



The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones

GORDON MCGRANAHAN, DEBORAH BALK and BRIDGET ANDERSON

Gordon McGranahan is Director of the Human Settlements Group at the International Institute for the Environment and Development (IIED) in London.

Address: IIED, 3 Endsleigh Street, London WC1H 0DD, UK; tel: +44 20 7388 2117; e-mail: Gordon.McGranahan@iied.org

Deborah Balk is Acting Associate Director of the Institute for Demographic Research at the City University of New York (CUNY) and Associate Professor at Baruch College (CUNY), New York.

Address: Baruch College, School of Public Affairs and Institute for Demographic Research, City University of New York, Box D-901, One Bernard Baruch Way, NY, NY 10010, USA; e-mail: deborah_balk@baruch.cuny.edu

Bridget Anderson is a Research Associate at the Centre for International Earth Science Information Network (CIESIN) at Columbia University, New York.

Address: CIESIN, Columbia University, 61 Route 9W, Palisades, NY 10964, USA; e-mail: banderso@ciesin.columbia.edu

Note: We have all made equally important contributions to this

ABSTRACT Settlements in coastal lowlands are especially vulnerable to risks resulting from climate change, yet these lowlands are densely settled and growing rapidly. In this paper, we undertake the first global review of the population and urban settlement patterns in the Low Elevation Coastal Zone (LECZ), defined here as the contiguous area along the coast that is less than 10 metres above sea level. Overall, this zone covers 2 per cent of the world's land area but contains 10 per cent of the world's population and 13 per cent of the world's urban population. A disproportionate number of the countries with a large share of their population in this zone are small island countries, but most of the countries with large populations in the zone are large countries with heavily populated delta regions. On average, the Least Developed Countries have a higher share of their population living in the zone (14 per cent) than do OECD countries (10 per cent), with even greater disparities in the urban shares (21 per cent compared to 11 per cent). Almost two-thirds of urban settlements with populations greater than 5 million fall, at least partly, in the zone. In some countries (most notably China), urbanization is driving a movement in population towards the coast. Reducing the risk of disasters related to climate change in coastal settlements will require a combination of mitigation, migration and settlement modification.

KEYWORDS climate change / coastal / global / hazards / population distribution / urbanization

I. INTRODUCTION

This paper focuses on human settlements, and in particular urban settlements, in low elevation coastal zones. To the extent that low elevation coastal populations are at risk from sea-level rise, stronger storms and other seaward hazards induced by climate change, it is important to assess the size of these populations and how they are distributed internationally. Similarly, it is important to gain a better understanding of how coastal settlements are changing, especially in light of the self-reinforcing and cumulative character of urban development and the difficulties inherent in shifting the direction of population movements and adapting to increasing risk. Mitigation may be the best means of avoiding risks related to climate change, but it is too late to rely solely on mitigation. Migration away from lowest elevation coastal zones will be important, but can be costly and difficult to implement without causing severe disruptions. Modification of the prevailing forms of coastal settlement, so as to protect local residents, will also be needed.

In addition to being at risk from seaward hazards, coastal populations can be a burden on coastal ecosystems, many of which are already under stress. As we have shown elsewhere, the coastal systems are more densely populated – in both urban and rural areas – than any other zones defined for the Millennium Ecosystems Assessment, except for the urban systems themselves.⁽¹⁾ This is a further reason for monitoring and adapting coastal settlements, particularly since in some circumstances the loss of ecosystem services can make urban settlements more prone to disaster, amplifying the risks of climate change.

Despite the spatial nature of changing human settlements and urban development – and their relation to environmental conditions such as coastal hazards – urbanization is often analyzed without any spatially explicit framework.⁽²⁾ Prior studies with moderate-resolution spatial data have shown that, historically, populations have preferred to live within 100 kilometres of coasts and near major rivers.⁽³⁾ But a systematic global assessment has not been undertaken of urban areas in a narrower coastal band – i.e. those at potential risk from events related to climate change. This paper fills that gap and begins to examine the implications for vulnerability to climate change.

This study integrates recently constructed, spatially explicit global databases and analyzes them to assess the distribution of population and settlement size in the low elevation coastal zone. The paper first examines the critical issues involving low elevation coastal zones and the risks of climate change. It then reviews the methodology for data integration and analysis. The findings are presented for different country groups (e.g. by region and by economic status), and for some of the countries with particularly large populations or population shares in the low elevation coastal zone. For China and Bangladesh, some of the changes between 1990 and 2000 are presented. The paper ends with a summary discussion, emphasizing some of the implications of these findings.

II. CLIMATE CHANGE, COASTAL SETTLEMENT AND URBAN VULNERABILITIES

Both urban disasters and environmental hot spots are already located disproportionately in low-lying coastal areas.⁽⁴⁾ Climate change will increase the risk of both. In particular, rising sea levels will increase the risk of floods, and stronger tropical storms may further increase the flood risk. Low-income groups living on flood plains are especially vulnerable. Given the long lead times required for climate change mitigation, this will be insufficient to prevent these risks from increasing. Moreover, most other measures, such as encouraging urban development in more environmentally suitable locations, or adapting coastal settlements to reduce their vulnerability, also have long lead times. The scale and nature of the risks need to be better understood in order to motivate and target timely measures. Much of the relevant information is local. However, given the global nature of climate change, it is also important to assess the international dimensions of the coastal risks it is already beginning to pose.

Human settlement has long been drawn to coastal areas, which provide many resources and trading opportunities but also expose residents to various hazards. Historically, the attraction of coasts has been

paper, but have followed the somewhat arbitrary convention of listing our names in order of authorship.

Acknowledgment: The authors thank Casey Hogan for assistance with the map, Karen von Muehldorfer for assistance with the graphs and Sheridan Bartlett and David Satterthwaite for their support and suggestions. Partial support for analysis of the GRUMP database was provided by the National Aeronautics and Space Administration (Contract No NAS5-03117) for the Continued Operation of the Socioeconomic Data and Applications Centre (SEDAC) at CIESIN at Columbia University. Partial support for preparing the article also came from the Swedish International Development Cooperation Agency and the Danish International Development Agency.

1. McGranahan, Gordon, Peter J Marcotullio, Xuemei Bai et al. (2005), "Urban systems", in Rashid Hassan, Robert Scholes and Neville Ash (editors), *Ecosystems and Human Well-Being: Current Status and Trends*, Island Press, Washington DC, pages 513–549.

2. Montgomery, Mark R, Richard Stren, Barney Cohen and Holly E Reed (editors) (2003), *Cities Transformed: Demographic Change and its Implications in the Developing World*, National Academy Press, Washington DC.

3. Small, C and R J Nicholls (2003), "A global analysis of human settlement in coastal zones", *Journal of Coastal Research* Vol 19, No 3, pages 584–599; also Small, Christopher and Joel Cohen (2004), "Continental physiography, climate and the global distribution of human population", *Current Anthropology* Vol 45, No 2, pages 269–277.

4. See maps in Pelling, Mark (2003), *The Vulnerability of Cities: Natural Disasters and Social Resilience*, Earthscan, London; also 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.

5. Hummels, David (1999), *Have International Transportation Costs Declined?*, University of Chicago, Chicago.

6. WTO (2004), *World Trade Report 2004*, World Trade Organization, Geneva.

7. Han, S S and Z X Yan (1999), "China's coastal cities: development, planning and challenges", *Habitat International* Vol 23, No 2, pages 217–229; also McGranahan, Gordon and Cecilia Tacoli (2006), "Rural-urban migration, urban poverty and urban environmental pressures in China", Contribution to the China Council Task Force on Sustainable Urbanization Strategies, International Institute for Environment and Development (IIED), London.

8. Rakodi, Carole and David Treloar (1997), "Urban development and coastal zone management: an international review", *Third World Planning Review* Vol 19, No 4, pages 401–424; also Timmermann, P and Rodney White (1997), "Megahydropolis: coastal cities in the context of global environmental change", *Global Environmental Change* Vol 7, No 3, pages 205–234.

9. Agardy, Tundi, Jacqueline Alder, Paul Dayton et al. (2005), "Coastal systems", in Hassan et al. (2005), see reference 1, pages 513–549.

10. Alder, Jacqueline, Russell Arthurton, Neville Ash et al. (2006), *Marine and Coastal Ecosystems and Human Well-Being*, United Nations Environmental Programme, Nairobi.

particularly strong among trading nations and empires. In Indonesia, for example, the Mataram Empire, which relied on tribute from rice farmers, favoured inland cities and monuments, while the Sri Vijaya Empire, which relied on controlling trade, favoured coastal cities. Colonialism and the expansion of international trade during the colonial period contributed to the coastal location of many contemporary cities. The recent expansion of international trade has also contributed to population movements towards the coast. The pre-eminence of ocean shipping has declined, with air freight growing in relative importance.⁽⁵⁾ At least in terms of ton-kilometres shipped, however, ocean shipping still dominates. Shipping now accounts for less than half of the value of the United States' merchandise imports and exports but about three-quarters of the weight. In other countries the decline in shipping is far less evident – for Japan the corresponding figures rise to almost three-quarters of the value and over 99 per cent of the weight.⁽⁶⁾ China's on-going economic boom is one of the clearest examples of trade-related coastward movement the world has ever seen, although one could argue that government economic policies have been as important as market pressures in causing this movement.⁽⁷⁾

The concentration of populations and economic activities on and near the coast has had serious environmental consequences. Urban systems have radically altered the flows of water, energy and materials, transforming the pre-existing ecosystems.⁽⁸⁾ The review of coastal systems undertaken for the Millennium Ecosystem Assessment concluded that coastal ecosystems, both onshore and offshore, are among the most productive in the world, and also among the most threatened by human settlement.⁽⁹⁾ It is estimated that about one-third of coastal mangrove forests and one-fifth of coral reefs have already been lost.⁽¹⁰⁾ In many parts of the world, coastal fish populations have declined considerably. When scientists recently reviewed conditions in 12 harbours of major Asian cities, all but one had exhibited drastic fishery declines (as well as numerous other environmental problems) in recent decades.⁽¹¹⁾

Many coastal populations are at risk from flooding – particularly when high tides combine with storm surges and/or high river flows. Between 1994 and 2004, about one-third of the 1,562 flood disasters, half of the 120,000 people killed, and 98 per cent of the 2 million people affected by flood disasters were in Asia, where there are large population agglomerations in the flood plains of major rivers (e.g. Ganges–Brahmaputra, Mekong and Yangtze) and in cyclone-prone coastal regions (e.g. Bay of Bengal, South China Sea, Japan and the Philippines).⁽¹²⁾

Some features of urban development increase the risk of flooding. Water drains more rapidly from built-over land, increasing peak flows and flood risks, particularly if the built drainage system is not adapted accordingly. In many parts of the world, developers have drained wetlands, sometimes reducing malaria prevalence or opening up valuable land for urban development, but also removing a buffer against tidal floods. Particularly in delta regions, land compaction, subsidence due to groundwater withdrawal and reductions in the rate of sediment deposition (due to water regulation) can lead, in effect, to sea-level rise, increasing flood risk (as well as creating various other problems).⁽¹³⁾

While economic activity and urban development often increase the environmental pressures that lead to flooding, low-income settlements, and poor groups within all settlements, tend to be the most vulnerable.

On the one hand, affluent settlements and groups are in a better position to take protective measures and to adapt or escape when flooding does occur (as media coverage and research on hurricane Katrina and New Orleans amply demonstrated).⁽¹⁴⁾ On the other hand, the poorest residents of the cities of low-income countries are often forced (implicitly or explicitly) to settle in flood plains or other hazard-prone locations, as they cannot afford more suitable alternatives.⁽¹⁵⁾

Climate change will increase the risk of flooding, as well as causing other environmental damage in coastal areas.⁽¹⁶⁾ The estimates of global-mean sea-level rise in the Special Report on Emissions Scenarios of the Intergovernmental Panel on Climate Change (IPCC) range from 22 centimetres to 34 centimetres, between 1990 and the 2080s.⁽¹⁷⁾ Far faster sea-level rise (more than a metre per century) could result from accelerated melting of the Greenland ice sheet or the collapse of the West Antarctic ice sheet, although this is not considered likely during the twenty-first century.⁽¹⁸⁾ It has been estimated that, in the absence of any other changes, a sea-level rise of 38 centimetres would increase five-fold the number of people flooded by storm surges.⁽¹⁹⁾

The risks to human settlements could be reduced if people and enterprises could be encouraged to move away from the coast, or at least from the most risk-prone coastal locations (this would also reduce the pressures human settlements place on coastal ecosystems). As described in more detail below, current population movements are in the opposite direction. Given the character of urban development, and that the factors driving coastward movement are still poorly understood, turning these flows around is likely to be slow, costly or both. In particular, there is the danger that ill-considered or politically short-sighted measures to shift population from the coastal areas will impose unnecessary economic costs on key coastal enterprises and fail to provide the basis for viable alternatives inland or in more appropriate coastal locations. More appropriate measures are sorely needed, and the earlier the better.

Few of the environmental disadvantages of coastal urbanization are reflected in the economic incentives that drive urban development. Moreover, the economic advantages typically ascribed to urban agglomeration are based primarily on the benefits that come from people and enterprises clustering, and only secondarily on the natural features that make some (e.g. coastal) locations more attractive than others.⁽²⁰⁾ A comparatively small natural advantage – which may soon cease to be an advantage at all⁽²¹⁾ – can eventually make the difference between a future megacity and a lightly developed stretch of coast or patch of farmland. Larger urban settlements, and more urban regions generally, tend to stay larger and more urban for very long periods.⁽²²⁾ Most urban infrastructure is immobile and long lasting, making rapid shifts in urban location very costly. Moreover, urban settlements tend to be nodes of growth, attracting more enterprises and people. As a result, urban settlement is highly path-dependent, with urban coastal settlement past and present likely to attract more urban coastal settlement in the future.

In order to support efficient and equitable means for moving the most vulnerable urban settlements, a better understanding is needed of why (and in some cases whether) urban settlements in coastal areas are growing more rapidly than inland. Avoiding policies that favour coastal development (such as the special economic zones in China, whose rapid population growth is described below), and imposing more effective

11. Wolanski, Eric (editor) (2006), *The Environment in Asia Pacific Harbours*, Springer, Dordrecht.

12. Few, Roger and Franziska Matthies (2006), *Flood Hazards and Health: Responding to Present and Future Risks*, Earthscan, London.

13. Ericson, Jason P, Charles J Vorosmarty, S Lawrence Dingman, Larry G Ward and Michel Meybeck (2006), "Effective sea-level rise and deltas: causes of change and human dimension implications", *Global and Planetary Change* Vol 50, pages 63–82.

14. Dreier, P (2006), "Katrina and power in America", *Urban Affairs Review* Vol 41, No 4, pages 528–549.

15. Hardoy, Jorge E, Diana Mitlin and David Satterthwaite (2001), *Environmental Problems in an Urbanizing World*, Earthscan, London.

16. For summaries of the range of different environmental consequences of climate change, see Nicholls, Robert J (2002), "Rising sea levels: potential impacts and responses", *Issues in Environmental Science and Technology* Vol 17, pages 83–107; also Nicholls, Robert J, Poh Poh Wong, Virginia Burkett et al. (2006), "Coastal systems and low-lying areas", in *IPCC WGII Fourth Assessment Report – Draft for Government and Expert Review*; and Klein, Richard J T, Robert J Nicholls and Frank Thomalla (2003), "Resilience to natural hazards: how useful is this concept?", *Environmental Hazards* Vol 5, pages 35–45.

17. Nicholls, Robert J (2004), "Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socioeconomic scenarios", *Global Environmental Change* Vol 14, No 1, pages 69–86.

18. See reference 16, Nicholls et al. (2006).

19. Nicholls, Robert J, Frank M J Hoozemans and Marcel

Marchand (1999), "Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses", *Global Environmental Change* Vol 9, pages 69–87.

20. See, for example, Fujita, Masahisa, Paul R Krugman and Anthony Venables (1999), *The Spatial Economy: Cities, Regions and International Trade*, MIT Press, Cambridge, Mass; also Fujita, Masahisa and Jacques-François Thisse (2002), *Economics of Agglomeration: Cities, Industrial Location and Regional Growth*, Cambridge University Press, Cambridge, UK; and Henderson, J Vernon and Jacques François Thisse (editors) (2004), *Handbook of Regional and Urban Economics: Volume 4, Cities and Geography*, Elsevier North Holland, Amsterdam.

21. Some argue that the ecological reasons why cities originally located in coastal areas have been reversed. See reference 8, Timmermann and White (1997).

22. United Nations (2004), *World Urbanization Prospects: The 2003 Revision*, United Nations, New York; also Gabaix, Xavier and Yannis M Ioannides (2004), "The evolution of city size distributions", in Henderson and Thisse (editors), see reference 20, pages 2341–2378.

23. See reference 12.

24. See reference 16, Klein et al. (2003).

25. Bigio, Anthony G (2003), "Cities and climate change", in Alcira Kreimer, Margaret Arnold and Anne Carlin (editors), *Building Safer Cities: The Future of Disaster Risk*, World Bank, Washington DC, pages 91–99.

26. As a validation to our LECZ zone, we generated summary statistics based on the Millennium Ecosystem Assessment's (MA) coastal boundary, which we also constrained to 10 metres or less in elevation. Although there were some inconsistencies between the MA boundaries and population/land area data sets used here, the results were quite similar.

coastal zone management, could make a difference in the longer term. Relatively small shifts in settlement location, out of a coastal plain onto more elevated ground, can make a major difference. However, experience after the Indian Ocean tsunami of 2004, in which over 200,000 people lost their lives and millions more their homes,⁽²³⁾ has demonstrated the profound difficulties involved in instituting more restrictive coastal settlement policies without further undermining the lives and livelihoods of the most vulnerable residents.

Coastal development can also be encouraged to adapt to the risks of climate change. To date, adaptation motivated by climate change has been minimal. However, measures to reduce exposure to existing weather-related hazards can also serve as means of adapting to climate change.⁽²⁴⁾ Embedding adaptive measures within the urban infrastructure is again either very costly or very slow. It is likely to be easier if action is taken as new areas are settled, rather than after their infrastructure is in place. It has been suggested that development assistance projects could introduce measures to assist in adaptation to climate change.⁽²⁵⁾ More generally, there are likely to be important areas of overlap between adaptation to climate change, other forms of disaster preparedness and measures to address local environmental health issues (e.g. improved water, sanitation, waste disposal and drainage systems). Particularly for the urban poor, an equitable resolution of the land issues that drive people to settle on land already susceptible to flooding could make a large difference.

Though local and regional information is needed in order to assess the risks of climate change and to identify opportunities for adaptation, climate change is a global phenomenon. Assessment of its international dimensions is important not only to target national, regional and local policy efforts but also to mount international responses.

III. ESTIMATING POPULATION AND HUMAN SETTLEMENT PATTERNS IN LOW ELEVATION COASTAL ZONES

This study integrates recently developed spatial databases of finely resolved global population distribution, urban extents and elevation data to produce country-level estimates of urban land area and population in low elevation coastal zones (LECZs). The data set is complex but the basic approach is simple: by overlaying geographic data layers, we calculate the population and land area in each country, in its LECZ, and then summarize by country, region and economic grouping.

Three geographic data sets are required. The first delineates the extent of the LECZ itself. We defined the LECZ as land area contiguous with the coastline up to a 10-metre rise elevation,⁽²⁶⁾ based on the measure from the Shuttle Radar Topography Mission (SRTM) elevation data set.⁽²⁷⁾ In some places, mostly the mouths of major rivers such as the Amazon in Brazil and the Yenisey river in Russia, the LECZ extends well beyond 100 kilometres inland, although for most of its extent, the zone is much less than 100 kilometres in width.⁽²⁸⁾

Sea-level rise is not expected to reach anything like 10 metres above the current mid-tide elevations, at least in the foreseeable future. Even with storm surges, the 10 metres elevation leaves a large margin of safety regarding direct flooding. Sea-level rise and storm surges can certainly cause damage to people living well above the high-water level, through

saline intrusion into the groundwater, for example. However, the principal reason for choosing this elevation is that estimates based on elevations below 10 metres could not be considered globally reliable, particularly in some types of coastal areas such as those characterized by mountainous bays.⁽²⁹⁾

The second required data set is one that delineates urban footprints. The only globally consistent urban footprint data set is Columbia University's Centre for International Earth Science Information Network's Global Rural Urban Mapping Project (GRUMP).⁽³⁰⁾ GRUMP urban extents are based largely on the NOAA's night-time light "city lights" 1994/95 satellite data set coupled with settlement information (e.g. name and population) to verify that the lighted area corresponds to a human settlement (rather than an industrial location, for example).⁽³¹⁾

While the lights are not a perfect proxy for the footprint of urban areas, the consistency of measurement and global coverage make them the most reliable satellite source available for this purpose. The lights are characterized by an "overflow", that is, an overestimation of areal extent due to the intrinsic characteristics of the sensor.⁽³²⁾ In practice, this means that the GRUMP urban footprints largely represent urban agglomerations including their surrounding suburban and perhaps peri-urban areas.⁽³³⁾

The third data set required for this analysis is a population grid for each country, and associated with each grid cell, the land area. Estimates for population (1990 and 2000) and land area are based on the GRUMP gridded data sets, which are created from a compilation of geo-referenced census data for each country as allocated to urban extents and surrounding rural areas.⁽³⁴⁾

All data are expressed at one-kilometre resolution. As with overlays of any geographic data sets, precision and spatial correspondence at coastlines can substantially influence estimates. In this analysis, the GRUMP urban footprints, population and land area grids all share the same coastal boundaries. In most instances, these corresponded very well with the elevation buffer, but small islands were the most likely to display inconsistencies due to imprecision and inaccuracies associated with the geo-coding of small islands. Therefore, the LECZ extends beyond the coastline to include areas with bathymetry down to -4,000 metres to accommodate minor mismatches between the elevation and GRUMP data sets. Calculations of exposed urban and rural persons and land area are made and summarized for each country and continent. Figure 1 illustrates, for the central China coast, the data layers with which the calculations were made.

IV. THE INTERNATIONAL DISTRIBUTION OF LOW ELEVATION COASTAL SETTLEMENT⁽³⁵⁾

The LECZ contains some 2 per cent of the world's land and 10 per cent of its population, based on estimates for 2000.⁽³⁶⁾ Of the somewhat more than 600 million people living in the zone, 360 million are urban. This implies an urbanization level of 60 per cent, compared to a world urbanization level of slightly less than 50 per cent.

There is considerable variation between countries in the shares of population, land and urban settlement in this LECZ. Thus, of the 224 countries for which there are data on all of the principal indicators being

27. ISciences (2003), SRTM30 Enhanced Global Map – Elevation/Slope/Aspect (release 1.0), ISciences, LLC, Ann Arbor (based on the raw SRTM data from Jet Propulsion Laboratory).

28. Only a small fraction of the buffer includes land areas beyond 100 kilometres. In contrast, some prior estimates of coastal population have relied exclusively on buffers of at least 100 kilometres (see reference 3).

29. Farr, T G and M Kobrick (2000), "Shuttle radar topography mission produces a wealth of data", *Transactions of the American Geophysical Union* Vol 81, pages 583–585; also Rabus, B, M Eineder, A Roth and R Bamler (2003), "The shuttle radar topography mission – a new class of digital elevation models acquired by spaceborne radar", *Journal of Photogrammetry & Remote Sensing* Vol 57, pages 241–262.

30. Global Rural–Urban Mapping Project, alpha version (GRUMP alpha), Centre for International Earth Science Information Network (CIESIN), Columbia University, International Food Policy Research Institute (IFPRI), The World Bank and Centro Internacional de Agricultura Tropical (CIAT) (2004), "Global Rural–Urban Mapping Project (GRUMP), alpha version: urban extents grids", Socioeconomic Data and Applications Centre (SEDAC), Columbia University, Palisades, NY, accessible at <http://sedac.ciesin.columbia.edu/gpw> (February 2006); also Balk, D, F Pozzi, G Yetman, U Deichmann and A Nelson (2005), "The distribution of people and the dimension of place: methodologies to improve the global estimation of urban extents", International Society for Photogrammetry and Remote Sensing, Proceedings of the Urban Remote Sensing Conference, March 2005, Tempe, AZ.

31. Where lights are insufficient to detect urbanized areas, alternate estimates of urban extent are used. Examples of alternate urban extent data

RISKS OF CLIMATE CHANGE IN LOW ELEVATION COASTAL ZONES

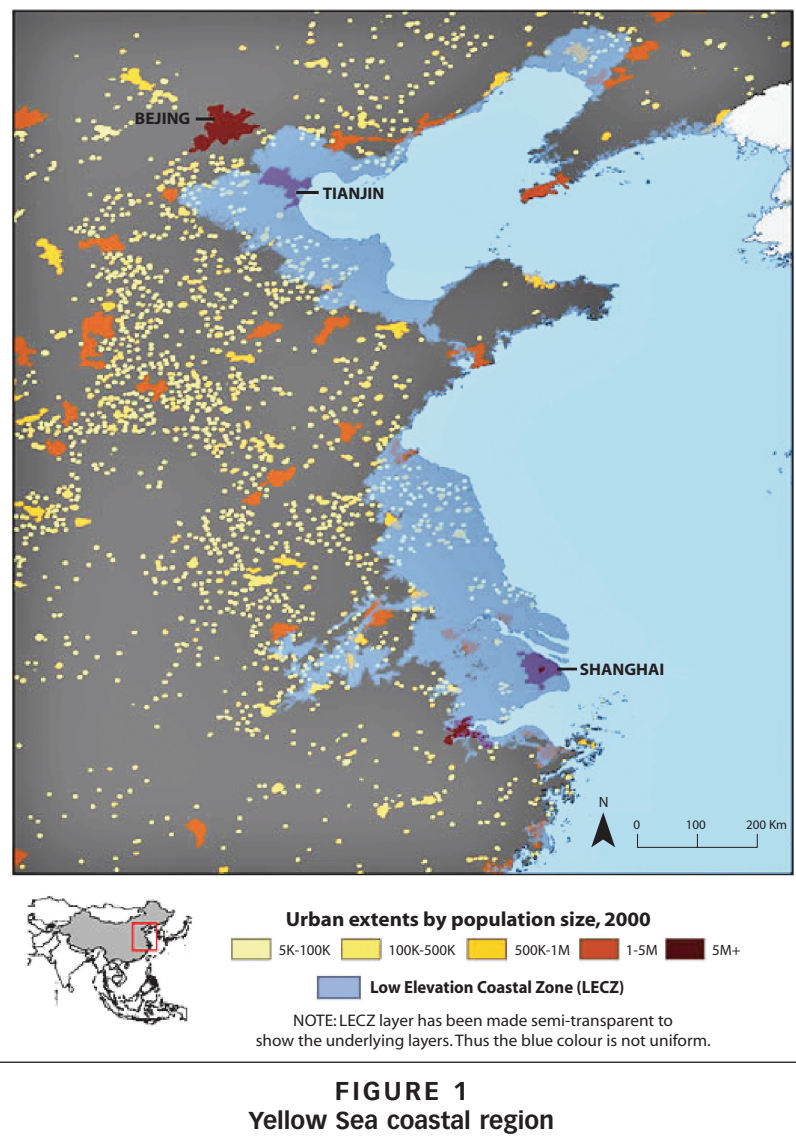
sets include Digital Chart of the World, Tactical Pilotage Charts. Extents are also modelled with regression estimators. See reference 30, Balk et al. (2005).

32. Elvidge, C D, J Safran, I L Nelson, B T Tuttle, V R Hobson, K E Baugh, J B Dietz and E H Erwin (2004), "Area and position accuracy of DMSP nighttime lights data", in R S Lunetta and J G Lyon (editors), *Remote Sensing and GIS Accuracy Assessment*, CRC Press, chapter 20, pages 281–292.

33. The lights "overglow" under all conditions, so that in coastal zones the lights would glow over the ocean where there was no corresponding land. Thus, we have determined the fraction of all lights that appear over water to be 6 per cent globally. For coastal urban areas, the areas over water have been clipped (as have all major water bodies), but for urban extents not intersecting a coastline we have adjusted the estimated land area total of those urban extents by 6 per cent. The urban footprints falling in coastal areas also experience overglow on their non-water edges but, at this time, no adjustment for those areas has been made.

34. Global Rural–Urban Mapping Project, alpha version (GRUMP alpha), Centre for International Earth Science Information Network (CIESIN), Columbia University, International Food Policy Research Institute (IFPRI), The World Bank and Centro Internacional de Agricultura Tropical (CIAT) (2004), "Gridded population of the world, version 3, with urban reallocation (GPW–UR)", Socioeconomic Data and Applications Centre (SEDAC), Columbia University, Palisades, NY, accessible at <http://sedac.ciesin.columbia.edu/gpw> (February 2006).

35. This section includes an updated version of major parts of McGranahan, Gordon, Deborah Balk and Bridget Anderson (2006), "Low coastal zone settlements", *Tiempo* No 59, pages 23–26. Please note that some of the statistics have changed as a result of



presented in this article, 41 are landlocked and have no population living in the LECZ,⁽³⁷⁾ while 21 have more than 50 per cent of their population in this zone (16 of these are Small Island States, or SISs). There is also considerable variation in the levels and rates of urbanization and in the distribution of population among settlements of different sizes. This variation is not always evident in the paragraphs and tables below, which rely heavily on averages and highly aggregated statistics.

a. Distribution by region

Table 1 provides a selection of statistics by IPCC region.⁽³⁸⁾ In absolute numbers, Asia accounts for about one-third of the world's land in the

TABLE 1
Population and land area in the Low Elevation Coastal Zone (LECZ) by region, 2000

Region	Population and land area in LECZ				Share of population and land area in LECZ			
	Population (million)		Land ('000 km ²)		Population (%)		Land (%)	
	Total	Urban	Total	Urban	Total	Urban	Total	Urban
Africa	56	31	191	15	7	12	1	7
Asia	466	238	881	113	13	18	3	12
Europe	50	40	490	56	7	8	2	7
Latin America	29	23	397	33	6	7	2	7
Australia and New Zealand	3	3	131	6	13	13	2	13
North America	24	21	553	52	8	8	3	6
Small Island States	6	4	58	5	13	13	16	13
World	634	360	2,700	279	10	13	2	8

LECZ, but because of far higher population densities it accounts for two-thirds of the urban population and almost three-quarters of total population in the zone.

The region with the highest share of its total land area in the zone is, not unexpectedly, the Small Island States, with about 16 per cent – roughly five times the share in Asia.³⁹ What is more surprising is that the share of the total population of the Small Island States that are in the zone is, at 13 per cent, only 3 per cent above the world average, while the urban population share, also at 13 per cent, is the same as the world average. On the other hand, Africa, the only region with as little as one per cent of its land in the zone and one of the lowest population shares in the zone, has 12 per cent of its urban population there.

b. Distribution by national income

A country's vulnerability to coastal hazards depends in part on its per capita income. Table 2 provides summary statistics for countries grouped according to the World Bank's national income classification (the world totals are slightly less in this table due to missing income data for some countries and territories).

There is no obvious reason to expect a country's income to be systematically related to the share of its population in the coastal zone, and none appears in this table. The upper-middle-income countries do, on average, have appreciably lower shares of their population and urban population in the LECZ, but otherwise the shares are similar across the different groups. Overall, there are about 247 million people in low-income countries living in the zone, of which some 102 million are urban.

While there is no statistically significant difference between the high-income and low-income countries in the fraction of the total populations living in the LECZ, the difference in average urban population shares is significant ($p < 0.05$). As illustrated in Figure 2, the tendency for the LECZ to be more urbanized than the rest of a country applies to all income

some of the data refinements discussed in the previous section.

36. Unless stated otherwise, estimates are for the year 2000.

37. There are 42 landlocked countries in the data set but the LECZ extends into one – Moldova.

38. IPCC regions used here are as defined by the Intergovernmental Panel on Climate Change (IPCC) for Working Group 2. Countries not in the IPCC list were assigned to one of the regions.

39. For the purposes of Table 1, this group has 65 members, 32 of which are not listed as Small Island States in the IPCC regional listing.

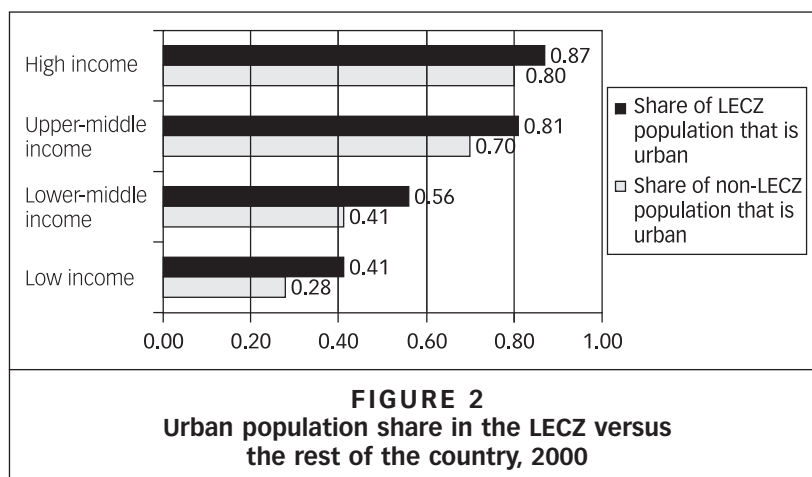
TABLE 2
Population and land area in the Low Elevation Coastal Zone (LECZ)
by national income, 2000

Income group	Population and land area in LECZ				Share of population and land area in LECZ			
	Population (million)		Land ('000 km ²)		Population (%)		Land (%)	
	Total	Urban	Total	Urban	Total	Urban	Total	Urban
Low income	247	102	594	35	10	14	2	8
Lower-middle income	227	127	735	70	11	14	2	8
Upper-middle income	37	30	397	42	7	9	2	8
High income	107	93	916	129	12	12	3	9
World	618	352	2,642	275	10	13	2	8

N.B. Total population estimate for the world does not match that found in Table 1 because no income classification was available for several countries.

levels, but the difference is more pronounced in the lower-income groups (41 per cent as compared to 28 per cent). It is not only evident that wealthier countries are more urban overall, but their balance between the fractions of urban dwellers within and outside of the LECZ narrows considerably. Thus, while the LECZ urbanization level is about 1.1 times that of the rest of the land area in high-income countries, this figure rises to almost 1.5 in low-income countries. One might wonder why the trend does not reverse (that is, with greater urban fractions outside the LECZ) among the higher-income countries. The fact that it does not underscores the strong preference for vulnerable and dense coastal dwelling, with greater relative vulnerabilities found in the poorest countries.

There are marked differences in the LECZ population shares of two politically important income-related groups engaged in climate change negotiations: the Least Developed Countries (LDCs), 50 very low-income



countries whose economic status is explicitly recognized as making them particularly vulnerable; and the Organization for Economic Cooperation and Development (OECD), 30 mostly high-income countries committed to fostering democratic government and market economy. The LDC group has a particularly high share of its population and urban population in the LECZ (14 and 21 per cent, respectively), despite a comparatively modest land share (1.2 per cent). OECD countries, in contrast, only have 10 per cent of their overall population and 11 per cent of their urban population in the zone, with about 2.8 per cent of the land in the zone.

As indicated above, these averages hide a great deal of variation, with some countries having far larger shares or quantities of land and population in the zone than others in the same group. Thus, for example, the figures for the Least Developed Countries are heavily influenced by Bangladesh, which accounts for two-thirds of the group's population in the LECZ.

c. Country rankings

The distribution of population in the LECZ closely corresponds to the list of the world's most populous countries: China, India, Brazil, the USA and Indonesia are all found among the top 20. The top 10 alone account for close to three-quarters of the total population of the zone, and the top 20 account for 85 per cent of the entire zone. Table 3 presents the top 10 countries, first in terms of the actual number of people living in the zone and then in terms of the share of the country population living in the zone.

TABLE 3
Ranking of countries with largest population counts and shares in the Low Elevation Coastal Zone (LECZ), 2000

Top ten	Ranked by total population in the LECZ				Ranked by share of population in the LECZ			
	Country	Overall rank*	Population in the LECZ Counts ('000)	%	Country**	Overall rank*	Population in the LECZ Counts ('000)	%
1	China	1	143,880	11	Bahamas	174	267	88
2	India	2	63,188	6	Suriname	170	318	76
3	Bangladesh	8	62,524	46	Netherlands	59	11,717	74
4	Vietnam	13	43,051	55	Vietnam	13	43,051	55
5	Indonesia	4	41,610	20	Guyana	157	415	55
6	Japan	9	30,477	24	Bangladesh	8	62,524	46
7	Egypt	16	25,655	38	Djibouti	160	289	41
8	USA	3	22,859	8	Belize	179	91	40
9	Thailand	19	16,478	26	Egypt	16	25,695	38
10	Philippines	14	13,329	18	The Gambia	150	494	38

*Refers to overall rank in total population.

**Countries with a total population of under 100,000 people, or smaller than 1,000 square kilometres were excluded from this list. If all countries were included, 7 of the top 10 would be places with fewer than 100,000 persons, the top 5 having more than 90 per cent of their country in the LECZ (Maldives, Marshall Islands, Tuvalu, Cayman Islands, Turk and Caicos Island).

RISKS OF CLIMATE CHANGE IN LOW ELEVATION COASTAL ZONES

The 10 countries with the highest numbers of people in the LECZ are not only populous but can mostly be characterized as large countries in Asia with significant delta regions. Indeed, there are only two non-Asian countries on the list – Egypt and the United States. The low elevation coastal zones of these top 10 countries combine to account for about 463 million people, or about 73 per cent of the people who live in the zone globally. These same countries account for about 241 million urban dwellers, or 67 per cent of the urban population in the zone. Indeed, the top 10 countries with the largest population in the zone are also among the top 10 ranked by their urban population in the zone, except that the Netherlands, with its highly urban population, replaces the Philippines in tenth place.

The shares of the 10 countries with the highest shares of population in the LECZ range from 38 per cent to 88 per cent, and only one is a Small Island State – top-ranked Bahamas. However, as indicated in a note to the table, this ranking would have been dominated by Small Island States were it not that countries with populations of under 100,000, or areas of less than 1,000 square kilometres, were excluded from Table 3. Looked at in another way, many of the smallest countries in the world are Small Island States with a large share of their population living in low elevation coastal zones. Thus, of the 20 smallest countries (by population) included in this analysis, 16 are Small Island States and more than half of these have over 38 per cent of their population in the zone. Even with these small countries eliminated, only three countries are in the top 10 in terms of both overall numbers of persons in the LECZ and the share of population in the zone: Bangladesh, Vietnam and Egypt.

A noteworthy aspect of the list of the top 10 countries with the highest shares of population in the LECZ is that, with the exception of the Netherlands and the Bahamas, these are all low- or lower-middle-income countries. This level of dominance of low- and lower-middle-income countries suggests a relationship between a country's income and its likelihood of being on the list. Low- and lower-middle-income countries make up only 56 per cent of the countries that could have been on the list and, if there were no relationship, the probability of finding eight or more of the countries on the list from this group would be about one in ten.

Figure 3 includes the 50 countries with the largest population shares in the LECZ, sorted by share of the population living in the zone, and illustrating the shares of rural and urban population in the zone. With some important exceptions – notably Bangladesh and Vietnam – most countries with large population shares in the zone have particularly large shares of their urban populations in the zone.

Turning to the top 10 countries with the largest land areas in the low elevation coastal zone (Table 4), Asia is less dominant, with the top three ranking countries being Russia, Canada and the United States. The top 10 countries account for about 61 per cent of the overall land in the zone and about 53 per cent of the population. As with population, the ranking in terms of the share of land in the zone is very different, with only Vietnam appearing in both lists. Also, just as India appeared second in the population ranking simply by virtue of its large overall population, Russia and Canada appear in the land area ranking simply by virtue of their large size.

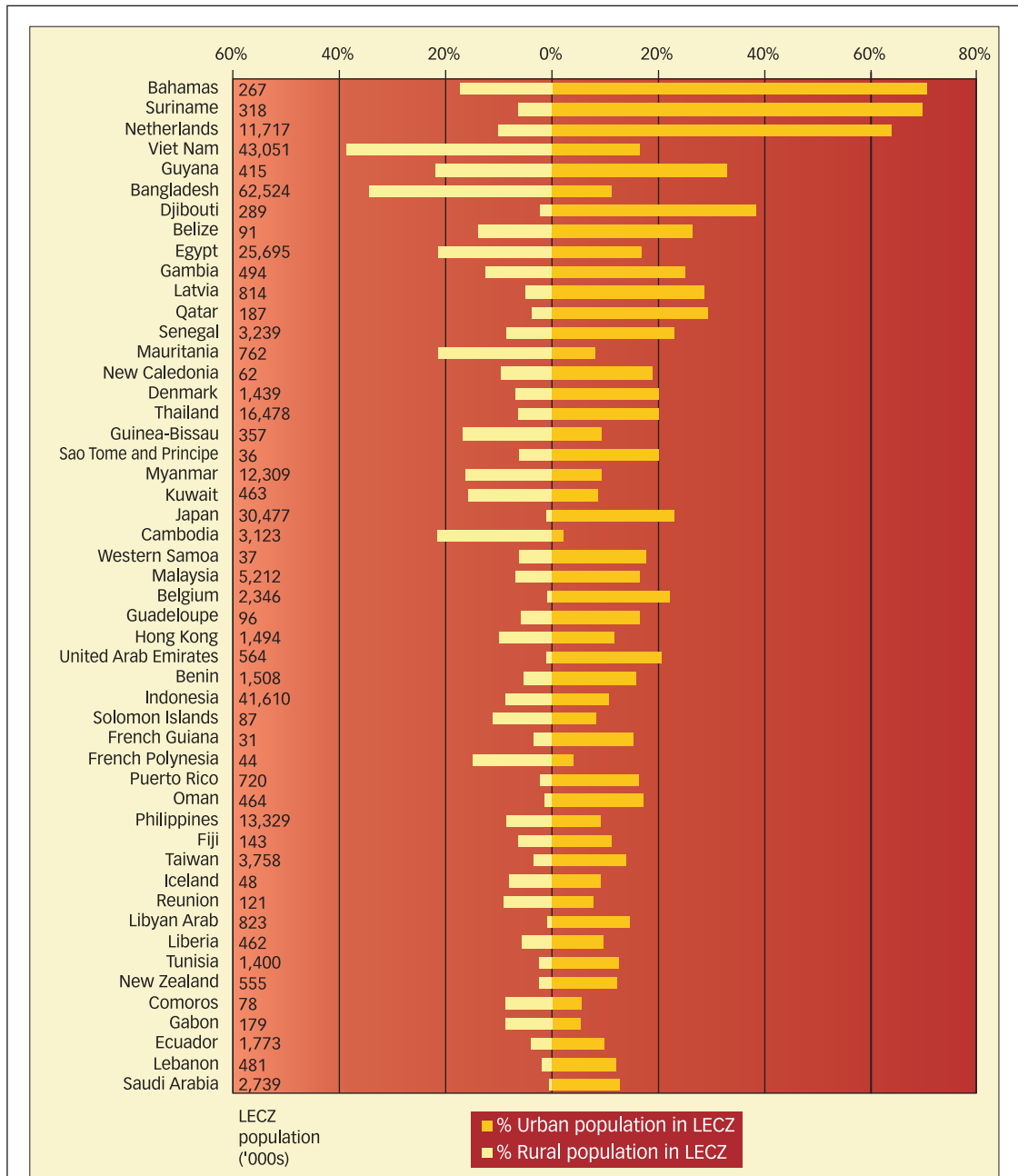


FIGURE 3
Share of country urban and rural population in the Low Elevation Coastal Zone for the 50 countries with the highest total share of population

N.B. Numbers next to country names refer to the total number of people in the country that live in the LECZ.

RISKS OF CLIMATE CHANGE IN LOW ELEVATION COASTAL ZONES

TABLE 4
Countries with largest amount and share of land in the Low Elevation Coastal Zone (LECZ), 2000

Ranked by total land area in the LECZ					Ranked by share of their land in the LECZ			
Top ten	Country	Overall rank*	Land area in LECZ		Country**	Overall rank*	Land area in LECZ	
			('000 km ²)	%			('000 km ²)	%
1	Russia	1	276	2	Bahamas	158	12	93
2	Canada	2	262	3	Netherlands	132	31	75
3	USA	4	235	3	Bangladesh	93	54	40
4	China	3	182	2	French Polynesia	171	1	32
5	Indonesia	15	177	9	The Gambia	163	3	26
6	Australia	6	122	2	Denmark	131	11	26
7	Brazil	5	122	1	Qatar	162	3	23
8	Mexico	13	93	5	Cuba	102	23	21
9	India	7	82	3	Vietnam	65	66	20
10	Vietnam	65	66	20	Guinea-Bissau	137	7	19

* Refers to overall rank in total land area.
** Countries with a total population of under 100,000 people, or smaller than 1,000 square kilometres were excluded from this list.

d. Distribution of settlements of different sizes

Just as the LECZ contains a greater share of the world's urban population than of its rural population, it also contains a greater share of large urban settlements (and their inhabitants) than of small urban settlements. This is not surprising. On the one hand, the higher population densities and concentrations of commerce and industry in coastal areas favour not only urbanization but also larger urban settlements. On the other hand, one of the roles of urban settlements inland is to link rural populations with the wider polity and economy, and since the rural populations are dispersed, their administrative and market centres tend to be comparatively small and dispersed, although many are large enough to be considered urban.⁽⁴⁰⁾

Table 5 displays the distribution of urban settlements of different sizes, treating a settlement as being in the zone if any part of it extends into the zone. Overall, while only 13 per cent of urban settlements with populations under 100,000 extend into the LECZ, the share rises steadily to reach 65 per cent of the settlements with populations over 5 million. While there are also regional variations, with the urban settlements of the small islands and of Australia and New Zealand being notably more coastal than those of any other region, the tendency for larger urban settlements to be more likely to overlap the low elevation coastal zone applies to every region.

The data in Table 5 should not be taken to reflect the degree to which residents of different-sized urban settlements live in the LECZ. On average, only 33 per cent of the population of an urban settlement whose footprint overlaps with the zone actually live in the zone. Moreover, there

40. Satterthwaite, D and C Tacoli (2003), "The urban part of rural development: the role of small and intermediate urban centres in rural and regional development and poverty reduction", Working Paper 9 in the Rural-Urban Interactions Series, IIED, London.

TABLE 5
Share of urban settlements whose footprints intersect the
Low Elevation Coastal Zone (LECZ) by urban settlement size, 2000

Region	<100K (%)	100–500K (%)	500K–1M (%)	1–5M (%)	5M+ (%)
Africa	9	23	39	50	40
Asia	12	24	37	45	70
Europe	17	22	37	41	58
Latin America	11	25	43	38	50
Australia and New Zealand	44	77	100	100	NA
North America	9	19	29	25	80
Small Island States	51	61	67	100	NA
World	13	24	38	44	65

are differences both regionally and by settlement size class. One would expect smaller coastal settlements to have, on average, a higher share of their population in the zone, if only because they are less likely to extend long distances inland. There is some evidence for this. Thus, for example, as illustrated in Figure 4, among those settlements that do intersect with the LECZ, the share that actually lives in the zone ranges from 45 per cent in the settlements of under 100,000 people to 26 per cent in the settlements with between 1 and 5 million, with considerable regional variation.⁽⁴¹⁾

Table 6 presents the shares of urban population in the low elevation coastal zone by settlement size, for all urban settlements including those that do not overlap with the zone. Here, the tendency for larger urban settlements to be more coastal is somewhat less evident, and the differences between the settlement size groupings appear to be less systematic. The world average share of the population of cities over 5 million in the zone is a very high 21 per cent, but this average is highly influenced by the coastal location of large Asian cities, in which 32 per cent of the population of cities over 5 million resides in the LECZ.

Africa, although it contributes much less to the statistics on largest cities, has higher shares of its population in cities of 100,000 to 5 million people living in the LECZ than does Asia, Europe or the Americas. This is noteworthy because Africa's medium-to-large cities are growing at much higher rates than cities in these other continents. Given that the African cities tend to be much poorer than cities elsewhere, this raises the question of their potential vulnerability.

Table 7 shows the shares of urban land area in the LECZ by settlement size for all urban settlements, including those that do not overlap with the zone. The land shares follow a similar pattern to those of population, although they are generally lower as coastal settlements tend to be more densely settled. The increasing share associated with larger urban settlements is most evident in Asia, and hard to discern in other regions. The pattern is very different in the Small Island States, where the smallest settlements have both the largest share of population and the largest share of land area in the zone. It should be noted, however, that more than 80 per cent of the SIS urban areas have a population of less than 100,000 (and all but nine urban areas, about 95 per cent, have a population of less than 500,000).

41. Based on the nature of the underlying gridded data sets, these estimates assume that population is distributed evenly within the urban area. This could exaggerate the share in the zone if, for example, people intentionally avoided settling in the flood plains, or could underestimate that share if, for example, the less densely populated urban fringe were located inland and out of the zone.

RISKS OF CLIMATE CHANGE IN LOW ELEVATION COASTAL ZONES

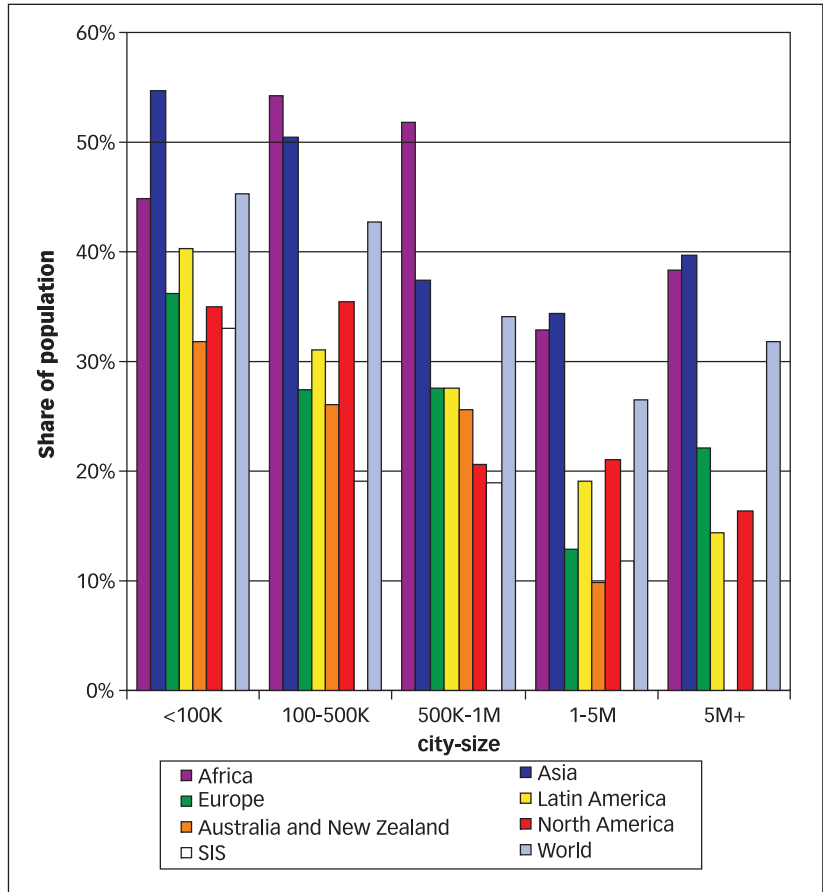


FIGURE 4
The share of population living in the LECZ for settlements intersecting the LECZ, grouped by settlement size and region, 2000

TABLE 6
Share of population (%) in the Low Elevation Coastal Zone (LECZ) for all urban settlements grouped by size, 2000

Region	<100K	100-500K	500K-1M	1-5M	5M+
Africa	5	15	20	18	10
Asia	8	13	14	16	32
Europe	6	7	11	6	12
Latin America	6	8	12	7	6
Australia and New Zealand	16	20	26	10	NA
North America	4	7	6	5	13
Small Island States	18	11	13	12	NA
World	7	11	13	12	21

TABLE 7
Share of land area (%) in the Low Elevation Coastal Zone (LECZ)
for all urban settlements grouped by size, 2000

Region	<100K	100–500K	500K–1M	1–5M	5M+
Africa	4	7	18	13	4
Asia	6	10	10	13	27
Europe	6	6	9	5	13
Latin America	6	9	12	6	6
Australia and New Zealand	12	18	26	9	NA
North America	3	8	6	5	13
Small Island States	17	11	4	11	NA
World	5	8	9	9	16

V. CHANGES IN LOW ELEVATION COASTAL SETTLEMENT BETWEEN 1990 AND 2000: THE EXAMPLES OF CHINA AND BANGLADESH⁽⁴²⁾

As described above, China is the country with the largest population in the LECZ, and Bangladesh has the third largest population in the LECZ. Moreover, China is one of the more rapidly urbanizing countries, with particularly rapid urban growth along the coast, while Bangladesh contains one of the most populous delta regions of the world and already has almost half (46 per cent) of its population in the LECZ. The settlement patterns in both of these countries raise serious concerns about the need for adaptation to climate change to start as soon as possible.⁽⁴³⁾

As illustrated in Table 8, for both Bangladesh and China, the population in the LECZ grew at almost twice the national population growth rate between 1990 and 2000. Moreover, in both countries, the urban populations in the LECZ grew particularly rapidly. Indeed, the urban population growth in China's LECZ was more than three times the national rate, although the GRUMP estimates of China's urbanization rate for the period are lower than estimates from the United Nations and the Chinese census estimates.⁽⁴⁴⁾

TABLE 8
Urban population counts and growth between 1990 and 2000
for China and Bangladesh – by total and in the
Low Elevation Coastal Zone (LECZ)

Country	Population ('000)		Annual growth rate 1990–2000 (%)
	1990	2000	
China	1,138,676	1,262,334	1.04
Urban China	336,577	423,730	2.33
LECZ China	119,103	143,880	1.91
Urban LECZ China	56,059	78,278	3.39
Bangladesh	110,024	123,612	1.17
Urban Bangladesh	23,097	26,865	1.52
LECZ Bangladesh	50,568	62,524	2.14
Urban LECZ Bangladesh	11,686	15,429	2.82

42. The GRUMP urban extents, which form a basis for this analysis, are based on estimates of urban footprint in 1994/95. This precludes an analysis of changes in spatial extents or in derived variables such as densities. For this reason, the discussion focuses on the question of whether the rate of population change – particularly in urban areas – is greater in the LECZ than elsewhere.

43. At the time of writing, estimates for 1990 and 2000 were not yet available for all countries. This analysis is thus restricted to the important examples of China and Bangladesh, although future updates will extend the analysis to the rest of the world.

44. The UN estimates that China (including Taiwan) was 27 and 36 per cent urban, respectively, in 1990 and 2000. See reference 22, UN (2004). The 1990 and 2000 census estimates were 26 and 36 per cent, as described in Kam Wing Chan and Ying Hu (2003), "Urbanization in China in the 1990s: new definition, different series and revised trends", *The China Review* Vol 3, No 2, pages 49–71. The GRUMP estimates are 30 and 34 per cent. GRUMP-based estimates differ from UN urban population estimates for several reasons: the UN estimates concentrate on understanding the growth

of large cities (especially those with more than 500,000 persons); UN estimates are not spatially derived, whereas GRUMP-based estimates are linked to spatially identified settlements of more than 5,000 persons; and GRUMP and the UN estimate growth by somewhat different methods. With respect to China in particular, the UN estimates may rely on county estimates of population for particular cities.

45. See reference 7, McGranahan and Tacoli (2006).

46. As a means of demonstrating the viability of a trade-oriented economic strategy, there is logic to setting up special economic zones in favourable (e.g. coastal) locations and giving them preferential treatment (e.g. less government regulation and lower taxes). This justification disappears, however, once a national strategy of economic liberalization has been adopted. Coastal locations will be favoured by markets and do not need to be given special treatment.

47. Demurger, S, J D Sachs, W T Woo, S M Bao and G Chang (2002), "The relative contributions of location and preferential policies in China's regional development: being in the right place and having the right incentives", *China Economic Review* Vol 13, No 4, pages 444–465; also Demurger, Sylvie, Jeffrey D Sachs, Wing Thy Woo, Shuming Bao and Gene H Chang (2004), "Explaining unequal distribution of economic growth among China provinces: geography or policy?", in Aimin Chen, Gordon G Liu and Kevin H Zhang (editors), *Urbanization and Social Welfare in China*, Ashgate, Aldershot, pages 269–306.

Thus, even as the seaward risks associated with climate change are increasing, the areas most at risk are experiencing particularly high population growth. Some of this may be due to urbanization, although in Bangladesh flooding is already a major concern and yet the predominantly rural population of Bangladesh's LECZ is growing at an even faster rate than the country's urban average. The movement towards the coast in China is linked to urbanization, but it is also being driven by the trade-oriented economic strategy, and policies that favour urban development along the coast.

China's rapid urbanization and coastward population movements, and the economic liberalization and growth that are driving these demographic trends, date back to the early 1980s.⁽⁴⁵⁾ The geographical advantages of coastal development have been enhanced by the creation of special economic zones in coastal locations.⁽⁴⁶⁾ It has been estimated that the advantages conferred by geography were about equal to those conferred by preferential policies.⁽⁴⁷⁾ By amplifying the advantages of coastal settlement with their special economic zones, China is not only attracting more people to the coast now, but is establishing an urban structure that will continue to attract people to the coast far into the future. Unless something is done, there is the possibility that, as well as the people living in the low elevation coastal zone, China's economic success will be placed at risk.

Overall, the risks of climate change are clearly far more threatening and intractable for Bangladesh than for China. Only about one-fiftieth of China's land area is in the LECZ, compared to more than two-fifths of Bangladesh's land. Nevertheless, China too faces potentially serious threats, the evolution of which depends on policy agendas that do not as yet treat climate change as a serious issue.

VI. SUMMARY DISCUSSION

From an environmental perspective, there is a double disadvantage to excessive (and potentially rapid) coastal settlement. First, uncontrolled coastal development is likely to damage sensitive and important ecosystems and other resources. Second, coastal settlement, particularly in the lowlands, is likely to expose residents to seaward hazards such as sea-level rise and tropical storms, both of which are likely to become more serious with climate change. Unfortunately, such environmental considerations do not have the influence on settlement patterns that they deserve.

As described above, although the low elevation coastal zone accounts for only about 2 per cent of the world's land area, about 10 per cent of the world's population and 13 per cent of the world's urban population live in the zone. In terms of the regional distribution, Asia stands out, as it contains about three-quarters of the population in the zone and two-thirds of the urban population (compared to about 60 per cent of world population and 49 per cent of the world's urban population).

Settlements in the LECZ are likely to be especially vulnerable in lower-income countries with limited resources. Effective adaptation will require a combination of effective and enforceable regulations and economic incentives to redirect new settlement to better-protected locations and to promote investments in appropriate infrastructure, all of which require political will as well as financial and human capital. A tabulation

of population and urban population shares in the LECZ for different national income classes does not provide, in itself, evidence of a systematic relationship between national income and settlement in the LECZ. However, the data did show a statistically significant difference between the urban population in the zone for low-income versus high-income countries. Politically notable is the appreciable difference found between the populations of the Least Developed Countries (LDCs) and OECD countries living in the zone: 14 and 10 per cent, respectively. This divide is even wider when looking at the urban population percentages in the LECZ: 21 per cent for the LDCs and 11 per cent for OECD countries.

There is considerable variation within regions and income categories, and there are a number of features that can lead a country to have a large share of its urban and rural populations in the LECZ. These include long coastlines (relative to the country's size), wide and heavily populated coastal lowlands, and sparsely populated interiors.

Most of the countries with large populations in the LECZ are also among the most populous countries overall, with large Asian countries dominating. The countries with large shares of population (or urban population) in the LECZ are a more varied group, and include countries characterized by each of the three factors mentioned in the previous paragraph.

Although Small Island States do not, in aggregate, have an especially large share of their population in the LECZ, some of them do, and they would dominate the listing if no additional population or land area criteria were used. If very small countries (under 100,000 people or 1,000 square kilometres) are excluded, among the SISs only the Bahamas is in the top ten. Vietnam, Bangladesh and Egypt reappear from among the top 10 listed in terms of population in the LECZ, and these are all countries with large, heavily populated delta regions, which at least originally attracted people primarily for agriculture. Alternatively, both Suriname and Guyana are countries with sparsely inhabited interiors and populations concentrated on a small coastal strip.

Of particular concern in terms of vulnerability, all but two of the countries with the largest shares of their population in the LECZ (excluding the very small countries) are of low or lower-middle income. This is despite the fact that urban settlements are generally more coastal than rural settlements, while low- and lower-middle-income countries are less urban than more affluent countries.

In the world as a whole, but most notably in Asia, not only are urban populations more likely to be in the LECZ than rural populations, but larger urban settlements are more likely to overlap with the LECZ than are smaller urban settlements. While only 13 per cent of urban settlements with populations under 100,000 overlap with the LECZ, this rises to 65 per cent among cities of 5 million or more. Perhaps even more striking, of the 183 countries with people living in the LECZ, 130 have their largest urban area extending into the zone. When large urban settlements at least overlap with the zone, they tend to have a smaller share of their population in the zone than do smaller settlements. Nevertheless, as one moves up through the size classes of urban settlements, the overall share of population and land in the LECZ does tend to increase – from 7 per cent in urban settlements of under 100,000 to 21 per cent in settlements of over 5 million.

There is a legitimate concern that continued urbanization will draw still greater populations and population shares into the low elevation coastal

zone. In recent decades, this tendency has been especially remarkable in China, where export-driven economic growth has been associated with very rapid coastward migration. Although the GRUMP database upon which the analysis in this paper is based estimates a considerably lower rate of urbanization between 1990 and 2000 than most other sources, a very high rate of growth is nevertheless evident in the LECZ. Moreover, in Bangladesh, with its lower rates of economic growth and urbanization, a shift towards the LECZ is also evident.

Looking to the future, the responses to the growing risks to coastal settlements brought on by climate change should include mitigation, migration and modification. To avoid severe disruptions, measures for each of these need a long lead time. As the effects of climate change become increasingly clear, the location of the coastal settlements most at risk should also become evident. Unfortunately, by this time, most of the easier options for shifting settlement patterns, and modifying them so that they are better adapted to the risks of climate change, will have been foreclosed. Large companies may be able to shift the location of their activities relatively quickly, using the same procedures that have allowed them to adapt to economic globalization. Others will not find it so easy. Moreover, it is already evident that settlements in the coastal lowlands, and particularly those in low-income countries and those also at risk from tropical storms, are especially vulnerable.

Particularly as the need for action becomes more urgent, care will be needed to prevent government responses themselves from being inequitable or unnecessarily disruptive economically. Economically successful urbanization is typically based on the decentralized decisions of economic enterprises and families, supported by their governments. When governments try to decide centrally where urban development should occur or where people should migrate, a range of political interests can intrude, favouring economically unviable locations and/or land use regulations that are particularly burdensome to the urban poor. Adaptation cannot be left to the market, but nor should it be left to arbitrary central planning.

In many cases, there may be measures that can both address present problems while also providing a means of adapting to climate change. These provide an obvious place to start, even if such coincidences of interest are unlikely to be sufficient to provide the basis for all of the adaptive measures needed.

At the national level, measures to support previously disfavoured inland urban settlements, away from the large cities on the coast, could not only reduce risks from climate change but also support a more balanced and equitable pattern of urban development. In China, for example, giving inland urban settlements the support needed to redress the imbalance caused by the creation of special economic zones along the coast would not only help reduce coastward migration but would also reduce the increasingly severe regional inequalities that threaten China's national integrity.

Alternatively, among coastal settlements in low-income countries, those that find more equitable means to resolve the land problems that so often push their poorest urban residents to settle informally on unserviced and environmentally hazardous land (such as flood plains) will also be in a far better position to adapt to the risks of climate change. More generally, measures that support more efficient and equitable resolution of

existing land issues are likely to provide a better basis for addressing the land issues brought on by climate change.

Vulnerable settlements in low-income countries clearly deserve international support in these and other measures to adapt to climate change. If climate change were simply an unfortunate accident of nature, such support could be justified on ethical grounds. In fact, climate change is closely associated with the past and present lifestyles of high-income groups in high-income countries. This makes it doubly important that the governments of these countries contribute to adaptation as well as mitigation. It also implies that this assistance should be viewed as additional to rather than part of development assistance. On the other hand, adaptive measures that respond to existing local needs, contribute to other development goals, and can be locally driven, are among the most likely to succeed.

REFERENCES

- Agardy, Tundi, Jacqueline Alder, Paul Dayton et al. (2005), "Coastal systems", in Rashid Hassan, Robert Scholes and Neville Ash (editors), *Ecosystems and Human Well-Being: Current Status and Trends*, Island Press, Washington DC, pages 795–825.
- Alder, Jacqueline, Russell Arthurton, Neville Ash et al. (2006), *Marine and Coastal Ecosystems and Human Well-Being*, United Nations Environmental Programme, Nairobi.
- Balk, D, F Pozzi, G Yetman, U Deichmann and A Nelson (2005), "The distribution of people and the dimension of place: methodologies to improve the global estimation of urban extents", International Society for Photogrammetry and Remote Sensing, Proceedings of the Urban Remote Sensing Conference, March 2005, Tempe, AZ.
- Bigio, Anthony G (2003), "Cities and climate change", in Alcira Kreimer, Margaret Arnold and Anne Carlin (editors), *Building Safer Cities: The Future of Disaster Risk*, World Bank, Washington DC, pages 91–99.
- Demurger, S, J D Sachs, W T Woo, S M Bao and G Chang (2002), "The relative contributions of location and preferential policies in China's regional development: being in the right place and having the right incentives", *China Economic Review* Vol 13, No 4, pages 444–465.
- Demurger, Sylvie, Jeffrey D Sachs, Wing Thye Woo, Shuming Bao and Gene H Chang (2004), "Explaining unequal distribution of economic growth among China provinces: geography or policy?", in Aimin Chen, Gordon G Liu and Kevin H Zhang (editors), *Urbanization and Social Welfare in China*, Ashgate, Aldershot, pages 269–306.
- 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.
- Dreier, P (2006), "Katrina and power in America", *Urban Affairs Review* Vol 41, No 4, pages 528–549.
- Ericson, Jason P, Charles J Vorosmarty, S Lawrence Dingman, Larry G Ward and Michel Meybeck (2006), "Effective sea-level rise and deltas: causes of change and human dimension implications", *Global and Planetary Change* Vol 50, pages 63–82.
- Elvidge, C D, J Safran, I L Nelson, B T Tuttle, V R Hobson, K E Baugh, J B Dietz and E H Erwin (2004), "Area and position accuracy of DMSP nighttime lights data", in R S Lunetta and J G Lyon (editors), *Remote Sensing and GIS Accuracy Assessment*, CRC Press, chapter 20, pages 281–292.
- Farr, T G and M Kobrick (2000), "Shuttle radar topography mission produces a wealth of data", *Transactions of the American Geophysical Union* Vol 81, pages 583–585.
- Few, Roger and Franziska Matthies (2006), *Flood Hazards and Health: Responding to Present and Future Risks*, Earthscan, London.
- Fujita, Masahisa, Paul R Krugman and Anthony Venables (1999), *The Spatial Economy: Cities, Regions and International Trade*, MIT Press, Cambridge, Mass.
- Fujita, Masahisa and Jacques-François Thisse (2002), *Economics of Agglomeration: Cities, Industrial Location and Regional Growth*, Cambridge University Press, Cambridge, UK.
- Gabaix, Xavier and Yannis M Ioannides (2004), "The evolution of city size distributions", in Henderson and Thisse (editors), see reference 20, pages 2341–2378.
- Global Rural–Urban Mapping Project, alpha version (GRUMP alpha), Centre for International Earth Science Information Network (CIESIN), Columbia University, International Food Policy Research Institute (IFPRI), The World Bank and Centro Internacional de Agricultura Tropical (CIAT) (2004), "Global Rural–Urban Mapping Project (GRUMP), alpha version: urban extents grids", Socioeconomic Data and Applications Centre (SEDAC), Columbia University, Palisades, NY, accessible at <http://sedac.ciesin.columbia.edu/gpw> (February 2006).

RISKS OF CLIMATE CHANGES IN LOW ELEVATION COASTAL ZONES

- Global Rural–Urban Mapping Project, alpha version (GRUMP alpha), Centre for International Earth Science Information Network (CIESIN), Columbia University, International Food Policy Research Institute (IFPRI), The World Bank and Centro Internacional de Agricultura Tropical (CIAT) (2004), “Gridded population of the world, version 3, with urban reallocation (GPW–UR)”, Socioeconomic Data and Applications Centre (SEDAC), Columbia University, Palisades, NY, accessible at <http://sedac.ciesin.columbia.edu/gpw> (February 2006).
- Han, S S and Z X Yan (1999), “China’s coastal cities: development, planning and challenges”, *Habitat International* Vol 23, No 2, pages 217–229.
- Hardoy, Jorge E, Diana Mitlin and David Satterthwaite (2001), *Environmental Problems in an Urbanizing World*, Earthscan, London.
- Henderson, J Vernon and Jacques François Thisse (editors) (2004), *Handbook of Regional and Urban Economics: Volume 4, Cities and Geography*, Elsevier North Holland, Amsterdam.
- Hummels, David (1999), *Have International Transportation Costs Declined?*, University of Chicago, Chicago.
- ISciences (2003), SRTM30 Enhanced Global Map – Elevation/Slope/Aspect (release 1.0), ISciences, LLC, Ann Arbor (based on the raw SRTM data from Jet Propulsion Laboratory).
- Kam Wing Chan and Ying Hu (2003), “Urbanization in China in the 1990s: new definition, different series and revised trends”, *The China Review* Vol 3, No 2, pages 49–71.
- Klein, Richard J T, Robert J Nicholls and Frank Thomalla (2003), “Resilience to natural hazards: how useful is this concept?”, *Environmental Hazards* Vol 5, pages 35–45.
- McGranahan, Gordon, Peter J Marcotullio, Xuemei Bai et al. (2005), “Urban systems”, in Rashid Hassan, Robert Scholes and Neville Ash (editors), *Ecosystems and Human Well-Being: Current Status and Trends*, Island Press, Washington DC, pages 795–825.
- McGranahan, Gordon, Deborah Balk and Bridget Anderson (2006), “Low coastal zone settlements”, *Tiempo* No 59, pages 23–26.
- McGranahan, Gordon and Cecilia Tacoli (2006), “Rural–urban migration, urban poverty and urban environmental pressures in China”, Contribution to the China Council Task Force on Sustainable Urbanization Strategies, International Institute for Environment and Development (IIED), London.
- Montgomery, Mark R, Richard Stren, Barney Cohen and Holly E Reed (editors) (2003), *Cities Transformed: Demographic Change and its Implications in the Developing World*, National Academy Press, Washington DC.
- Nicholls, Robert J, Frank M J Hoozemans and Marcel Marchand (1999), “Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses”, *Global Environmental Change* Vol 9, pages 69–87.
- Nicholls, Robert J (2002), “Rising sea levels: potential impacts and responses”, *Issues in Environmental Science and Technology* Vol 17, pages 83–107.
- Nicholls, Robert J (2004), “Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socioeconomic scenarios”, *Global Environmental Change* Vol 14, No 1, pages 69–86.
- Nicholls, Robert J, Poh Wong, Virginia Burkett et al. (2006), “Coastal systems and low-lying areas”, in *IPCC WGII Fourth Assessment Report – Draft for Government and Expert Review*.
- Pelling, Mark (2003), *The Vulnerability of Cities: Natural Disasters and Social Resilience*, Earthscan, London.
- Rabus, B, M Eineder, A Roth and R Bamler (2003), “The shuttle radar topography mission – a new class of digital elevation models acquired by spaceborne radar”, *Journal of Photogrammetry & Remote Sensing* Vol 57, pages 241–262.
- Rakodi, Carole and David Treloar (1997), “Urban development and coastal zone management: an international review”, *Third World Planning Review* Vol 19, No 4, pages 401–424.
- Satterthwaite, D and C Tacoli (2003), “The urban part of rural development: the role of small and intermediate urban centres in rural and regional development and poverty reduction”, Working Paper 9 in the Rural–Urban Interactions Series, IIED, London.
- Small, C and R J Nicholls (2003), “A global analysis of human settlement in coastal zones”, *Journal of Coastal Research* Vol 19, No 3, pages 584–599.
- Small, Christopher and Joel Cohen (2004), “Continental physiography, climate and the global distribution of human population”, *Current Anthropology* Vol 45, No 2, pages 269–277.
- Timmermann, P and Rodney White (1997), “Megahydropolis: coastal cities in the context of global environmental change”, *Global Environmental Change* Vol 7, No 3, pages 205–234.
- United Nations (2004), *World Urbanization Prospects: The 2003 Revision*, United Nations, New York.
- Wolanski, Eric (editor) (2006), *The Environment in Asia Pacific Harbours*, Springer, Dordrecht.
- WTO (2004), *World Trade Report 2004*, World Trade Organization, Geneva.