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Editorial

Cities in the earth system

The human city is often studied in close-up or pondered from afar by geoscientists, but it is under-investigated as a true component of the earth system. For example, atmospheric research in urban areas tends to focus on local to regional air quality. Cross-comparison of urban atmospheres could shed substantial light on the role human settlements will play in biogeochemical change, but it is largely lacking. Energy technologists compile fuel use distributions at the national level but rarely break them down by city. Ecologists have begun to consider collective human behavior by analogy with biological metabolism, but again synthesis of data and models lags. The biological reasoning must be more completely elaborated, for example at the ecosystem level. Urban growth and succession will be major determinants of biogeochemical change for decades into the near future. Experiment and simulation must eventually be brought to bear upon the functioning of human communities within the planetary scale biogeochemical system.

In this opinion piece, we build a qualitative case for constructing a more comprehensive view of the global city. An earth system perspective is advocated, with studies conducted to enhance understanding not just of individual localities, but of the full spectrum of urban zones. We recommend that resources be applied immediately to the synthesis of existing data from fields such as environmental quality, energy management, sociology, landscape ecology, and demographics. Ideally this early step would generate research momentum such that earth system issues become integral to localized future studies. We also envision international level research which contrasts and interprets the behavior of multiple urban zones by cutting across geographic, political and economic boundaries. An ultimate goal will be prediction of the evolution of a unified, global urban ecosystem.

The mega-settlements of our era are actually evolving ecosystems, and they are among the most important on the planet. In contrast to other ecosystems, however, they receive little emphasis in the literature. For example, the uptake of carbon by terrestrial forests receives close examination (Schimel et al., 2000). El Niño driven shifts toward phosphorous limitation are carefully documented in the vast North Pacific central gyre (Karl, 1999). Several traditionally defined major biomes merit their own chapters in the influential climate reviews (Houghton et al., 1995). All of this is as it should be. But a new ecosystem is emerging and it will demand the same level of treatment. We will soon be compelled to consider fuel, nutrient and other material cycles through the distribution of human communities. Energy and material processing by people will be intimately linked to the evolution of the city. Climate change will feed back into that evolution. All these connections must become the subject of intense scientific inquiry, as are their analogs in more remote and familiar places.

It might be asked: Why is it necessary to emphasize the existence of something so obvious as a city? Ecologists have argued persuasively that the globe is transforming into a vast, human-dominated ecosystem (Vitousek et al., 1997). Today only a relatively small fraction of the total population dwells in built-up areas, but historical trends and demographic projections indicate that within a few decades a large majority of the people on most of the continents will be urbanites (UN, 1994). Processing of materials and energy by humans will be focussed within our cities even as we are altering the face of the globe. A detailed knowledge of urban infrastructure and evolution is not possible, but it is not necessary for projection of human usage and emissions of geochemically relevant substances. This is clear because projections are already being done (Houghton et al., 1995). Our position is that a close coupling of urban dynamics and ecology into the earth system sciences will improve the skill of such projections. Further, we maintain that data and experimental/analytical techniques are at hand to make real and rapid progress.

The concepts we are exploring are perhaps best illustrated in the modeling arena. Simulation of activities in and around cities has developed exponentially in sophistication over the last few years. Traffic patterns can now be computed on a time dependent basis for highway networks serving millions of people, and at the 10 meter scale (LANL, 2000). The flow of air through street canyons can be simulated on regional grids containing cells only a meter or so across (Smith et al., 2000).

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Photochemistry and aerosol microphysics modules representing many hundreds of transformations are on hand to insert in such calculations (Seinfeld and Pandis, 1998). But the driving force for all of this research remains primarily the comfort, safety, and health of the population. In a more comprehensive view, traffic variations might profitably be coupled with emissions data, and downwind effects of the urban effluent could well be elucidated by meter-scale simulation of photochemical/microphysical processing. Applying these tools in an integrated fashion from the perspective of cities as ecosystems would address the issues raised here.

The groundwork for this new perspective has been laid. Pioneering work on the analogies of cities with metabolism and succession began in the 1960s. Theoretical frameworks were developed for analysis of the total of energy and material fluxes through urban areas (Odum, 1969, 1971). Nevertheless, today it is still difficult to find the concepts applied in the literature. During recent writing of a review article on these matters (Decker et al., 2000), studies of Hong Kong and small Baltic cities were among the only examples we could locate. The various chemical species in urban air were treated as a single mass of air pollutant exiting the urban zones. The suite of true megacities (UN, 1992) is utterly without representation. Certain urban areas have been designated Long Term Ecological Research Sites (LTERs; CAP LTER, 2000; BES 2000), but the distribution is heavily weighted toward the developed world. The recent NASA Chinese Metroagroplexes campaign (ChinaMAP; Chameides et al., 1999) has been among the most successful ever at combining atmospheric chemistry and ecology issues. ChinaMAP demonstrated that Asian air pollution impacts crop and terrestrial plant growth both through oxidant attack on leaf surfaces and through particulate reductions in PAR. Although the title and acronym refer directly to the metropolises of Asia and the research was highly interdisciplinary, urban dynamics were not dealt with. Yet another Mexico City air quality project is now in the planning stages — the Valley of Mexico is clearly becoming something of a Mecca for atmospheric chemistry research. Although an effort is being made to treat feedback loops from the airborne pollution into human activities, the emphasis is intra-urban. Visibility and health remain the major selling points. This may be an economic necessity, but it can still be argued that the viewpoint is restrictive.

Occasional research articles regarding the megacities treat NO_y compounds as mobilized, bioavailable nitrogen (Riggan et al., 1985; Elliott et al., 1997a). Commercial gas leakage is sometimes assessed for its effects on downstream photochemistry (Elliott et al., 1997b). The latest WRI publication of resource tables includes sewage data for some cities (WRI, 1998). This is a positive step because past information sets have not been resolved at finer than the national scale. However, compilations of urban fuel use distributions are still wanting within the international scholarly literature. Food input data have not been collected and nutrient inputs are rarely monitored. Waste storage will be a strong contributor to urban methane generation but it is seldom mapped or integrated. Export of the wide variety of airborne chemical species is treated mainly as nonpollution, peripheral to the usual health concerns.

Currently available information could be synthesized to improve the situation. Moreover, the pace of accumulation could readily be increased by building interdisciplinary units into program design. As the right kinds of data are recovered or generated, biogeochemical interpretation must occur in order to characterize the role of future cities in the planetary system. This will require strong coupling among geoscientists, demographers, biologists and others. It will be desirable to develop predictive capabilities. One might like to state, for example, that certain megacities will evolve toward high food and waste throughput and reliance on natural gas, while lagging in the development of infrastructure such as paved feeder roads. It would then be possible to estimate simultaneously the growth of landfill carbon storage, methane leakage from the gas distribution system and mobilization of iron via local soil dust suspension (followed by photochemical reduction within hydrometeors).

We feel that the anecdotal evidence is quite strong for an undersaturated niche in urban geosystemics. Our recent review article details both the data and lack thereof upon which we base our position (Decker et al., 2000). If we are correct, it is useful to ask why such gaps in the knowledge base have developed. Part of the explanation is, of course, inertia. But it may also be a case of trees obscuring the forest. Most of our best earth system scientists live, work and spend their entire lives within the megacities. They are the ecosystem. Also, we must acknowledge the level of difficulty which will be encountered as the community attempts to understand the global city as a geochemical and biological entity. Other ecosystems remain under-explored even after many decades of concentrated research effort. New species are discovered in the tropics only as the rainforest falls around them (Sala et al., 2000). Major photosynthesizers of the central ocean gyres have only been known for a few years (Karl, 1999). Here the proximity of the urban system will prove an advantage. For the moment it may be hard for us to see our cities as deserving of scientific attention, but at least they are close to us.

What can or should be done? Some of the steps to be taken are inexpensive and will yield substantial dividends. Huge preexisting data bases can be mined, organized, and interpreted. Our recent review effort indicates that the volume of information is tremendous in each of the fields urban air and water quality, energy technology, waste management, economics and demographics. Biogeochemical studies are sparse, but that is one of our points here; overlap can be exploited to construct interdisciplinary products. Many large cities are closely scrutinized from within. The central problem has been that the information remains internal. Once it has been pooled, standard statistical analyses should permit multivariate relationships to be identified. It should be possible to quantify interactions between fuel, food, material and biological throughput along with the flux and distribution of chemical species. A current model for implementation is offered by the US National Center for Ecological Analysis and Synthesis (NCEAS, 2000). Principal investigators are funded to attend workshops regarding project design. Graduate students and post-doctoral researchers stay for extended periods to collect and manipulate data. The center has been operating only a few years but has produced an extraordinary amount of high quality scientific literature.

New measurement and study approaches are at hand which can also lead to fast progress. Small research groups are adopting the strategy of bouncing from city to city to perform cross comparisons. Two concrete examples are instructive. A team from the University of Denver couples ten-meter scale remote sensing of auto exhaust composition with license plate photography (Zhang et al., 1995). Their studies show that vehicle maintenance is a primary determinant of carbon monoxide emissions. Links can no doubt be made with income levels and other socioeconomic variables. Several of us have participated in a concerted effort to sample volatile hydrocarbon distributions in multiple, large urban areas. We have quantified methane emissions to the free troposphere, leakages of the light alkanes from liquefied petroleum gas networks and the generation of methyl bromide by automobiles (Blake et al., 1984; Blake and Rowland, 1995; Elliott et al., 1997b; Chen et al., 1999). While we are readily able to examine gas-phase-concentration differences among cities, correlations with other variables are yet to be sought. The vehicle exhaust and hydrocarbon studies are already underway because they are small in scope and so are affordable. Eventually we envision that entire geochemical research teams will move from city to city. Again recent analogs are of interest. The NASA Pacific Exploratory Mission series (PEM) has conducted complete atmospheric chemistry studies roughly every three years for the past decade, with each experiment focusing upon a different ecosystem scale section of the Pacific troposphere (e.g. Hoell et al., 1997). Although the research is mostly intradisciplinary, the PEM scientists have been among the most productive in their field.

Having described a set of near-term concepts for earth system level study of the global city, we will conclude with some speculation regarding the future of the discipline, based on results of our recent review (Decker et al., 2000). On a decadal time scale, we anticipate the design and construction of high-resolution, time-dependent models of material and energy flow through urban areas. These models will be based on results of past research and in particular on the accumulated, interlocking datasets that are available. The information base and simulations will enable the definition of state variables for the comprehension of urban composition in the human, structural, and biogeochemical dimensions. The variables may also provide the foundation for a theory of city growth and even of urban evolution. Manipulative, settlement-scale experiments will be possible in order to test developing theories. The science generated could well feed back into city design.

All this will necessarily encompass the analogy with organism or ecosystem level metabolism, since substances utilized as sources of structure and energy will all be included. A more important biological analogy will be with ecosystem succession. Ecological entities tend to penetrate new or newly opened geographical spaces through a sequence of biomass accumulation (Odum, 1969). Typically, the process leads to a climax state of efficient material recycling and renewable energy harvests (Karl, 1999). The human city once functioned in this mode. In the Neolithic, townships were stable in size and flux for extended periods (White and Whitney, 1992). Today, the global distribution of cities is moving through a successional stage where ever more structural material builds up, far flung but depletable energy stores are sought, and impact on the planetary environment is expanding. It is possible that reliance on fossil fuels will persist until homogeneity is attained and much of the globe is in service to a single vast human community (Decker et al., 2000). Standard ecological systems then function mainly to provide human kind with food and recreation (Daily, 1997). It is possible that air quality problems will not be solved at the local and regional levels even as they are merging into the hemispheric scale. The planetary ecological climax will be reached only with conversion to a solar economy. An ultimate extrapolation of the prospects we broach here is that this state can be conceived and examined scientifically. An ultimate conclusion may be that the urban climax will take place at the earth system level.

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