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New directions: Air pollution challenges for developing megacities like Delhi

Most major cities around the world experience periods of elevated air pollution levels, which exceed international health-based air quality standards (Kumar et al., 2013). Although it is a global problem, some of the highest air pollution levels are found in rapidly expanding cities in India and China. The sources, emissions, transformations and broad effects of meteorology on air pollution are reasonably well accounted in air quality control strategies in many developed cities; however these key factors remain poorly constrained in the growing cities of countries with emerging economies. We focus here on Delhi, one of the largest global population centres, which faces particular air pollution challenges, now and in the future.

In 1970 there were eight megacities (population >10 millions) worldwide, which increased to 32 in 2015, with a total population of 620.4 million (City Population, 2015). Delhi and its National Capital Region (NCR; Fig. 1a) ranked fifth among these megacities, with a population of 25.8 million (SI Figure S1). There were 4.74 million road vehicles in Delhi in 2010 and that number is predicted to increase to 25.6 million by 2030 (Kumar et al., 2011). This increase has major consequences for energy consumption, and hence, emission of air pollutants. For example, total energy consumption from stationary and mobile sources in Delhi had grown by 57.16% from 2001 levels to 230,222 TJ in 2011 (Kennedy et al., 2015). There are no reliable sources available to give corresponding values for energy consumption in the NCR of Delhi. However, a comparable increase in energy consumption can be expected, given a population growth of about 25% in 18 NCR cities (i.e. 9, 7 and 2 in Haryana, Rajasthan and Uttar Pradesh states, respectively) in 2011 compared with ~21% in Delhi from the 2001 levels (Regional Plan, 2021). These surrounding states in NCR follow Central Pollution Control Board (CPCB) standards or evolve their own standards which should be stringent than the CPCB standards for *pollution control*, but use their own norms for *fuel quality* and *vehicle registration* that are usually lenient to those in Delhi.

There are many distinctive features in Delhi which impact on air pollution: (a) uncontrolled sources in its *surrounding perimeter* (where city regulations do not apply and those that apply are not followed stringently), (b) a number of unregulated and unaccounted sources *within the city*, and (c) unfavourable geographic location and regional meteorology, with windy and dusty conditions during summer that are (i) exacerbated by low relative humidity enhancing particle resuspension, (ii) by episodic dust transport events from surrounding areas (Guttikunda and Gurjar, 2012), (iii) input of ozone as regional background, and (iv) influence of long-range transport of precursor emissions from both the subcontinent and intercontinental sources (West et al., 2009). The deterioration of air quality is further exacerbated by the diurnal cycle of "trucks" which are allowed to pass through the city after about 10 pm (local time) when the height of the mixing layer is also relatively low, due to cold northern and north-easterly winds passing through the city (Guttikunda and Goel, 2013).

The geography of Delhi results in the advection of air into the city from the surrounding areas, which can sometimes be significantly more polluted than the city centre itself. As a land-locked megacity, there are limited avenues for the flushing of polluted air out of the city, or its replacement with air from relatively unpolluted marine regions, which means that atmospheric transport from all directions, is likely to add to inner-city pollution. Such features are common in many growing non-coastal megacities (e.g. Tehran, Cairo), where urban growth is increasingly heterogeneous, sometimes unplanned, and is generally at its greatest in the peripheral areas, given the already saturated development of housing and commercial space within the core of these cities. In contrast, those megacities which are located close to coastlines benefit from *sea breezes* that can exchange maritime and urban air on a diurnal cycle. Therefore, cities surrounded by a densely built environment (e.g. Delhi, Mexico City) are at a clear disadvantage in terms of air pollution, which is made worse if those regions have unregulated emission sources, and/or they are semi-isolated by topographical features (e.g. Santiago).

Air pollutants are typically classified as primary (directly emitted) or secondary (those formed in the atmosphere). While secondary air pollutants (such as ozone, volatile organic compounds and nitrogen dioxide) are major contributors to pollution in cities such as Delhi, effective mitigation of these pollutants requires scientific understanding of their precursors and formation processes. Recent measurements in Delhi during winter show that organic carbon and ions (e.g. nitrate and sulphate) contributed about 37 and 20% of the mean $PM_{2.5}$ mass concentrations, respectively (Pant et al., 2015). Much of the organic carbon and the inorganic components such as nitrate would be expected to be secondary in origin, although both the precise budget and precursor source identities require definitive confirmation. The purpose of this work, however, is to highlight the critical importance of unregulated and unaccounted *primary* sources of pollutants within and around the periphery of developing megacities. Here we focus on the unique air pollution features of land-locked megacities, such as Delhi, and present a discussion of the challenges associated with developing effective control strategies, and identify corresponding directions for future research requirements.

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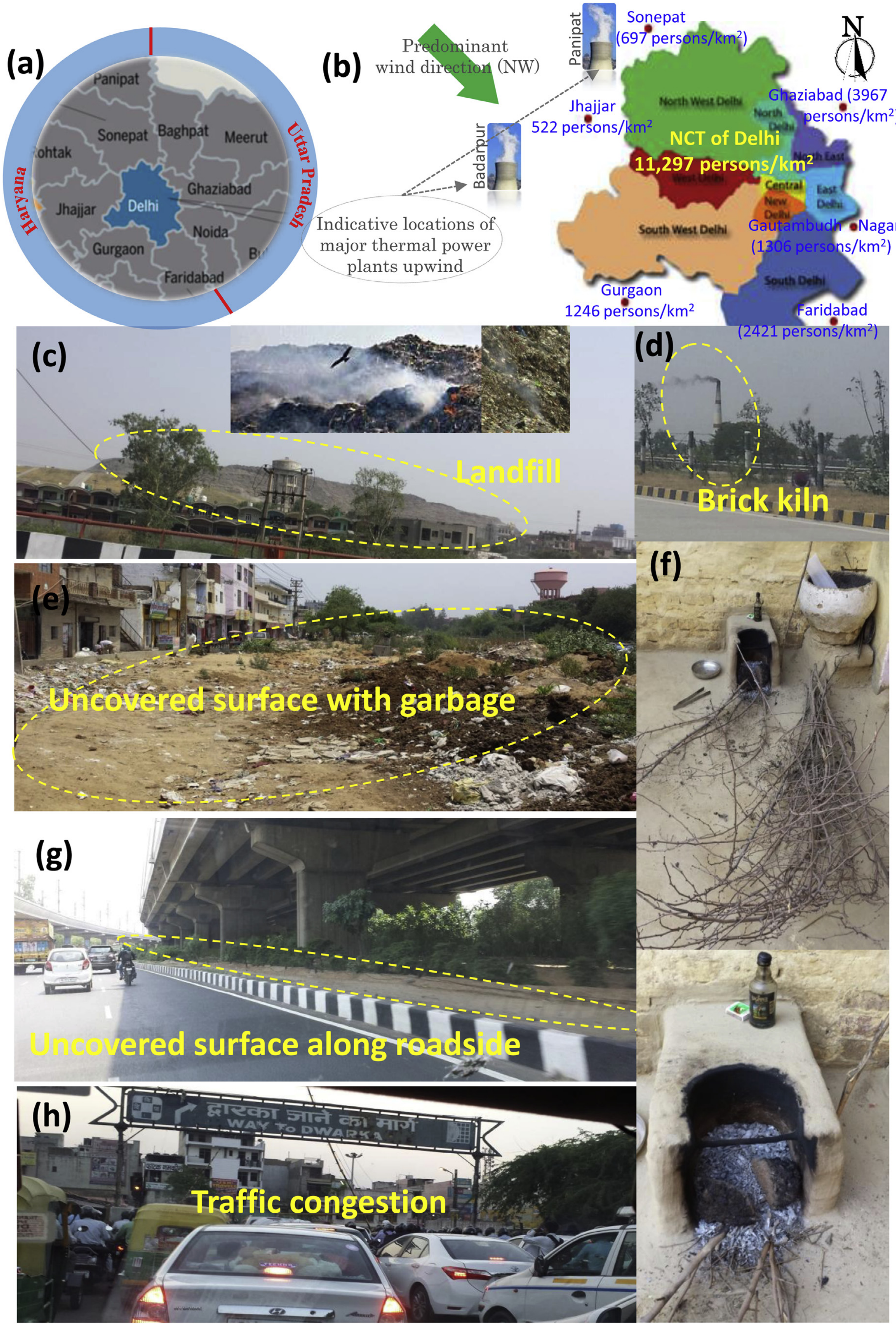

Fig. 1. Map of Delhi showing (a) surrounding states, (b) location of upwind power plants and population density in Delhi and its surrounding NCR cities in 2011 (Regional Plan, 2021) as well as the unregulated and unaccounted sources such as (c) landfill, (d) brick kiln, (e) loose soil and waste dumping, (f) biomass burning for cooking using chulhas, (g) dry uncovered surface along the roadside, and (h) traffic congestion.