Improved Estimates of Coastal Population and Exposure to Hazards Released

Though it is well known that the world's coastlines are heavily populated, the combined implications of population growth and climate change are still subject to debate. Models of hazard impact, adaptation, and vulnerability stress the importance of understanding both exposure and adaptive capacity of the threatened systems [e.g., *Smit et al.*, 2001]. Combining geophysical and socio-economic data sets can greatly improve our understanding of exposure at a range of scales from local to global.

Here we estimate an upper bound on the global exposure to coastal hazards based on 1990 population distribution. The focus is on exposure to natural hazards, but these estimates also provide an indication of the direct human pressure on the coastal zone. Data from 1990 were used, as this global population distribution was the most robust currently available.

While a coastal location provides important benefits for residents, there are also drawbacks. A variety of natural hazards such as erosion, saltwater intrusion, subsidence, tsunamis, and floods due to both surges and rivers affect coastal dwellers. Multiple exposure to natural hazards is common. This is dramatically illustrated by recent life-taking events such as Typhoon Linda in Vietnam and Thailand in 1997, the 1998 tsunami in Papua New Guinea, and the 1999 cyclone in Orissa, India. Over the longer term, some estimates of deaths due to cyclones over the last 200 years just around the Bay of Bengal exceed 1.3 million [*Nicholls et al.*, 1995]. In developed countries such as the United States, the death toll is much lower, but economic losses due to coastal storms are increasing, with major losses in events such as Hurricane Andrew, which hit Florida and Louisiana in 1992. We know that coastal populations are growing and urbanizing, and future coastal hazards may be exacerbated by climate change and sea-level rise, but the current exposure is poorly quantified.

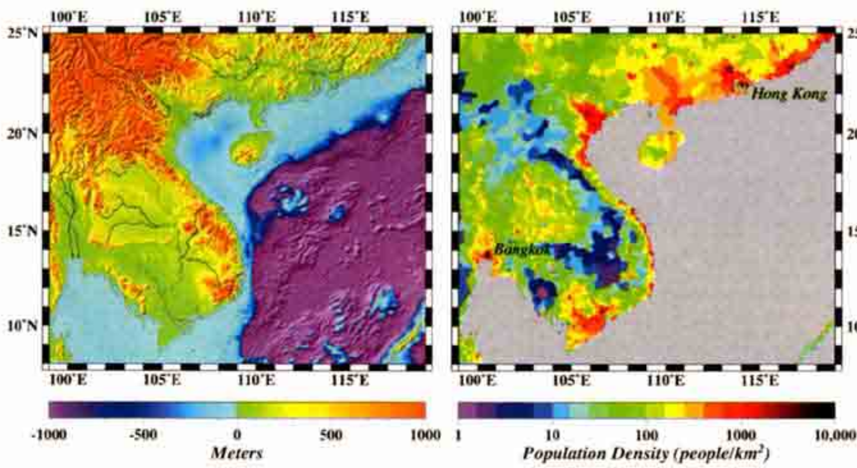

Fig. 1. Elevation and population density maps for southeast Asia emphasize the dense habitation of the near-coastal regions and the low-lying deltas. Very dense populations (>10,000 people/km^2) of large cities are shown in black.

A focused program of data collection and modeling in coastal areas to increase our understanding of human exposure, and to support hazard mitigation efforts could greatly benefit coastal populations.

Defining Coastal Population

While the term coastal population is widely used, a single consistent definition of the "coastal zone" does not seem to exist. Defining the populations directly exposed to natural

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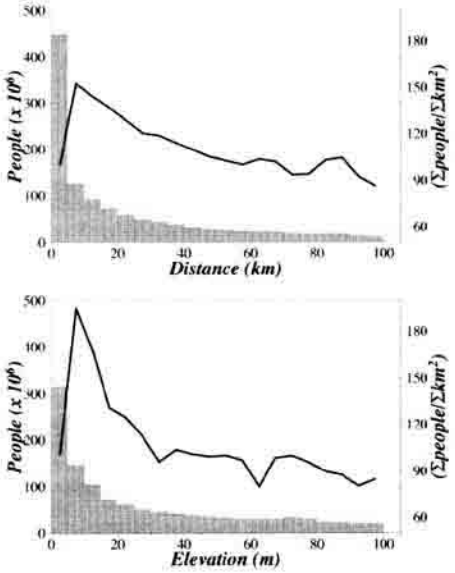

Fig. 2. Global population and integrated population density are shown versus distance and elevation from the shoreline. Population decreases with elevation and distance inland, but so does land area. Integrated population density (population divided by land area) accounts for this and indicates how average population density diminishes away from the shoreline.

hazards is conceptually straightforward, but the appropriate bounds of more indirect exposure, including wider socio-economic impacts, are less clear. For instance, a storm surge might only directly affect life and livelihoods within a short distance of the shoreline. However, indirect impacts could extend over much greater distances if critical infrastructure or services, such as water treatment facilities, ports, and harbors, or even government institutions, were incapacitated by the surge. Disparities in the definition of the coastal zone lead to conflicting estimates of exposure to coastal hazards, and it is therefore difficult to objectively define the true magnitude of this exposure.

Here we pose the following question: What is the potential global exposure of human population to present and future coastal hazards? To answer, we used two data sets:

- Population distribution from Gridded Population of the World, Version 2 (GPW2), [*Center for International Earth Science Information Network et al.*, 2000]. This version of GPW uses 127,105 administrative units, as compared to about 19,024 units in Version 1. The median resolution of the underlying data is 31 km, but with significant variation among countries. Assuming uniform distribution within administrative units, the data are gridded at 2.5 arc-minute resolution (about 5 km at the equator). For a more detailed resolution analysis, see http://www.LDEO.columbia.edu/~small/population.html
- Elevation data from the global, 30-arc-second resolution (about 1 km at the equator) gridded elevations provided by the Earth Resource Observation Systems Data Center, Sioux Falls, South Dakota (see http://edcwww.cr.usgs.gov/landdaac/landdaac.html).

Figure 1 illustrates the two data sets for the southeast Asian region.

Using the methods of Cohen and Small [1998], the GPW2 data set was co-registered to the elevation model to estimate the population living both within 100 m of sea level and 100 km of the shoreline in 1990. This 100-m/100-km zone, henceforth referred to as the near-coastal zone, is chosen on the basis of the steep vertical and horizontal gradients in population density that characterize the global population distribution near coasts [*Small and Cohen*, 1999; *Small et al.*, 2000]. The new results presented here are based on the higher resolution GPW2 data set and focus exclusively on the near-coastal zone. The intention is to examine the characteristics of the population distribution within the near-coastal zone in more detail than in previous studies. The higher population densities observed in the near-coastal zone are taken to represent the people who are most exposed to the effects of coastal hazards, either directly or indirectly.

Characteristics of the Near-coastal Population Distribution

Global analyses with the new data verify the common assertion that significant populations are located near coasts. Figure 2 shows two measures of near-coastal population distribution and the variation in these measures with coastal proximity and vertical elevation. The histograms show diminishing population with distance and elevation but do not account for available land area at each distance and elevation. The Integrated Population Density curves show the number of people in each interval divided by the available land area in the interval. The average population density (112 people/km^2) of the near-coastal zone is several times higher than the average global population density of 44 people/km^2. The population inhabiting the 100-km/100-m near-coastal zone is about 1.2×10^9 people, or about 23% of global population in 1990. This is similar to earlier estimates [*Small et al.*, 2000], but this new result is more robust, as it is based on considerably more detailed census data. Note that this estimate is significantly smaller than the $>3 \times 10^9$ people that is widely cited in some discussions of "coastal" population [e.g., *Hinrichsen*, 1998].

In spite of the fact that global populations are heavily concentrated near coasts, the actual population density of these areas varies widely. Figure 3 shows the cumulative population of the near-coastal zone as a function of the cumulative land area, integrated from the lowest to the highest population densities. If all coastal areas were populated at equal density, this curve would be a straight line. According to this analysis, 40% of the near-coastal population occupies about 4% of the near-coastal land area at local population densities greater than 1000 people/km^2. The most densely-populated near-coastal areas are in Europe and south, southeast, and east Asia (e.g., Figure 1). Thus, despite the concentration of people near coasts, at the global scale, the majority of the land area within the near-coastal zone is relatively sparsely populated.

Absolute population numbers and integrated population density both decrease with elevation and distance from the shoreline, even when land area is taken into account. The maximum in population density at 10-m elevation and 10-km inland highlights two important aspects of global coastal population distribution. First, the global analysis combines widely variable population densities, so that large areas of sparsely-populated coastal land tend to offset the densely-populated near-coastal areas. This reduces integrated densities at distances less than the characteristic scale of the coastline as more tortuous coastlines have more land area in close proximity to the shore than do smoother coastlines: the effect is greatest for sparsely-populated coastlines with islands, such as in southern Chile, British Columbia, and parts of Scandinavia. Second, the displaced peak in integrated density is partly related to the distribution of coastal population centers. The maximum population density of coastal cities is usually not focused on the shoreline, but instead on some small distance inland, as illustrated in Figure 1; for example, Bangkok, and in global maps of near-coastal population distribution. See http://www.LDEO.columbia.edu/~small/CoastalPop.html, for a more detailed analysis of the results summarized here.

These estimates highlight another frequently-overlooked aspect of coastal population distribution. While coastal cities are an important focus of attention [e.g, *Timmerman and White*, 1997], most of the near-coastal population does not live in large cities. Only about one tenth of the near-coastal population identified here is found at the high population densities (>10,000 people/km^2) associated with large urban areas. Thus, the exposed population in the near-coastal zone is mainly located in smaller cities/towns and also in rural settings, such as densely-populated deltaic areas at an average density near 1000 people/km^2 (Figure 3, inset). Discussions of coastal hazard that focus on large cities and their environs therefore overlook the majority of the near-coastal population. However, urbanization has and is expected to continue to be an important process in near-coastal areas during the 21st century, so these patterns are also expected to change.

Implications

These estimates verify and quantify the common assertion that human population is heavily concentrated in coastal regions at a global scale. However, they should be interpreted as liberal upper bounds on the number of people potentially exposed to coastal hazards in 1990. While these estimates are based on the most detailed global data sets presently available to us, there are significant uncertainties due to the resolution of the underlying geophysical and socio-economic data. It is important to recognize that neither the population nor the elevation data are of sufficient resolution or accuracy to directly estimate coastal exposure to the various coastal hazards for the majority of the world's coastal regions.

The importance of coastal zones for human habitation and the uncertainties about future climatic and socio-economic conditions require a better baseline on exposure at regional and global scales, as well as at local and national scales. In particular, there is a need for transparent and consistent estimates that allow comparison between regions and the development of credible scenarios for the analysis of future conditions. Many potential users would benefit from improved estimates of coastal population and hazard exposure, from global change and hazard scientists to a range of international policy-makers and institutions interested in sustainable development. More detailed information on present and future exposure is essential to the ultimate goal of mitigating these hazards, including selecting the most appropriate mitigation policies and technologies. Sea-level rise and climate change is one area where there is widespread concern, and there has been significant assessment of coastal areas at local-national to regional-global scales [e.g., *Nicholls et al.*, 1998; *Nicholls*, 2000]. Improved data on exposure could be rapidly incorporated into active projects such as Synthesis and Upscaling of Sea-Level Rise Vulnerability Assessment Studies (SURVAS) (http://www.survas.mdx.ac.uk/) and DINAS-COAST (http://www.pik-potsdam.de/~richardk/dinas-coast/).

Improved estimates of coastal population and its exposure to hazards will require more detailed population data, higher-resolution digital elevation models, and better delineation of the areas potentially affected by each hazard, including both direct and indirect effects. Elevation is the simplest of these parameters to measure directly, and ongoing efforts are in progress to improve the available data. However, further efforts are required to produce the appropriate density of sub-meter vertical accuracy that studies of coastal hazards require. This would include the need for dedicated, detailed radar and lidar elevation mapping of coastal zones. The spatial extent of hazard zones can be modeled for known geophysical forcing and landscape characteristics. A range of methods are available, depending on the hazard and the context; for example, flood hazard maps such as those used by the U.S. National Flood Insurance Program (see http://www.fema.gov/mit/tsd/).

Indirect effects are more difficult to assess, as discussed earlier, and require detailed

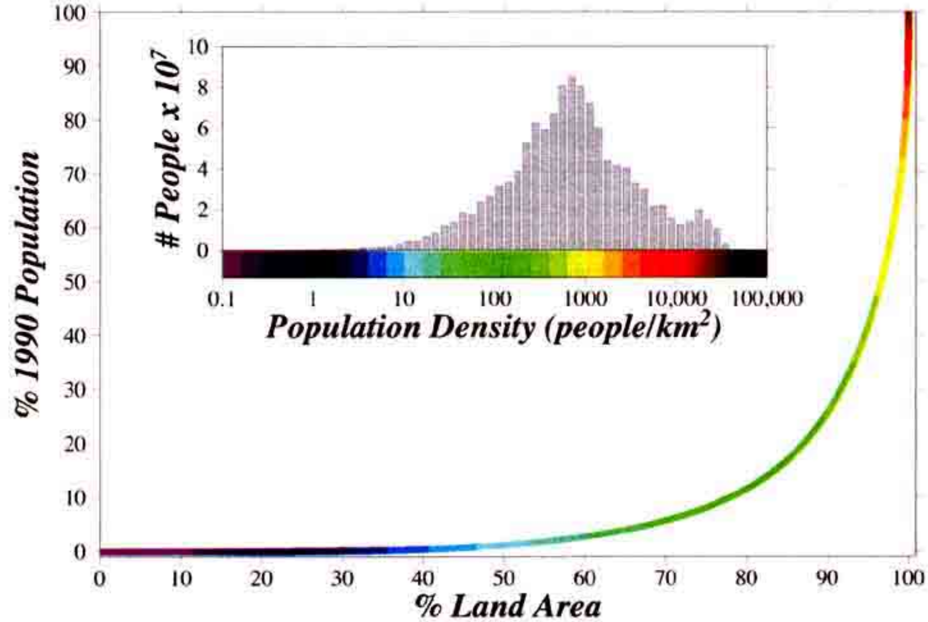

Fig. 3. Global distributions of population and land area in the near-coastal zone are shown. When cumulative population is plotted as a function of cumulative land area for increasing population density, the resulting Lorenz curve indicates how much land area is occupied by a population fraction. The inset shows the density distribution of the world's coastal populations and indicates that most coastal zone inhabitants do not live in large, high-density urban environments.

vulnerability assessment. Population data are most difficult to improve, and hence better models of distribution may be the best innovation. This includes links to data that are indicative of human population distribution such as urban areas and infrastructure. Additional population distribution constraints and assumptions are used in higher-resolution population models such as LandScan (http://www.ornl.gov/gist/projects/LandScan/SIMPLE/smaps.htm). High-resolution satellite imagery currently facilitates assessments of coastal settlement distributions, but detailed analyses of coastal exposure and risk will ideally also require detailed, spatially-explicit census collection at resolutions of hundreds of meters. While such data exist in some developed countries, comparable data are rarely available in developing countries, where coastal populations are often larger, expanding more rapidly, and more vulnerable. Focusing on those areas with the largest and most rapidly-expanding coastal populations would be one way to target resources where the benefits would be largest.

The goal of further research should be to provide the baseline information necessary for quantitative studies of the physical and socio-economic dynamics involved in the dense human habitation of these potentially hazardous areas.

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