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# The geography of greenhouse gas emissions from within urban areas of India: a preliminary assessment

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## ABSTRACT

This paper examines the patterns of greenhouse gas (GHG) emissions from urban areas in India—a rapidly growing and urbanizing nation. It uses a new dataset, Emission Dataset for Global Atmospheric Research (EDGAR) to estimate the urban share of national GHG emissions. It presents a geographic picture of emission variation by *urban form* (urban population size, area size, density, and growth rate), and *economic* (GDP and GDP per capita), *geographic* (location of emissions released: 20, 40, and 80 km from urban areas), and *biophysical* (ecosystem and climate: cooling degree days) characteristics. Dependent variables include emissions of carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and hexafluoride ($SF_6$) from 14 source activities (agricultural soils, agricultural wastes, aviation, energy, fossil-fuel fires, fugitive escapes from solids, industry, livestock, navigation, non-road transport, oil and gas production, residential, road transport, and waste) for the year 2000 that are allocated on a 0.1° global grid. We examine 721 urban areas with more than 50,000 residents (accounting for 92% of the total Indian urban population), present findings, and compare our results with urban-level carbon footprint analyses. The results demonstrate that GHG emissions from urban areas in India are lower than that presented in the literature, and that differences in emissions levels vary with urban form, economic, geographic, and biophysical variables.

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## Introduction

Over the past several decades, India, the second-most populated country in the world, has experienced rapid development. These changes are evident in the demographic, economic, and social characteristics of the country. The Asian Development Bank (ADB 2010b) estimates that in a short span of 20 years–between 1990 and 2010—India's population grew from 835 million to 1.166 billion. Much of this growth has occurred within India's urban areas, resulting in an increase in the country's urbanization rate (from 25.6% in 1990 to 29.8% in 2008).

Of late, India's economy has grown at an extremely fast pace, reaching annual average growth rates in real gross domestic product (GDP) of between 3.8% and 9.7%. The result was that India's GDP (at PPP) rose by more than 110% (from $1.5 trillion in 1990 to $3.8 trillion in 2009), and per capita GDP (at PPP) increased from $1,520 to $3,287 over the same period. India is rapidly becoming a middle-income nation (ADB 2010b).

The impacts of rapid demographic and economic change in India are reflected in some of its key social indicators. Life expectancy in the country has risen from 58.2 years in 1990 to 62.3 years in 2008. Those in poverty (defined as living below $2 a day) have declined from 81.7% of the population in 1993 to 77.6% of the population in 2005. Car ownership has increased from 3 per thousand in 1990 to 12 per thousand by 2003. These, and other changes, have helped to boost India's human development index (HDI) by over 33 %—from 0.389 in 1990 to 0.519 in 2010 (UNDP 2010).

The role of population and economic and social changes have also been reflected in the nation's environmental impact, including, for instance, greenhouse gas (GHG) emissions. In 1994, the nation reported emitting a total of 1,251.95 million metric tonnes of $CO_2$-equivalents. By 2007, its GHG emissions had increased by more than 50%—to 1,904.73 million metric tonnes (INCCA 2010). However, India's GHG emissions have grown at a rate slower than that of its GDP, thereby indicating a favourable reduction in emissions intensity as the country develops. Nevertheless, India now ranks as the fifth largest emitter of GHG emissions worldwide.

India's population and economy are expected to grow further. The UN (2005) predicts that by 2030 India will be the most populous country in the world, overtaking China. Moreover, the Indian economy remains robust, despite the global financial crises. The ADB recently readjusted India's economic growth for 2010 to 8.5% and expects further similar increases in the middle-term future (ADB 2010a).

These changes may indeed translate into significant impact on the environment at the global scale. Between 2000 and 2050, India is expected to experience over a 100-fold increase in automobile ownership (from 5.4 million to 610.9 million vehicles). The country's crude oil consumption is predicted to rise more than ten-fold (from 2.1 thousand barrels a day to 23.1 thousand barrels of day) during this period (Wilson, Purushothaman, and Fiorakis 2004 ).

This paper explores and identifies patterns of GHG emissions in India. We establish a baseline estimation of GHG emissions from within 721 urban areas in India in 2000, and identify patterns associated with variation among urban emissions levels. This analysis, being the first of its type, can provide a springboard for further studies and inspire discussion for both mitigation and adaptation policies.

## Literature review

Over the last two decades, scholars across a variety of disciplines have paid increasing attention to the impacts of cities, and effects of urbanization on the environment (Jacquet, Pachauri, and Tubiana 2010; Hardoy, Mitlin, and Satterthwaite 2001; McDonald, Kareiva, and Forman 2008; McDonnell and Pickett 1997; Alberti 2008). Activities that take place in cities and the urbanization process are often portrayed as important factors in local—if not regional and global—change (White 1983; Srinivas 2000; Brown and Jacobson 1987; Odum 1991; Wackernagel and Rees 1996). Analysts focused more strictly on global-scale impacts, for example, have suggested that urbanization is a major driver of global biodiversity loss (Millennium Ecosystem Assessment 2005; York, Rosa, and Dietz 2003; McKinney 2006; McKinney 2008). Others have emphasized the role of cities in terms of their contribution to climate change. According to Satterthwaite (2008), many sources suggest that cities are responsible for 75–80% of all GHG emissions. For example, both Kajumulo Tibaijuka (Executive Director, UN-HABITAT) (United Nations 2007) and the transnational Munich Reinsurance Company (Munich Reinsurance 2004) suggest that cities are responsible for 80% of total anthropogenic GHG emissions. However, Satterthwaite's (2008) back-of-the-envelope estimations reveal that the urban share may actually be as low as 40% of total. Hence, global estimates of urban emissions vary between 40 and 80%. Despite the importance of this basic accounting component, there has yet to be a reliable estimate for emissions from urban areas at the global level (Dhakal 2010). Moreover, there exists only one global set of regional estimates, produced through a limited number of up-scaled national studies of urban energy consumption (IEA 2008).

The reasons behind the lack of consensus on GHG contribution of cities fall into, at least, two inter-related categories. On the one hand, identifying what should be included in an inventory of urban emissions is not clear. For instance, Lebel, Garden, Banaticla, *et al.* (2007) describe four different types of emissions that could be associated with urban activities. Their matrix uses two axes—defined by consumption versus production-related emissions and whether the emissions are directly produced by the activity or whether they are produced up-stream in the production process (so-called 'deemed' emissions). Hence, there are three issues of concern: 1) where the emissions are released (within the urban area or outside of it); 2) how emissions are related to the urban activity (production or consumption); and 3) whether emissions are directly or indirectly associated with the activity (embodied or 'deemed' emissions). This multi-faceted perspective describes a complex range of cross-scale interactions and product lifecycle relationships. A debate continues on the rights and obligations over these emissions, which influence how scientists are generating protocols. For example, researchers are still deliberating on how to allocate responsibility for GHG emissions from cities of the developing world, which may include emissions from manufacturing processes for items consumed in the developed world. While there is no centralized reporting protocol for local GHG emissions, scholars are increasingly suggesting that cross-scale, lifecycle, and consumption-based inventories would be the most reliable (Kennedy, Ramaswami, Carney, *et al.* 2009; ICLEI 2009; Dhakal 2010; Bader and Bleischwitz 2009).

On the other hand, the complexity of carbon accounting at the local level is reflected in the significant data requirements for creating the emissions inventories described above. Some of the initial attempts at developing local inventories express 'there is no end to the minutiae of detailed information that is necessary to fully characterize greenhouse gas emissions' (Kates, Mayfield, Torrie, *et al.*1998). Typically, given the lack of data at the urban level, local inventories are based on energy supply and consumption figures (Parshall, Gurney, Hammer, *et al.* 2010). As a result, those aspiring to include data necessary for the cross-scale, lifecycle-oriented, consumption-based protocols have produced studies with a limited number of cities (the most inclusive one covers 44 cities), and even a smaller number of those in the developing world (11 of the 44 cities) (Kennedy, Ramaswami, Carney, *et al.* 2009). Moreover, urban regions of South Asia have been studied less, with the focus being mainly on capital or large cities (Gurjar, v Aardeene, Lelieveld, *et al.* 2004; Kennedy, Steinberger, Gasson, *et al.* 2010; Mitra, Sharma, and Ajero 2003).

Not only have most of the carbon footprint studies focused on cities of the developed world, but they have also largely restricted the research to carbon dioxide ($CO_2$) emissions. One recent exception to the latter limitation is a project that examined methane ($CH_4$) emissions from one megacity, Los Angeles, USA. It estimated that global urban emissions of this compound may account for 7–15% of the total, based on the findings for this city (Wunch, Wennberg, Toon, *et al.* 2009). Certainly, standardizing protocols that use multiple GHGs amongst an international set of cities and generating global estimates have been challenging.

While it is important to obtain a full accounting of all consumption- and production-related, cross-scale, embodied energy-related GHG emissions for urban areas, it can also be helpful to provide a national baseline accounting of emissions strictly released from within urban areas. Indeed, given the complexity and data demands of performing local emissions studies, it may be helpful to attempt to integrate the more detailed studies with global analyses, using high-resolution data on GHG emissions. In this way, the limitations of global analyses can be overcome with studies of individual cities at the local level (see discussion in Butler, Lawrence, Gurjar, *et al.* 2008) .

To this end, global studies of GHG emissions are emerging. One recent global study, for example, has used nighttime satellite observation data and gridded population data, combined with national-level social, economic, and resource use data, to provide information on the spatial structure of $CO_2$ emission from fossil fuels (Raupach, Rayner, and Paget 2010). While this is a significant push forward, a systematic and comprehensive global analysis of GHG emissions from urban areas has yet to be produced.

These issues and concerns form the background for this project. The research focuses on GHG emissions from within urban areas in India. Our estimates do not represent a full accounting of emissions for all activities within urban areas, as energy production sites are often located outside of urban boundaries. At the same time, we use a database with expanded urban boundaries. These boundaries include, arguably, the urban field of economic activity associated with cities (Friedmann 1973; Fox and Kumar 1965). That is, they are much larger than urban area boundaries based upon political considerations. Moreover, we investigate GHG emissions from energy production centres that are located outside the boundaries of cities.

Given the scope of the analysis, we were able to examine patterns in differences of GHG releases from urban areas under a variety of conditions. We used socio-economic, geographic, urban form, and biophysical characteristics to identify these patterns. Our goal was to identify and describe a first accounting of GHG emissions from within urban areas and point to areas for further research. We hope that this analysis will cast light on the differences in environment impact between densely-settled areas and other areas, so as to gauge the role of urbanization on global environmental change. Ultimately, this project facilitates exploring the constraints and opportunities for environmental benefits that dense settlements afford.

## Research design

The analysis is based on recently published, global, spatially disaggregated (high resolution) GHG emissions data and a number of already well-known spatial datasets (see **Table 1**). The dependent variables represent GHG emissions from grid cells within urban boundaries. Given the geographic extent of the databases, and the fact that there are several greenhouse gases included in the dataset, there is an opportunity to provide the first such analysis of the global share of urban GHG emissions. This analysis will be more complete than those discussed above in certain ways. The study includes all urban areas (over 50,000 people) in India and almost all types of GHG emissions.

The first question addressed concerns itself with the extent to which GHG emissions from urban areas are contributing to national anthropogenic emissions. As important as the share is to the research community, however, we also estimated the share of total urban emissions by source activity and for four greenhouse gases. The second objective was to explore

**Table 1** Datasets

| Dataset name | Source | Description | Notes |
|---|---|---|---|
| Emissions Dataset for Global Atmospheric Research (EDGAR) v.4 (2009) | European Commission Joint Research Centre (JRC), Ispra, Italy | GHG emissions for $CO_2$, $CH_4$, $N_2O$ are available by sector for 2000 | 0.1° cell resolution |
| Global Rural-Urban Mapping Project (GRUMP) v. beta (2009) | Columbia University, Centre for International Earth Science Information Network, New York, USA (CIESEN) | Population distribution, density, and urban extents with names are available for 1990–2000 | 30 arc seconds cell resolution |
| Global Land Cover 2000 Dataset (GLC2000) | European Commission Joint Research Centre, Ispra, Italy (JRC) | Approximately 23 categories of land use | 1km at the equator (0.0089285714dd) |
| GDP (Income) | International Institute for Applied Systems Analysis, Laxenburg Austria (IIASA) | B1 scenario for the year 2000 ($1990) | 0.5° cell resolution |
| Eco-regions | Millennium Ecosystem Assessment (MA) | Nine ecosystem types including coastal, cultivated, dry land, forest land, inland waterways, island, marine, mountain, and polar | Variety of vector and raster maps |
| Climate (temperature and temperature range) | University of East Anglia, Climatic Research Unit (CRU), East Anglia, UK | Temperature and diurnal temperature range (DTR) | 10-minute cell resolution |
| Power plant location | Carbon Monitoring for Action (CARMA) | Location and emissions of over 50,000 power plants and 4,000 power companies | Points on latitude and longitude coordinates |

patterns of emissions from urban areas based on urban, economic, geographic, and biophysical characteristics. Below are brief descriptions of the major databases we used. This is followed by a section briefly describing how we managed these datasets and the types of analyses we employed.

## Data and sources

The dependent variables comprised the Emissions Dataset for Global Atmospheric Research, or EDGAR (European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL), version 4, 2009).[1] The database presents volumes of direct GHGs interpolated from national-level statistics, and based upon a number of spatial parameters. The data do not represent directly measured emissions. For our analyses, we used emissions in metric tonnes estimated for four greenhouse gases, namely, carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and sulphur hexafluoride ($SF_6$). All version 4 spatial EDGAR emissions data are allocated at a 0.1° resolution geographic grid[2] using data such as location of energy and

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[1] See http://edgar.jrc.ec.europa.eu/index.php

[2] 0.1° resolution creates a grid of approximately 11 kilometres at the equator. At the latitude of New Delhi, a 0.1° resolution is based upon a grid rectangle of approximately 11.0 x 9.7 km grid.

manufacturing facilities, road networks, shipping routes, human and animal population density, and agricultural land use. We limited our emissions sources to anthropogenic influences, including agricultural soils, agricultural wastes, aviation, energy, fossil-fuel fires, fugitive from solids, industry, livestock, navigation, non-road transport, oil and gas production, residential, road transport, and waste. We aggregated these 14 sources into six categories: agriculture, energy, industry, residential, transport, and waste.[3] Residential emissions include those GHGs emitted through the burning of fuelwood, crop residues, and dung in such technologies as fireplaces, stoves, single household boilers, and boilers for multi-residential/commercial buildings.

We converted the dependent variables into units of $CO_2$-equivalents through the use of global warming potential (100-year timelines) published by the Intergovernmental Panel on Climate Change, Fourth Assessment Report (IPCC-AR4).[4] Each EDGAR year dataset includes 39 files based upon the gas and source. We assigned emissions from individual grid cells to urban areas and summed up the results. The urban area totals (by gas) were then transformed into metric tonnes of $CO_2$-equivalent emissions.

EDGAR data have already been used in urban research. A comparison of EDGAR with an inventory used in several recent multi-model inter-comparison studies for the IPCC-AR4 and RETRO, an inventory of ozone precursors designed to be used in a re-analysis of tropospheric chemical composition over the past 40 years, examined levels of non-methane hydrocarbons, carbon monoxide, and nitrogen oxides for a small sample of cities (fewer than 35), and also used low resolution (1.0°) version 3 EDGAR data (Butler, Lawrence, Gurjar, *et al.* 2008). Another study used EDGAR data version 3, to estimate the $CO_2$ emissions from 12 cities around the world (Sovacool and Brown 2010). This study was limited, however, by the low resolution of the data used (1.0°) and the small number of cities in the sample. It also used population data that were not entirely consistent across study units (some being for the urban region and others for the city itself). Despite these problems, the Sovacool and Brown (2010) study provided interesting preliminary findings and policy relevance for metropolitan carbon footprint mitigation strategies.

We used population and urban area boundary data generated by the Global Rural-Urban Mapping Project (GRUMP), developed by researchers at the Columbia University's Earth Institute's Center for International Earth Science Information Network (CIESIN). CIESIN compiled a global spatial dataset of urban settlement points, which are cities or towns with at least 1,000 residents. Using settlement points and night time satellite imagery, CIESIN came up with two products: fine-scale global population grids for 1990 and 2000 (at 30 arc-seconds resolution, or approximately 1km by 1km at the equator) and a polygon file of 'urban extents', which represent the spatial boundaries of urban areas circa 2000.[5] CIESIN aggregated multiple political jurisdictions into one urban extent, where the urban fabric was contiguously developed, similar to the process used in the United States to designate consolidated metropolitan statistical areas.[6] Thus, the GRUMP methodology applies a globally-consistent and conceptually-defensible approach to identifying urban land for global spatial analysis. We secured the latest version of the GRUMP database (Beta version), which will have a public release in 2011. We limited our study to

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[3] While EDGAR grid data are organized by 14 sources, the national scale data are further disaggregated into approximately 50 sources. Spatial data were validated at the global scale by comparing total figures to those developed at the national level.

[4] See http://www.ipcc.ch

[5] See http://www.ciesin.columbia.edu/repository/metadata/ig/Browse/Global Rural Urban Mapping ProjectGRUMPAlphaVersion.html

[6] In some cases, this aggregation process leads to extremely large urban boundaries, such as for the Tokyo-Nagoya corridor in Japan with nearly 76 million residents in 2000.

urban extents with more than 50,000 residents in 2000, which amounted to 7,041 urban extents globally. Figure 1 (below) presents the 721 urban extents in India with more than 50,000 residents, as defined by GRUMP. Note that the urban extent for Delhi includes several outlying dense settlements. These urban extents house approximately 230 million (of the 248 million) urban inhabitants of India in 2000 (United Nations 2006).

Other databases have been constructed for use in spatial analysis of global urban land cover. A recent study compared 10 global-urban and urban-related mapping efforts (Schneider, Friedl, and Potere 2009). It found that GRUMP data identified the largest areas allocated to urban uses at the global level (over 3.5 million km$^2$). By contrast, the MODIS urban land-cover mapping effort found urban areas comprised only 20% of that area (657,000 km$^2$). We chose GRUMP urban extents for several reasons. First, the dataset has been used and validated by several international efforts, such as the Millennium Ecosystem Assessment (McGranahan,

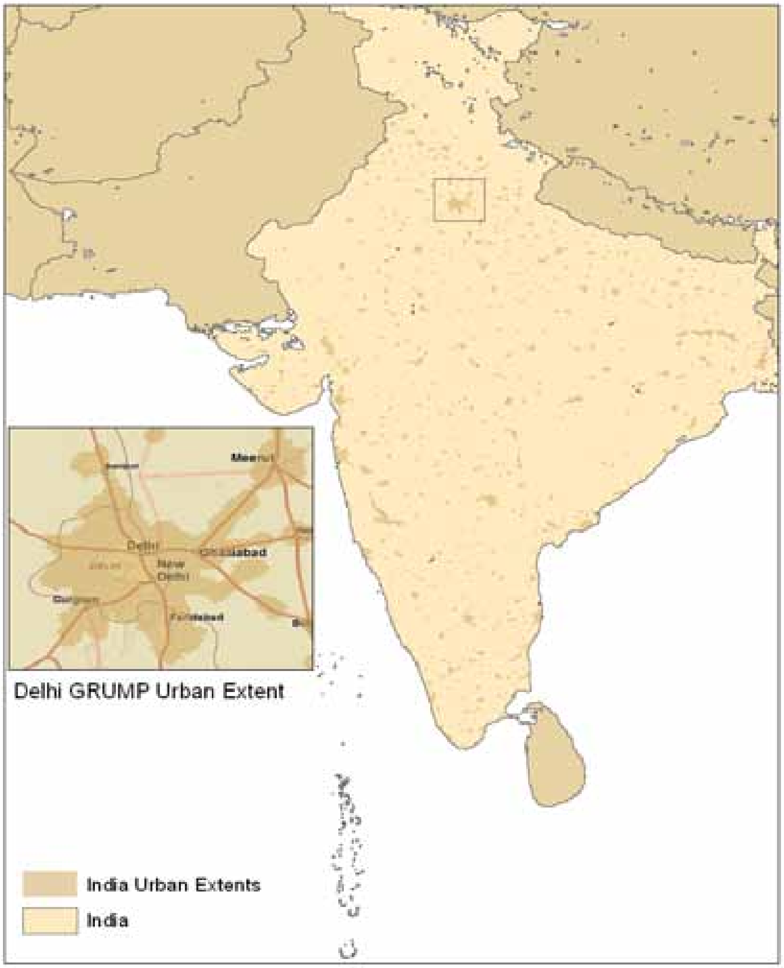

Figure 1 Location of 721 urban extents in India with close up on Delhi

Marcotullio, Bai *et al.* 2005). Second, the data are consistent with urban areas of several developed countries. For example, urban extents are spatially consistent with the metropolitan area boundaries used by the US Census Bureau. Third, we are interested in identifying the emissions related to 'urban' activities. The inclusive areas defined by GRUMP urban extents are more closely aligned to what urbanists call 'urban fields' (Friedmann 1973) or 'functional urban economic areas' (Fox and Kumar 1965). These areas identify a geographic space where, arguably, urban activities occur.

We derived population, land area, density, and urban growth rates using the GRUMP urban extent boundaries and population grids. First, we extracted population figures from the GRUMP grid of population for 1990 and 2000. From these figures, we calculated the annual average rate of increase in population for each extent over the 10-year period. We also calculated the geographic area covered by each extent. Because the GRUMP urban boundaries are generalized and may include some land covered by water or ice, we used global land cover data provided by the GLC2000 project to exclude land broadly covered in water or ice when calculating population densities. The GLC2000 data uses the UN Food and Agricultural Organization (FAO) Land Cover Classification System (LCCS).[7] This is a hierarchical classification, which describes approximately 23 standardized land cover classes, including water and ice.

One concern with the EDGAR emissions is that data are originally aggregated at the national level and dispersed spatially through a series of algorithms. As a result, the energy-related emissions may not be allocated accurately for the purposes of assigning emissions to urban areas. Some power plants producing electricity for urban residents are located beyond the GRUMP urban extent boundaries. While, as mentioned above, the GRUMP urban extents do not conform to political boundaries and are geographically generous (are larger than political boundaries), they may still preclude many thermal power plants, where electricity is produced for urban residents. We, therefore, supplemented the EDGAR emissions from the energy category with data from the Carbon Monitoring for Action (CARMA) database, containing carbon dioxide emissions of over 50,000 power plants and 4,000 power companies worldwide in 2000.[8] The data include point locations of power plants, spatially identified by latitude and longitude coordinates. We used the location and emissions from these plants to reallocate the electricity-related emissions data to urban extents. In India, there are approximately 845 carbon-emitting plants in the CARMA database, of which only 63% (541 plants) are within urban extent boundaries. We considered how the urban share of energy emissions for India might change if all electricity emissions for the country were allocated to the urban extents, which we treated as an an upper limit of the total emissions from the energy category. In this regard, we calculated the percentage of national area coverage for each urban extent. Then, we distributed the total sum of all $CO_2$ emissions from power plants in India according to the relative size of each urban extent. This adjustment allowed us to provide a range of emissions levels for the energy category.[9]

We examined the GHG emissions per capita of urban extents by eco-region. Eco-region data were obtained from the Millennium Ecosystem Assessment (MA).[10] The MA identified 10 non-exclusive eco-regions (including urban) across the globe. For the present study, we excluded marine and polar systems because they do not apply to India. We also excluded agricultural

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[7] See http://bioval.jrc.ec.europa.eu/products/glc2000/products.php

[8] See http://carma.org/

[9] This reallocation is complicated by the formatting of EDGAR data, as the EDGAR gridded data for energy include some manufacturing (1A1, 1A2, and 2A IPCC categories). Therefore, our GHG estimates provide a range of emissions possibilities rather than an exact amount. We suggest that including this analysis identifies the top level of emissions from urban extents in the country.

[10] See http://wdc.nbii.gov/ma/datapage.htm

systems, as the MA dataset suggests that most, if not all, urban extents in India include agricultural systems within their urban boundaries. That is, of the 721 urban extents in the country, only one is located in a non-agricultural eco-region.[11]

We examined variation in emissions per capita by cooling degree days (CDD), which is an indicator of the energy needed to cool a structure to a comfortable temperature. We used this indicator of climate as opposed to heating degree days (HDD) or the energy needed to heat a structure because there is greater variation in CDD than in HDD in India. The proxy is an indicator of varying climate, which may affect fossil-fuel use, and therefore, GHG emissions. Temperature data were obtained from the Climatic Research Unit (CRU) at University of East Anglia[12]. We used point data for temperature and diurnal temperature range (averaged over the years 1961–1990). From these, we calculated the CDDs for each location. These are derived from the outside air temperature and the range of temperature during any given period. CRU provides the monthly temperature means and ranges at various points globally. From these, we calculated the number of annual days necessary to heat or cool a structure to 65 °F or 18 °C. Researchers have identified HDD as an influence on carbon emissions from cities (Kennedy, Ramaswami, Carney, *et al.* 2009).

Lastly, we examined variation in emissions per capita by income. Income data were from the International Institute for Applied Systems Analysis (IIASA) downscaled spatial socio-economic dataset. We used the gross domestic product (GDP) at market exchange rate (MER) per cell for the year 2000 in US. For the economic data, we extracted the total GDP for each urban extent from the IIASA B1 scenario global database (after further downscaling the IIASA grids from 0.5 degree resolution to match the 30 arc-second resolution of the GRUMP datasets).[13] We also used the GDP and population totals per extent to calculate GDP per capita for 2000.

Nominal categories were created for all interval data by defining quartiles at the global level, which were then applied to the information for India. In this way, we classified the urban extents in India in clearly defined and comparable categories. We created at least four categories for each of the following variables: urban area, urban density, urban growth rates, total urban GDP, urban GDP per capita, and cooling degree days. Other categories we used included urban size (we matched categories defined by the UN World Urbanization Prospects), eco-region (defined by the MA, as noted above), and geographic distance from urban extent boundary. To establish the geographic location of GHG emissions from urban extents, we created buffers for each of the 721 Indian urban extents at 20, 40, and 80 kilometres. We merged all buffers of similar distance from the urban extent and extracted the emissions in each layer (see Figure 2). The buffers were used to test the sensitivity of the urban boundary with respect to capturing 'urban' emissions. We suspected that most of the emissions activity related to urban consumption, such as agriculture, energy production or waste generation, should be located within an upper-bound distance of 80 kilometres from the urban extent boundary in India.

## Findings

The results are divided into six sub-sections, based on the different analyses. These sections include the total GHG emissions of India and

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[11] According to the MA (2005), agricultural or cultivated ecosystems cover approximately 24% of the terrestrial surface of the earth.

[12] See Ten Minute Climatology at http://www.cru.uea.ac.uk/cru/data/hrg/tmc/

[13] The IPCC global B1 scenario is characterized by rapid economic growth with changes towards a service and information economy, population rising to 9 billion in 2050 and then declining thereafter, reductions in material intensity, and the introduction of clean and resource-efficient technologies. We see the B1 scenario as the middle-level economic future, as compared to the A2R and B2 scenarios.

**Figure 2** Buffers around India urban extents
(Urban extent boundaries not shown, but are within the '20 km buffer' area)

India urban extents, listing of the highest GHG emitters and the highest per capita urban extent emitters in India, followed by three sections that identify the differences in emissions from within urban extents by scale and form, and socio-economic and biophysical characteristics. The final section presents the differences in emissions within India by distance from urban extent boundaries.

## Total and per capita GHG emissions for India and its urban extents

For the year 2000, the total GHG emissions from anthropogenic sources in India were 1.97 billion tonnes of $CO_2$-equivalents (see Table 2). This number is similar to the one (1.90 billion tonnes) provided by the country's Ministry of Environment and Forests (2010). This level of emissions suggests that, while India has 16.8% of the world's population (UN 2006), it accounted for 5.4% of the total global emissions in 2000.

Of the national emissions for India, the largest share was for energy (43%), followed by agriculture (30.5%), residential (8.4%), waste (6.7%), industry (6.3%), and transportation (5.1%) (see Table 2). Emissions from agriculture within the country represent 11.9% of global agricultural emissions. India accounts for 8.3% of global waste-related emissions, while its residential emissions comprise 5.1% of the world's residential emissions. The energy-related emission share of India is approximately 5% of the global total. Industry and transportation amount to between 2% and 3% of global emissions from these sectors.

According to our analysis, in 2000, emissions from within urban areas amounted to approximately 397 million metric tonnes of $CO_2$-equivalents (see Table 2). This amount represents approximately 20% of India's total emissions. We suggest this amount as the lower-bound within a range of GHG emissions from urban extents in India for the year 2000. The largest urban sector contribution was from energy (33.3%), followed by industry (23.5%), waste (20.5%), transportation (14%), residential (10%), and agriculture (4.7%).

A sectoral comparison of the GHG emissions per capita between the national averages and the urban extent averages is presented in Table 3. It needs to be noted that the table depicts higher level of GHG emissions in energy-related emissions per capita in urban extents than the national average. On the other hand, the GHG emissions per capita are approximately equal from industry and waste at the national and urban extent scales. Finally, the emissions per capita from agriculture and transportation are lower in urban extents than the national average. This relationship reveals that fewer

**Table 2** GHG emissions for India and for Indian urban extents, by sector for the year 2000

| | India GHG emissions | | India urban extents GHG emissions | | Urban share of total |
|---|---|---|---|---|---|
| Sector | (tonnes $CO_2$ eq.) | (%) | (tonnes $CO_2$ eq.) | (%) | (%) |
| Agriculture | 601,229,731 | 30.5 | 28,434,950 | 7.2 | 4.7 |
| Energy | 847,006,360 | 43.0 | 281,867,177 | 71.0 | 33.3 |
| Industry | 123,813,459 | 6.3 | 29,068,542 | 7.3 | 23.5 |
| Residential | 165,821,682 | 8.4 | 16,547,446 | 4.2 | 10.0 |
| Transportation | 101,113,338 | 5.1 | 14,150,485 | 3.6 | 14.0 |
| Waste | 131,749,015 | 6.7 | 27,019,635 | 6.8 | 20.5 |
| Total | 1,970,733,586 | 100.0 | 397,088,235 | 100 | 20.1 |
| Adjusted with CARMA re-allocation | | | | 43.4 | |

**Table 3** Per capita GHG emissions in India and India urban extents by sector for the year 2000

| Source | India GHG emissions per capita (tonnes $CO_2$ eq./capita) | India urban extents GHG emissions per capita (tonnes $CO_2$ eq./capita) |
|---|---|---|
| Agriculture | 0.59 | 0.12 |
| Energy | 0.83 | 1.23 |
| Industry | 0.12 | 0.13 |
| Residential | 0.16 | 0.07 |
| Transportation | 0.10 | 0.06 |
| Waste | 0.13 | 0.12 |
| Total | 1.93 | 1.73 |

agricultural activities are located within urban boundaries in India. The latter relationship is not intuitive, as arguably most fossil-fuel, intensive transportation occurs within urban extents. What will be evident in the later analysis is that a large amount of transportation emissions are located in areas directly outside urban areas in India (see section on *urban GHG emissions by geographic distance from urban area*).

Of these six sectors, we suspect that urban emissions from energy production may be under-represented. In many countries, power plants that produce energy for urban occupants are located outside urban boundaries. As such, the figures previously presented are not full carbon signatures. With the reallocation of GHG emissions using the CARMA database (as previously discussed), we suggest that urban energy-related emissions may represent as much as 43.4% of India's GHG emissions. This adjustment adds approximately 54.1% of total energy production emissions (459 million metric tonnes) to urban extents, thus resulting in an urban share of 87% of all national energy production-related GHG emissions.

## The top GHG emitting and per capita GHG emitting urban extents

The major urban emitters of GHGs in 2000 were not always the biggest cities of India (see Table 4). Several of the largest urban areas in India, including Bengaluru, Kanpur, Jaipur, Lucknow, Patna, Indore, Bhopal, Coimbatore, Ludhiana, Kochi, Agra, Varanasi, and Madurai did not make the list of highest emitters. On the other hand, some of the smaller urban extents, including Anugul, Bankura, Mettur, Puruliya, and Khammam made the list due to the concentration of energy, industry, and fossil-fuel activity within their urban boundaries. For example, Anugul is home to big coalmines and several large industrial firms such as the National Aluminum Company, Mahanadi Coalfields Ltd, National Thermal Power Corporation, Jindal Steel and Power Ltd, and Indian Aluminum Company Ltd. In West Bengal's Bankura district, industrial development has been slow but the urban extent is squeezed in between the Durgapur-Asansol industrial belt and the industrial areas outside Kolkata. Moreover, approximately 19,000 biogas plants are located in this district.

Urban areas with the highest per capita emissions generate high levels of emissions, even though they have small populations (see Table 5). The population in the urban extents of this group is typically under 500,000 (except for Nashik and Visakhapatnam), and in many cases is under 200,000. At the same time, some urban extents on this list were also at the top of the total emissions group, including Anugul, Bankura, Mirazapur-cum-Vindhyachal, and others. Many of these locations are sites of large thermal power plants (Baran, Betul, Tuticorin, Bathinda, and Nashik), heavy industries (Mettur and Visakhapatnam), important coal mining locations (Neyveli and Brajarajnagar) or sites with combinations of these GHG-intensive economic activities.

## Urban GHG emissions by scale and form characteristics

According to our analysis, the highest emitters per capita are not the largest cities in terms of their population, but are those urban areas with '100,000–500,000' inhabitants (see Table 6). These smaller areas have emissions levels almost 58% higher, on an average, than the urban

Table 4 Top 25 urban GHG emitters in India in 2000

| Name of urban extent | Area (km$^2$) | Population | GHG emissions (tonnes $CO_2$ eq.) | GHG emissions (tonnes $CO_2$ eq./capita)) |
|---|---|---|---|---|
| Delhi | 3,755 | 16,842,200 | 31,264,601 | 1.86 |
| Kolkata | 2,325 | 15,847,000 | 25,824,191 | 1.63 |
| Visakhapatnam | 791 | 1,963,680 | 22,827,234 | 11.62 |
| Chandrapur | 509 | 388,635 | 20,180,709 | 51.93 |
| Anugul | 470 | 144,488 | 17,689,487 | 122.43 |
| Mumbai | 2,158 | 17,402,500 | 17,347,933 | 1.00 |
| Ahmedabad | 1,879 | 6,322,630 | 13,923,913 | 2.20 |
| Chennai | 1,354 | 7,755,660 | 12,255,195 | 1.58 |
| Karimnagar | 151 | 211,348 | 11,271,502 | 53.33 |
| Durgbhilainagar | 975 | 2,122,790 | 9,782,847 | 4.61 |
| Bilaspur | 276 | 285,969 | 9,605,563 | 33.59 |
| Neyveli | 315 | 221,202 | 9,276,755 | 41.94 |
| Baharampur | 228 | 327,654 | 8,154,904 | 24.89 |
| Hyderabad | 2,069 | 5,918,310 | 8,083,366 | 1.37 |
| Duragapur | 3,440 | 3,766,350 | 6,916,508 | 1.84 |
| Mirazapur-cum-vindhyachal | 151 | 234,565 | 6,801,503 | 29.00 |
| Nagpur | 715 | 2,430,220 | 6,759,021 | 2.78 |
| Nashik | 492 | 1,107,270 | 6,052,029 | 5.47 |
| Bankura | 94 | 101,105 | 5,737,205 | 56.75 |
| Surat | 1,583 | 3,636,820 | 5,045,648 | 1.39 |
| Korba | 474 | 116,542 | 4,524,535 | 38.82 |
| Mettur | 98 | 78,305 | 4,354,989 | 55.62 |
| Vadodara | 584 | 1,480,980 | 3,821,646 | 2.58 |
| Pune | 1,072 | 3,432,540 | 3,132,386 | 0.91 |
| Purulia | 91 | 112,045 | 3,119,742 | 27.84 |

average for the country (1.73 metric tonnes per capita). This group also exceeds the national average of 1.93 metric tonnes per capita.

Table 7 describes a pattern of increasing GHG emissions with geographic size of the urban extent. The larger urban extents (more than 120 km$^2$) have higher average GHG emissions per capita than the urban national average. The emissions per capita of all other urban extent groups are lower than the national per capita average.

Table 8 presents the distribution of India's urban extents by population density from categories spanning 518 persons per km$^2$ to those urban extents with over 1,711 persons per km$^2$. In this case, a trend of decreasing emissions

**Table 5** Top 25 urban GHG emitters per capita in India in 2000

| Name of urban extent | Area (km$^2$) | Population | GHG emissions (tonnes $CO_2$ eq.) | GHG emissions (tonnes $CO_2$ eq./capita) |
|---|---|---|---|---|
| Anugul | 470 | 144,488 | 17,689,487 | 122.43 |
| Bankura | 94 | 101,105 | 5,737,205 | 56.75 |
| Mettur | 98 | 78,305 | 4,354,989 | 55.62 |
| Karimnagar | 151 | 211,348 | 11,271,502 | 53.33 |
| Chandrapur | 509 | 388,635 | 20,180,709 | 51.93 |
| Neyveli | 315 | 221,202 | 9,276,755 | 41.94 |
| Korda | 474 | 116,542 | 4,524,535 | 38.82 |
| Bilaspur | 276 | 285,969 | 9,605,563 | 33.59 |
| Mirazapur-cum-Vindhyachal | 151 | 234,565 | 6,801,503 | 29.00 |
| Purulia | 91 | 112,045 | 3,119,742 | 27.84 |
| Khammam | 88 | 112,740 | 3,042,363 | 26.99 |
| Baharampur | 228 | 327,654 | 8,154,904 | 24.89 |
| Mangrol | 129 | 54,110 | 942,192 | 17.41 |
| Baran | 116 | 76,679 | 1,025,362 | 13.37 |
| Brajarajnagar | 430 | 148,271 | 1,925,028 | 12.98 |
| Visakhapatnam | 791 | 1,963,680 | 22,827,234 | 11.62 |
| Betul | 103 | 91,127 | 784,175 | 8.61 |
| Vriddhachalam | 266 | 142,761 | 1,182,669 | 8.28 |
| Ratnagiri | 144 | 66,283 | 502,234 | 7.58 |
| Tuticorin | 198 | 435,874 | 2,725,781 | 6.25 |
| Bardhaman | 128 | 228,298 | 1,375,074 | 6.02 |
| Bathinda | 158 | 415,775 | 2,501,474 | 6.02 |
| Rewa | 312 | 178,398 | 1,035,725 | 5.81 |
| Panipat | 204 | 277,968 | 1,528,333 | 5.50 |
| Nashik | 492 | 1,107,270 | 6,052,029 | 5.47 |

per capita with increasing density is clearly visible. The least dense areas have average GHG emissions per capita that is over three times the national average, while those in the medium-high and high-density categories have average levels lower than the national urban average.

Finally, Table 9 demonstrates that emissions vary with population growth rates. In this case, growth rates of urban extents vary between 1.0% per year to over 3.6% per year and are based upon population change during the 1990–2000 period. These data suggest a pattern of decreasing emissions per capita with speed of growth, if we exclude the urban extents with the slowest growth.

**Table 6** GHG emissions by population size of urban extent in 2000

| Urban extent population size category | | Total population | | |
|---|---|---|---|---|
| 50,000–100,000 | 21,607,080 | 24,726,239 | 0.87 | 367 |
| 100,000–500,000 | 155,142,628 | 56,733,139 | 2.73 | 284 |
| 500,000–1 million | 18,778,984 | 22,233,078 | 0.84 | 33 |
| 1–5 million | 92,860,344 | 56,225,020 | 1.65 | 31 |
| 5–10 million | 34,262,474 | 19,996,600 | 1.71 | 3 |
| > 10 million | 74,436,725 | 50,091,700 | 1.49 | 3 |
| All urban | 397,088,235 | 230,005,776 | 1.73 | 721 |

*Note* There was a statistically significant difference among the categories as determined by one-way ANOVA (F [5,711] = 9.705, p = 0.000). A Tukey post-hoc test revealed that the GHG emissions per capita from the 50,000–100,000 group were statistically significantly lower than the 100,000–500,000 and 1–5 million groups. There were no statistically significant differences in GHG emissions levels among other groups.

**Table 7** GHG emissions by area size of urban extent in 2000

| Urban extent area size category | Total GHG emissions (tonnes CO$_2$ eq.) | Total population | GHG emissions per capita (tonnes CO$_2$ eq./capita) | Sample size (n) |
|---|---|---|---|---|
| Small urban extent (< 54.78 km$^2$) | 3,007,799 | 8,162,241 | 0.37 | 131 |
| Medium-small urban extent (54.78–119.74 km$^2$) | 38,163,407 | 30,884,051 | 1.24 | 324 |
| Medium large urban extent (119.75–302.20 km$^2$) | 76,402,101 | 41,034,205 | 1.86 | 178 |
| Large urban extent (> 302.21 km$^2$) | 279,514,928 | 149,925,279 | 1.86 | 88 |
| All urban | 397,088,235 | 230,005,776 | 1.73 | 721 |

*Note* There was a statistically significant difference among the categories as determined by one-way ANOVA (F [3,713] = 52.773, p = 0.000). A Tukey post-hoc test revealed that GHG emissions per capita from all four groups of urban-extent sizes were statistically significant from each other—each smaller urban extent has lower carbon equivalent emissions per capita than larger categories.

**Table 8** GHG emissions by density of urban extent in 2000

| Urban extent population density category | Total GHG emissions (tonnes $CO_2$ eq.) | Total population | GHG emissions per capita (tonnes $CO_2$ eq./capita) | Sample Size (n) |
|---|---|---|---|---|
| Low density (<518 people/km$^2$) | 30,377,624 | 4,413,922 | 6.88 | 43 |
| Medium-low density (518–1,053 people/ km$^2$) | 75,784,483 | 32,603,354 | 2.32 | 258 |
| Medium-high density (1,054–1,710 people/ km$^2$) | 65,167,629 | 43,590,595 | 1.49 | 243 |
| High density (> 1,711 people/ km$^2$) | 225,758,499 | 149,397,904 | 1.51 | 177 |
| All urban | 397,088,235 | 230,005,775 | 1.73 | 721 |

*Note* There was a statistically significant difference among the categories as determined by one-way ANOVA (F [3,713] = 26.265, p = 0.000). A Tukey post-hoc test revealed that GHG emissions per capita from the low-density group was statistically significantly higher than all other groups, and the GHG emissions per capita from the medium-low density group were statistically significantly higher than that of the medium-high and high density groups. There was no difference in carbon equivalent emissions per capita between the medium-high and high density groups.

**Table 9** GHG emissions by growth rate of urban extent in 2000

| Urban extent growth rate category | Total GHG emissions (tonnes $CO_2$ eq.) | Total population | GHG emissions per capita (tonnes $CO_2$ eq./capita) | Sample size (n) |
|---|---|---|---|---|
| Low growth (< 0.01) | 3,620,532 | 6,359,098 | 0.57 | 46 |
| Medium-low growth (0.01–0.025) | 270,943,831 | 148,534,205 | 1.82 | 354 |
| Medium-high growth (0.025–0.036) | 115,773,352 | 70,894,841 | 1.63 | 293 |
| High growth (>0.036) | 6,750,520 | 4,217,632 | 1.60 | 28 |
| All urban | 397,088,235 | 230,005,776 | 1.73 | 721 |

*Note* There was a statistically significant difference among the categories as determined by one-way ANOVA (F [3,713] = 9.932, p = 0.000). A Tukey post-hoc test revealed that the GHG emissions per capita from the low-growth group were statistically significantly lower than that of the medium-low group; and that the GHG emissions per capita from the medium-low group were statistically significantly higher than that of the medium-high group. There were no differences in GHG emissions per capita among other groups.

## Urban GHG emissions by economic characteristics

Table 10 demonstrates the distribution of emissions in India's urban extents by total GDP. The data suggest an inverted-U function similar to those found in Environmental Kuznets Curve (EKC) studies (Grossman and Krueger 1995). The inverted-U function implies average emissions per capita increase with increasing GDP, and then decrease after reaching a threshold value. Hence, the highest levels of GHG emissions per capita appear in the medium-high GDP group of urban extents, with average per capita emissions in this group being higher than both the urban and national averages.

Table 11 presents urban extent distributions by GDP per capita. Again, these data suggest that average GHG emissions per capita increase

**Table 10** GHG emissions by total GDP of urban extent in 2000

| Urban extent GDP category | Total GHG emissions (tonnes $CO_2$ eq.) | Total population | GHG emissions per capita (tonnes $CO_2$ eq./capita) | Sample size (n) |
|---|---|---|---|---|
| No data | 3,797,026 | 2,099,445 | 1.81 | 18 |
| Low GDP (< $8,359) | 6,164,578 | 9,899,855 | 0.62 | 144 |
| Medium-low GDP ($8,359–22,367) | 30,429,627 | 30,275,571 | 1.01 | 286 |
| Medium-high GDP ($22,368–97,928) | 142,583,210 | 53,966,285 | 2.64 | 219 |
| High GDP (>$97,929) | 214,113,794 | 133,764,620 | 1.60 | 54 |
| All urban | 397,088,235 | 230,005,776 | 1.73 | 721 |

*Note* There was a statistically significant difference among the categories as determined by one-way ANOVA (F [3,713] = 49.848, p = 0.000). A Tukey post-hoc test revealed that GHG emissions per capita from the low GDP group of urban extents sizes were statistically significantly lower than that of all other groups. The GHG emissions per capita from the medium-low GDP group were significantly lower than that of the medium-high and high GDP groups. There were no differences in emissions per capita between the medium-high and high GDP groups.

**Table 11** GHG emissions by GDP per capita of urban extent in 2000

| Urban extent GDP per capita category | Total GHG emissions (tonnes $CO_2$ eq.) | Total population | GHG emissions per capita (tonnes $CO_2$ eq./capita) | Sample size (n) |
|---|---|---|---|---|
| No data | 3,831,398 | 2,175,215 | 1.76 | 19 |
| Low GDP (< $893) | 43,211,276 | 37,990,920 | 1.14 | 121 |
| Medium-low ($894–2,149) | 227,525,566 | 134,690,288 | 1.69 | 371 |
| Medium-high ($2,150–5,027) | 120,704,673 | 54,087,635 | 2.23 | 193 |
| High (>$5,027) | 1,815,322 | 1,061,718 | 1.71 | 17 |
| All urban | 397,088,235 | 230,005,776 | 1.73 | 721 |

*Note* There was a statistically significant difference among the categories as determined by one-way ANOVA (F [3,713] = 43.378, p = 0.000). A Tukey post-hoc test revealed that GHG emissions per capita from all four groups of urban extents were statistically significant from each other. The low GDP per capita emissions levels were significantly lower than those from all other groups. The medium-low GDP per capita group had emissions levels significantly lower than that of the medium-high and high GDP per capita groups. The medium-high GDP per capita group had GHG emissions levels significantly higher than that of all other groups.

as GDP per capita increases upto a point, after which the trend reverses and GHG per capita levels fall. Thus, as with the total GDP distribution, the group of urban areas with medium-high levels of GDP per capita has, on an average, the highest levels of emissions per capita. The average level of GHG emissions per capita for the medium-high category is also higher than both the urban and national averages.

### Urban GHG emissions by biophysical characteristics

Table 12 presents the distribution of urban extents by eco-region and its sub-categories. Geographic location within an ecosystem is associated with difference in per capita emissions. Urban areas not located in inland waterway, forest or mountainous eco-regions have, on an average, higher GHG emissions per capita than their non-urban counterparts. Similarly, urban areas in coastal regions have higher GHG emissions per capita levels than those in non-coastal areas. At the same time, semi-arid and arid regions exhibit lower GHG emissions per capita, while those in dry sub-humid regions have higher-than-national average per capita emissions.

Table 13 presents the distribution of urban extents in India by CDD. If the lowest category is excluded, a pattern of increasing GHG emissions per capita with increasing CDD is observed. The urban extents in the highest category demonstrate average per capita emissions levels above the national average.

### Urban GHG emissions by geographic location within the region

In our final analysis, we present the distribution of GHG emissions spatially in the nation defined by distance from urban extents (Table 14). The largest share of estimated GHG emissions is found in areas immediately beyond urban extents (up to 20 km outside the boundaries of urban areas). Approximately, 45% of all of India's GHG emissions are released in this space. This finding should not be too surprising as, according to our data, approximately 43.5% of the Indian population resides in these spaces. Hence, as these areas are also highly populated, they generate high levels of GHG emissions per capita (1.98 metric tonnes per capita). Much of the industrial- and energy-related emissions are also released within the urban extents and within an area of 20 km around them. As such, approximately 72% of industry-related emissions and 80% of all energy-related emissions are released within these areas. Another interesting point is the varying intensity of residential emissions, which peak within 20–40 km from urban areas. Within this range, residences account for approximately 63% of all emissions related to residential activities within the country, including burning fuelwood, dung, and agricultural scraps for heat and cooking.

The area between 40 and 80 km from urban areas accounts for only 9% of all GHG emissions in India. Moreover, this ring has the lowest per capita GHG releases on an average, as compared to any other area, despite its larger geographic size. Residents with the highest per capita emissions are those in the 'most rural' areas (farthest from any urban extent), where emissions levels are over 3 metric tonnes per capita. However, the emissions from these areas account for only 2.1% of the national emission. In these rural areas, emissions result largely due to agricultural activities. It is interesting to note that for the most part, the area in India outside 80 km (the remainder) is in the far north, where elevations increase rapidly and population is low.

## Discussion and limitations

The spatial patterns of GHG emissions within India and their relationships with urban scale, form, and economic and biophysical factors are complex. Before we discuss the implications of our findings, it is imperative to qualify the results of our descriptive analyses. In our understanding, this is one of the first analyses of GHG emissions from urban areas in a developing country using a wide variety of data sources. We used a new database, EDGAR, keeping in mind all the promises and shortcomings of any

**Table 12** GHG emissions by eco-region per capita of urban extent in 2000

| Urban extent Eco-region category | Total GHG emissions (tonnes $CO_2$ eq.) | Total population | GHG emissions per capita (tonnes $CO_2$ eq./capita) | Sample size (n) |
|---|---|---|---|---|
| Non-waterway | 145,824,319 | 77,469,032 | 1.88 | 483 |
| Inland waterway | 251,263,916 | 152,536,744 | 1.65 | 238 |
| Lake and reservoir | 96,725,199 | 65,548,896 | 1.48 | 87 |
| River | 3,960,744 | 4,596,240 | 0.86 | 6 |
| Freshwater marsh | 46,024,428 | 24,054,238 | 1.91 | 39 |
| Swamps and flooded forest | 28,681,451 | 19,379,211 | 1.48 | 4 |
| Brackish saline wetland | 2,903,308 | 3,960,574 | 0.73 | 7 |
| Bog, fen, and mire | 24,662,307 | 15,273,293 | 1.61 | 14 |
| Intermittent wetland | 48,306,479 | 19,724,292 | 2.45 | 81 |
| Non-forest | 143,723,797 | 80,351,078 | 1.79 | 290 |
| Forest | 253,364,438 | 149,654,698 | 1.69 | 431 |
| Broadleaf evergreen | 257,867 | 912,925 | 0.28 | 10 |
| Broadleaf deciduous closed | 246,250,679 | 138,376,924 | 1.78 | 388 |
| Broadleaf deciduous open | 2,892,689 | 4,724,312 | 0.61 | 21 |
| Needle leaf evergreen | 2,481,167 | 3,955,960 | 0.63 | 8 |
| Needle leaf deciduous | 134,400 | 272,804 | 0.49 | 1 |
| Mixed leaf | 806,548 | 1,002,897 | 0.80 | 2 |
| Mosaic leaf | 541,088 | 408,876 | 1.32 | 1 |
| Non-arid | 127,003,799 | 77,459,313 | 1.64 | 232 |
| Dryland | 270,084,436 | 152,546,462 | 1.77 | 489 |
| Dry sub-humid | 146,539,917 | 63,644,415 | 2.30 | 199 |
| Semi-arid | 122,884,633 | 87,397,906 | 1.41 | 284 |
| Arid | 659,886 | 1,504,141 | 0.44 | 6 |
| Non-mountain | 312,895,459 | 177,661,589 | 1.76 | 615 |
| Mountain | 84,192,776 | 52,344,186 | 1.61 | 106 |
| 300–1,000 metres elevation | 83,577,318 | 50,439,430 | 1.66 | 94 |
| 1,000–2,500 metres elevation | 615,458 | 1,904,756 | 0.32 | 12 |
| Non-island | 373,392,173 | 206,922,194 | 1.80 | 716 |
| Island | 23,696,062 | 23,083,582 | 1.03 | 5 |
| Non-coastal | 249,326,285 | 147,255,267 | 1.69 | 586 |
| Coastal | 147,761,950 | 82,750,509 | 1.79 | 135 |
| All urban | 397,088,235 | 230,005,775 | 1.73 | 721 |

**Table 13** GHG emissions by cooling degree days of urban extent in 2000

| Urban extent<br>Cooling Degree Day category | Total GHG emissions (tonnes $CO_2$ eq.) | Total population | GHG emissions per capita (tonnes $CO_2$ eq./capita) | Sample size (n) |
|---|---|---|---|---|
| Low CDD (<40.4) | 66,130,819 | 47,348,020 | 1.40 | 430 |
| Medium-low CDD (40.5–661.0) | 450,112 | 1,156,046 | 0.39 | 2 |
| Medium-high CDD (661.1–2,285.8) | 15,325,965 | 18,461,699 | 0.83 | 40 |
| High CDD (>2,285.9) | 315,181,339 | 163,040,011 | 1.93 | 249 |
| All urban | 397,088,235 | 230,005,776 | 1.73 | 721 |

*Note* There was a statistically significant difference among the categories as determined by one-way ANOVA (F [3,713] = 3.593, p = 0.000). A Tukey post-hoc test revealed that GHG emissions per capita from the low CDD group were statistically significantly lower than that of the high CDD group. There were no other significant differences among the groups.

**Table 14** GHG emissions by geographic location, distance from urban extents, and by sector in 2000

(% and metric tonnes $CO_2$ eq. per capita)

|  | Remainder | 80–40 km | 40–20 km | 20 km-urban extent boundary | Urban extent | All India |
|---|---|---|---|---|---|---|
| Population | 1.3 | 8.9 | 23.8 | 43.5 | 22.5 |  |
| Agriculture (%) | 2.71 | 14.36 | 31.71 | 46.49 | 4.73 |  |
| (per capita) | 1.25 | 0.26 | 0.78 | 0.63 | 0.12 | 0.59 |
| Energy (%) | 1.66 | 5.21 | 12.61 | 47.24 | 33.28 |  |
| (per capita) | 1.09 | 0.13 | 0.44 | 0.90 | 1.23 | 0.83 |
| Industry (%) | 1.32 | 8.98 | 18.11 | 48.11 | 23.48 |  |
| (per capita) | 0.13 | 0.03 | 0.09 | 0.13 | 0.13 | 0.12 |
| Residential (%) | 2.11 | 9.62 | 62.58 | 15.72 | 9.98 |  |
| (per capita) | 0.27 | 0.05 | 0.43 | 0.06 | 0.07 | 0.16 |
| Transportation (%) | 3.29 | 11.12 | 24.70 | 46.90 | 13.99 |  |
| (per capita) | 0.26 | 0.03 | 0.10 | 0.11 | 0.06 | 0.10 |
| Waste (%) | 1.86 | 7.20 | 20.38 | 50.04 | 20.51 |  |
| (per capita) | 0.19 | 0.03 | 0.11 | 0.15 | 0.12 | 0.13 |
| Total (%) | 2.10 | 9.05 | 24.13 | 44.58 | 20.15 |  |
| (per capita) | 3.18 | 0.53 | 1.95 | 1.98 | 1.73 | 1.93 |

new tool. This analysis should be viewed as a first and preliminary assessment of trends. Moreover, it needs to be kept in mind that we chose the year 2000 as a baseline. As discussed in the introduction, a lot has ensued in India since 2000 that can make our findings appear dated. At the same time, the data provide a basis for future studies that can utilize more updated information.

Notwithstanding the limitations of the data and the various combinations of datasets, readers should understand that our analysis might not represent full carbon signatures, but rather represents 'partial carbon footprints' (Brown, Southworth, and Sarzynski 2008; Sovacool and Brown 2010). There are innumerable activities that occur within Indian cities that have GHG release associated with them. We may not have captured them fully in this study. Our biggest concerns relate to the emissions from power plants that are generating electricity for urban residents. We attempt to quantify the magnitude of possible missing emissions from electricity by reallocating the energy emissions to urban areas based upon the CARMA dataset. This procedure, however, only provides the high-end of a range of emissions because not all electricity is consumed within urban areas. Despite our adjustments, there remains uncertainty in regard to the full carbon accounting for cities in our findings.

One way to validate these data is to compare them to carbon accounting studies that have been conducted in Indian urban areas. In this regard, there are a few analyses (Mitra, Sharma, and Ajero 2003; Kennedy, Ramaswami, Carney, *et al.* 2009; Gurjar, v Aardeene, Lelieveld, *et al.* 2004). **Table 15** presents the comparison of findings between the earlier studies and the present one. As can be seen from the table, a disagreement exists on the issue of full carbon accounting for Delhi and Kolkata. The findings from different research projects suggest that Kolkata's GHG emissions are approximately 1.1 tonnes per capita ($CO_2$ emissions only), while those for Delhi are between 1.5 and 1.6 ($CO_2$ only) and 2.07 ($CO_2$, $N_2O$, and $CH_4$) tonnes per capita. Our estimates for Kolkata range from 1.4 and 1.6 tonnes per capita. This range is higher than that of other studies, while our estimates for Delhi (1.0–1.5 tonnes per capita) are similar to that in the previous studies.

Given the similarities in these findings, we can state with some confidence that the preliminary results are reasonable. There are

**Table 15** Comparison of results for urban carbon emissions studies

| Urban area | Study | Year | Compound | GHG emission per capital (tonnes $CO_2$ eq./capita) |
|---|---|---|---|---|
| Kolkata | Mitra, Sharma, and Ajero (2003) | 2000 | $CO_2$ | 1.1 |
| Delhi | Mitra, Sharma, and Ajero (2003) | 2000 | $CO_2$ | 1.5 |
| Kolkata | Kennedy, Steinberger, Gasson, *et al*. (2010 | 2000 | $CO_2$ | 1.1 |
| Delhi | Kennedy, Steinberger, Gasson, *et al*. (2010) | 2000 | $CO_2$ | 1.6 |
| Delhi | Gurjar, v. Aardeene, Lelieveld, *et al*. (2004) | 2000 | $CO_2$ | 1.67 |
| | | | $N_20$ | 0.36 |
| | | | $CH_4$ | 0.04 |
| | | | Total | 2.07 |
| Kolkata | This study | | | 1.4–1.6 |
| Delhi | This study | | | 1.0–1.5 |

at least four areas where further research should be conducted. First, the varieties of patterns of GHG emissions from urban areas presented are complex and difficult to decipher, given the likely associations across multiple factors such as population and GDP. More work on a multivariate model that could explain these differences is needed. At the same time, analyses at other levels of comparison are also worth generating for validation of these national-level results. We suggest that a study at the Asian level and another at the global level be performed and compared with various national-level projects.

Second, in terms of the influences of income, the apparent EKC pattern of GHG emissions with GDP and GDP per capita categories is intriguing. The EKC has been used widely by economists, although a variety of concerns over the techniques needed to identify the relationship, the determinants of the shape of the EKC, and the variety of different empirical results (some confirming, while others refuting the existence of the EKC) have been published (for a review of the EKC, see Dinda 2004). Interestingly, the EKC relationship has not been identified for GDP and GHG emissions per capita at any other scale of analysis. Indeed, the World Bank (1992) analysis suggests that this type of relationship defies an inverted-U type function. The question of whether this function defines the relationship at the urban level suggests that there are benefits from urban agglomeration related to energy use and total GHG emissions that overwhelm economic scale effects. This finding reveals that further exploration and identification of this relationship—both within India and beyond—will lead to valuable policy-related results.

There is also the possibility of micro-scale work at the household level that can shed more light on this relationship. For example, researchers have conducted studies on the urban household energy transition (see, for example, Barnes, Krutilla, and Hyde 2005). The transition model defines changes in fuel type from wood to cooking gas and electricity. Within India, there exist social surveys with extensive data on these and other issues, such as automobile ownership, air conditioning, market penetration, and so on, but because of costly access, such research has been limited. Certainly, the variation in residential GHG emissions with distance from urban areas requires further study.

Thirdly, the results suggest an important role for urban form in defining GHG emissions. Earlier studies have suggested that urban form is related to energy consumption in developed countries (Newman and Kenworthy 1989; Newman and Kenworthy 1999). This relationship, however, turns complicated with income. Researchers have, in some cases, found that cities in rapidly developing countries have higher per capita emissions than the national averages (IEA 2008). The EDGAR data provide a valuable source to extend these studies, as the data provide GHG emissions by source.

Furthermore, our study points to the concentration of energy and industrial emissions in locations directly outside urban areas. This result suggests that these locations are sources of production, while the urban areas act as sources of consumption. Some studies have suggested that foreign direct investments in industry have targeted areas directly outside Asian cities, and that these investments have stimulated manufacturing production (Marcotullio 2003). But this relationship has only been suggested, and not empirically validated. More work on the emerging urban form of Asian cities and how these structures impact the environment is necessary.

Finally, the study supports the notion that geography seems to matter—not only at the national level, but also at the level of urban areas (Neumayer 2004). According to our analyses, GHG emissions per capita levels vary by eco-region, climate, and distance from urban extent. That is, urban areas with warmer climates (higher cooling degree days) have higher average per capita emissions than their cooler-climate counterparts. This is most probably due to the concentration of commercial and industrial activity in warmer climates, and as a result of higher energy demands for cooling offices, industries, and residential buildings.

Moreover, urban areas along coastlines have higher emissions than inland cities, presumably because of the more intensive industrial development associated with trade and access to global transportation (particularly port) activity. Here, as with the other areas, we identified areas where more research could yield potentially important results. Finally, the finding that the majority of India's GHG emissions is released from areas directly around urban extents points to the significance of peri-urban regions. Up until this point in time, much of the effort in urban carbon emissions has been pointed towards core urban areas, while these findings suggest that peri-urban areas are also important sources of emissions in India.

In general, our results reveal that the EDGAR database is a good starting point for further research in the field of urban GHG emissions. What is needed is further comparison with global patterns, additional detailed models to gauge the various influences on these types of emissions from urban areas, as well as more updated information to perform trend studies.

## Conclusion

Our data suggest that per capita emissions in urban areas are lower than the national average, meaning that urban areas are more efficient than non-urban areas, on an average. At the same time, not all urban extents are efficient. First, according to our findings, GDP and GDP per capita are important influences on GHG emissions, but in interesting ways. A cross-sectional analysis using broad categories hints at an EKC-type curve. Second, differences in emissions per capita appear across scale, form, and biophysical characteristics associated with urban extents. Identifying the relative importance of these factors needs more work. Finally, in India, emissions are concentrated largely in areas directly around cities (20–40 km from urban extent boundaries), thereby highlighting the importance of peri-urban areas as GHG emitters.

The descriptive analyses are loosely consistent with similar findings from case studies on carbon footprints of individual cities. While more work is needed to identify minute details, this preliminary analysis suggests that the database is worthy of further examination and analyses, which could be performed at both larger and smaller scales.

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