In return, Chinese involvement will inject fresh force to speed up worldwide geothermal development. According to the draft of *New Energy Industry Development Plan 2011–2020* that is under review by the State Council, China is expected to invest RMB Yuan 5 trillion (about US$800 billion) in new energy in a 10-year period. The greater the portion of this money to be invested in geothermal research and development, the more likely China is to help reshape the worldwide geothermal market. ❐

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## Acknowledgements

The author acknowledges helpful discussions with J. Wang, Z. An, W. Zhou, S.Hu, S. Dong, Z. Gu and X. Li, and the technical assistance of Y. Xiong. This study is supported by the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment of Chinese Academy of Sciences via Grant SKLLQG1006.

COMMENTARY:

# Measuring the carbon emissions of megacities

Riley M. Duren and Charles E. Miller

**Carbon emissions from cities represent the single largest human contribution to climate change. Here we present a vision, strategy and roadmap for an international framework to assess directly the carbon emission trends of the world's megacities.**

Urbanization has concentrated more than 50% of the global population, at least 70% of fossil-fuel carbon dioxide emissions and a significant amount of anthropogenic methane into a small fraction of the Earth's land surface[1]. Carbon emissions from cities are projected to undergo rapid change over the next two decades with growth in developing countries and stabilization in developed countries. No current or planned system is capable of monitoring the atmospheric trends of carbon attributed to the world's largest cities despite recent field experiments demonstrating scientifically robust methods for assessing carbon emissions, and rapid improvements in measurement technology. A concerted effort is needed to transform emerging scientific methods and technologies into an operational monitoring system to support urban carbon management decisions.

For robust verification of emission changes due to growth or stabilization policies we need to establish measurement baselines and begin monitoring representative megacities immediately. This urgency is driven by explosive growth in carbon dioxide emissions from fossil-fuel use. Global growth in carbon dioxide emissions from fossil fuels outpaced global growth in gross domestic product in 2010 at an unprecedented 5.6% per year, and in 2009 consumption-based emissions from developing countries surpassed those of developed countries[2]. Global urbanization is projected to increase dramatically over the coming decades, with the world's urban population doubling by 2050. Even with the recent global economic slowdown, the gross domestic products of China and India are predicted to continue to grow at least 6% per year through to 2025 (ref. 3), portending a similar or greater annual increase in their urban emissions without significant mitigation actions. Despite slow progress in reaching emissions stabilization agreements between nations, many of the largest cities are now taking actions that should have detectable impacts on emission trends[4]. For example, the City of Los Angeles initiated a programme in 2007 to cut greenhouse-gas emissions to 35% below 1990 levels by 2030 (ref. 5).

Sustained atmospheric observations have accurately quantified the unprecedented increase in global atmospheric carbon dioxide concentrations over the past 50 years and show strong correlation with estimates of global fossil-fuel consumption during the same period[6]. However, so far it has not been possible to directly attribute observed trends in atmospheric carbon dioxide to the actions of any nation, state or city. Attribution is challenging given that the 9.1 ± 0.5 Gt C emitted from global fossil-fuel use and cement production in 2010 (ref. 2) constituted only about 2% of the gross surface–atmosphere carbon flux. Inventories derived from bottom-up accounting of activity data and emission models carry varying degrees of uncertainty; typically 5–20% per year for carbon dioxide emissions from individual nations — resulting in

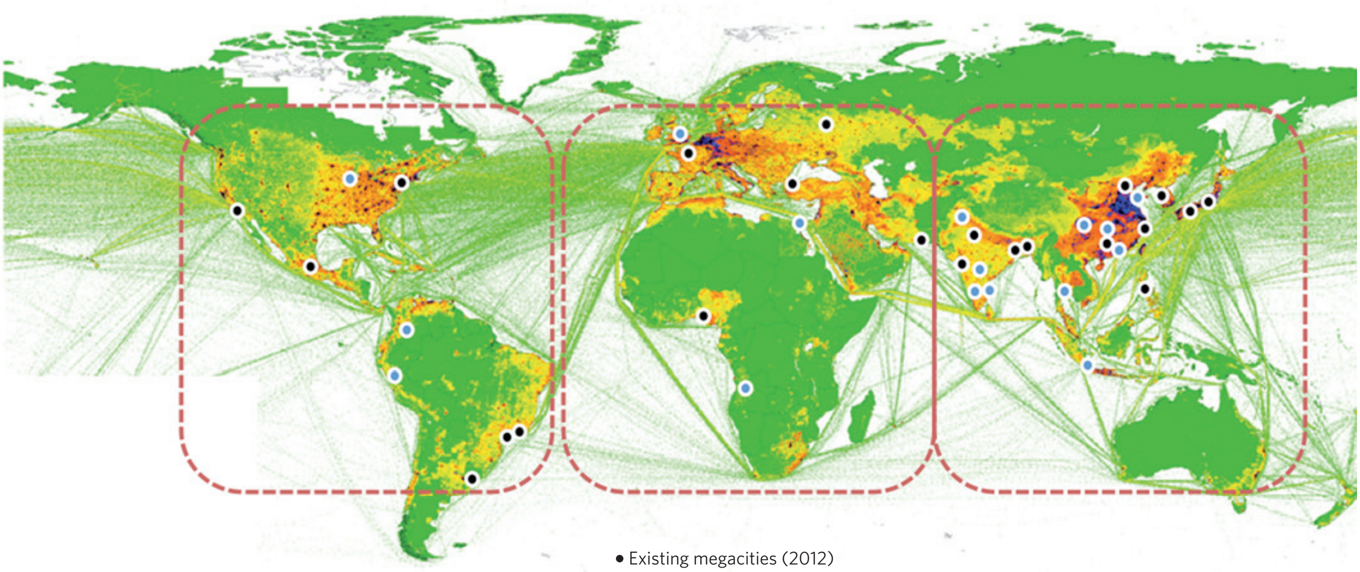


**Figure 1 |** A strategy for monitoring megacity carbon emissions. A 10-km-resolution gridded inventory of anthropogenic greenhouse-gas emissions in carbon dioxide equivalents indicates the distribution and intensity of emission sources, ranging from 0–55 Mg C per cell per year. Urban areas are indicated in orange, red and black. The darkest areas correspond to the emissions of urban and heavily industrialized areas. The black circles indicate proposed surface measurement networks concentrated within and around the 23 existing megacities. Blue circles indicate the 14 additional megacities projected to exist by 2025 (ref. 17). The dashed rectangles indicate the fields of regard of three remote-sensing instruments that if hosted on commercial communication satellites in geostationary orbit would offer sustained, wall-to-wall measurements of column-averaged carbon dioxide, methane and carbon monoxide mixing ratios several times per day for the vast majority of the Earth's populated areas. With such a system, a typical megacity would be sampled by over 2,500 measurements per day on average. An existing network of surface remote-sensing stations enables calibration of satellite data. Emission map taken from European Commission-Joint Research Council/Netherlands Environmental Assessment Agency (PBL ). Emission Database for Global Atmospheric Research (EDGAR) version 4.0 (http://edgar.jrc.ec.europa.eu) 2009.

uncertainties in multiyear trend estimates that often exceed the expected change in emissions. Signatories to the United Nations Framework Convention on Climate Change are required to report annual greenhouse-gas inventories, but the reporting guidelines and best practices pertain only to national level records. This can translate into significant discrepancies between inventories at different levels of governance; a recent study noted a 20% discrepancy between the reported national total and summation of provincial carbon dioxide emissions for China in 2010 — equivalent to 5% of global total emissions[7]. The research community has developed methods for downscaling national inventories to finer spatial and temporal scales, but downscaling introduces significant additional uncertainties and disagreements. For example, a comparison between two such products at a 25 km scale in the United States shows a 50% difference[8].

Monitoring trends in urban domes of atmospheric carbon — stable air masses that form over cities with significantly enhanced concentrations of carbon dioxide and other greenhouse gases — has been suggested as a means of directly assessing the efficacy of stabilization policies with reduced levels of uncertainty[6]. Measurements of the mixing ratios or airborne fractions of these gases combined with models of atmospheric circulation (for example, tracer-transport techniques) can be used to provide independent, top-down estimates of the locations and strengths of carbon fluxes. In particular, megacities — metropolitan areas with populations greater than 10 million — have further concentrated carbon dioxide emissions from fossil fuels: emissions from the 50 largest cities collectively contribute the third-largest anthropogenic source, trailing only China and the United States[9]. The emissions intensity and relatively confined spatial extent of megacities translate into carbon dioxide flux signals of 20 to 160 kg C $m^{-2}$ $yr^{-1}$ at spatial scales smaller than 10 km within these regions[10]. At such localized scales, these fluxes exceed the largest carbon fluxes from the biosphere by factors of 20 to 200 and are far easier to detect than at the spatial scales of states, countries and continents.

Similar arguments can be made for methane, which is less abundant than carbon dioxide but has a global warming potential 77 times greater than carbon dioxide on 20-year time horizons. Current inventory-based estimates of methane report high uncertainty (>50% for some sectors) and atmospheric measurements indicate that fugitive emissions are much larger than previously assumed[11]. Cities contribute a significant fraction of anthropogenic methane emissions from landfills, wastewater treatment facilities and natural-gas infrastructure. This opportunity to achieve high payoff with localized efforts has motivated action by multiple entities to stabilize urban methane emissions[12].

An observation system designed to monitor megacity carbon dioxide and methane domes must include a tiered set of surface, airborne and satellite sensors. Frequent surface observations of atmospheric mixing ratios of carbon dioxide, methane and carbon monoxide using networks of commercially available electronic sensors clustered within the largest urban domains would provide a foundation for accurate, stable and traceable emissions estimates across a global framework. Carbon monoxide can help disentangle the relative contributions of fossil-fuel and biogenic sources of carbon dioxide, by serving as a tracer of combustion activity. The urban surface networks would be overseen by the research laboratories whose global data sets have withstood intense internal and external scrutiny for decades with long-term uncertainty quantification, as well as careful calibration with reference gases and protocols facilitated by international metrology agencies. Whole-air samples would be collected regularly, cross-validated by multiple laboratories, and analysed for other important tracers of anthropogenic activity such as halocarbons and radioisotopes (for example, carbon-14). Measurements of carbon-14 are too cumbersome and costly to make with high frequency at many locations, but expanded sampling tailored to specific cities is warranted, given that they are critical for calibrating the fossil-fuel carbon dioxide emissions fraction determined from carbon dioxide/carbon monoxide data. Observations of surface winds and atmospheric boundary layer height would help reduce errors associated with tracer-transport models. Periodic mobile measurement campaigns would locate and characterize individual fugitive emissions sources within the urban domain. Periodic aircraft campaigns would help constrain boundary conditions (such as inflow/outflow beyond the urban domain).

Satellite observations would complement the surface-based network with observations over regional scales, providing boundary conditions as well as insight into emissions from cities that lack surface networks. Recent studies have demonstrated the critical importance of remotely sensed column-averaged mixing ratios in minimizing the impacts of small-scale atmospheric processes on estimating emission fluxes and trends[13]. Remote-sensing studies of urban domes[14] indicate that column-averaged observations with single-measurement precisions of 1.5 parts per million (ppm) for carbon dioxide, 15 parts per billion (ppb) for methane, and 15 ppb for carbon monoxide at spatial scales of 2–4 km would be sufficient to detect the enhancements typically associated with megacities. Higher spatial resolution is desirable but not required for detecting the emission trends of major cities, power plants and other intense point sources. Current and planned polar-orbiting satellites such as the Japanese Space Agency's Greenhouse Gases Observing Satellite (GOSAT) and NASA's Orbiting Carbon Observatory (OCO-2) are optimized to provide column data sets that can be used to infer natural carbon cycle fluxes at continental and seasonal scales but provide very limited coverage of cities. Similarly, NASA's Measurement Of Pollution In The Troposphere (MOPITT) has detected carbon monoxide emissions from cities but at fairly coarse resolution and infrequent intervals[15]. Newly developed remote-sensing technology offers the measurement precision, high spatial resolution, near-continuous mapping and rapid revisit times required for robust monitoring of urban domes. Three such instruments deployed on geostationary satellites (one each over the Americas, Europe/Africa and Asia) would provide simultaneous measurements of carbon dioxide, methane and carbon monoxide column-averaged mixing ratios for the majority of the Earth's populated land surface, including nearly every major urban area and power plant (Fig. 1). Sustained, high-density column measurements of these species, including the aggregation of many samples, would allow reliable trend assessments over periods of five years or longer.

As with weather satellites, the geostationary vantage point allows multiple revisits per day, reducing the impact of clouds on measurements and enabling assessments of diurnal trends. Commercial communication satellites are routinely placed in orbit roughly once per month, offering a relatively low cost and high reliability opportunity to launch the instruments as hosted payloads. Sustained observations from the existing surface network of remote-sensing stations would calibrate and reduce biases in the satellite data[14].

Useful assessments of policy efficacy would require linking the top-down estimates of fluxes with improved bottom-up estimates of urban emissions at space–time scales of a few kilometres and several hours. A parallel effort to collect and assimilate activity data is needed. Ultimately, the effective integration of top-down and bottom-up methods would lead to urban full-carbon accounting, offering reliable diagnostic and prognostic models for urban planners and policymakers.

Although methodological studies have been conducted in relatively straightforward environments such as medium-size cities with stable emissions[13,16], there has not yet been an effort to extend these techniques to the more complex and representative environments of megacities. To address this gap, a coordinated pilot project for the megacities of Los Angeles and Paris is being initiated that leverages and extends established measurement infrastructure in those cities, and techniques being developed in methodological studies.

Phase 1 of the megacity pilot activity seeks to resolve residual scientific and technical barriers, provide a framework for transparent data sharing between international partners and establish within the next 12–24 months the baselines needed for trend assessment. Meanwhile, ongoing engagement with local policymakers, regulatory agencies and other stakeholders will inform definition of the ultimate data sets and potentially extend the pilot to include an additional megacity in the developing world. Phase 2 is expected to last between three and five years and will provide a first estimate of emission trends in the initial pilot cities. Phase 3 could commence by 2020 or sooner with a goal of expanding the framework to include surface networks in all of the world's megacities (25–30 by that time) with complementary satellite observations; while applying the scientific knowledge, protocols and measurement methods demonstrated in the pilot cities.

Sustained monitoring of the atmospheric domes of carbon dioxide, methane and carbon monoxide for the world's cities, scientifically robust analysis and transparent data sharing will provide decision-makers with information critical to assessing the ultimate efficacy of emission mitigation policies. It will also help local policymakers who are taking action now explain to their communities and stakeholders the importance of and progress towards addressing the single biggest human contribution to climate change: carbon emissions from cities. ❐

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## Acknowledgements

The authors are grateful for discussions with many colleagues in the international carbon cycle science community, local officials, government agencies and non-governmental organizations. This work was done at the Jet Propulsion Laboratory, a division of the California Institute of Technology under contract to the National Aeronautics and Space Administration.