derived. Grid resolutions and averaging times are chosen to retain as much information as possible given the resolution of the input data. While these resolutions are appropriate for global and regional analysis, the resolution may be inadequate for more detailed local analyses.

Understanding the spatial and temporal scaling properties of these parameters may greatly simplify large, high dimensional analyses by suggesting optimal measurement scales for some parameters.

A detailed understanding of the relationships between population and environmental parameters such as those shown here requires a more detailed analysis in a high dimensional parameter space with explicit time dependence. Most global datasets currently available still lack sufficient resolution in either space or time to accomodate this level of analysis. Spatiotemporal resolution is a critical consideration for studies of dynamics because spatial and temporal aliasing of finer scale variance can corrupt the representation of larger scale structure.

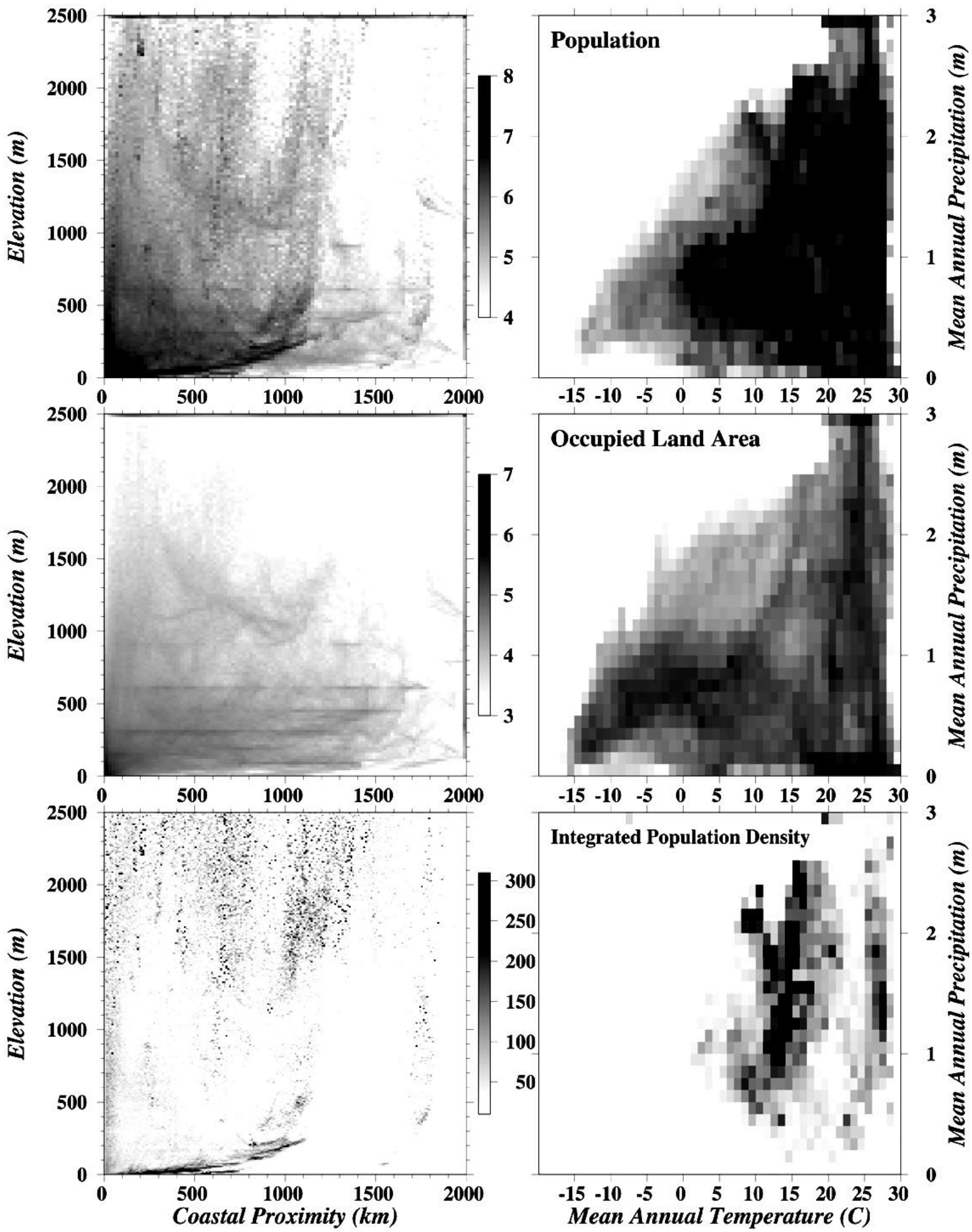

Figure 5. Global bivariate distributions of population and land area with respect to continental physiography and climate. Shading is logarithmic for population and area and linear for integrated density. Color figures available from http://www.ldeo.columbia.edu/~small/population.html.

For this reason, it will be important for coordinated efforts, like Digital Earth, to define self-consistent sampling procedures so that databases can be synthesized from independent, distributed sources without introducing this type of artifact.

The results we report here are an early step in a larger program of describing and understanding human interactions with the physical, chemical and biological features of the earth. Our more detailed comparative analysis of regional distributions discriminates between the global patterns that are observed at regional and local scales and those that are the product of combinations of disparate regional patterns. One objective is to determine which relationships exhibit spatial and temporal scaling behavior. Our next step will be to develop an integrated approach to analyzing joint distributions of all the parameters considered here as well as additional factors such as land cover class and temporal phase of temperature and precipitation.

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