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RESEARCH ARTICLE

Air quality improvement in Los Angeles—perspectives for developing cities

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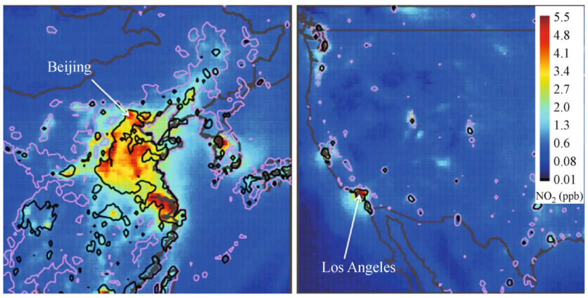
HIGHLIGHTS

- Air quality improvement in Los Angeles can inform air quality policies in developing cities.
- Emission control efforts, their results, costs and health benefits are briefly summarized.
- Today's developing cities face new challenges including regional pollution.
- Air quality issues in Beijing are briefly compared and contrasted with Los Angeles.
- Opportunities for co-benefits for climate and air quality improvement are identified.

GRAPHIC ABSTRACT



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ABSTRACT

Air quality improvement in Los Angeles, California is reviewed with an emphasis on aspects that may inform air quality policy formulation in developing cities. In the mid-twentieth century the air quality in Los Angeles was degraded to an extent comparable to the worst found in developing cities today; ozone exceeded 600 ppb and annual average particulate matter <10 μm reached ~150 $\mu g \cdot m^{-3}$. Today's air quality is much better due to very effective emission controls; e.g., modern automobiles emit about 1% of the hydrocarbons and carbon monoxide emitted by vehicles of 50 years ago. An overview is given of the emission control efforts in Los Angeles and their impact on ambient concentrations of primary and secondary pollutants; the costs and health benefits of these controls are briefly summarized. Today's developing cities have new challenges that are discussed: the effects of regional pollution transport are much greater in countries with very high population densities; often very large current populations must be supplied with goods and services even while economic development and air quality concerns are addressed; and many of currently developing cities are located in or close to the tropics where photochemical processing of pollution is expected to be more rapid than at higher latitudes. The air quality issues of Beijing are briefly compared and contrasted with those of Los Angeles, and the opportunities for co-benefits for climate and air quality improvement are pointed out.

1 Introduction

The current air quality in many developing cities of the world is quite poor. The World Health Organization estimates that ambient air pollution causes 3.7 million premature deaths per year globally, and that about 88% of these deaths occur in developing countries [1]. Importantly these premature deaths are not limited to the elderly, who might die soon regardless of the air pollution impact; the deaths occur throughout the population age spectrum, and are primarily attributable to ischemic heart disease (40%), stroke (40%), chronic obstructive pulmonary disease (11%), and lung cancer (6%). Along with harming human health, air pollution causes a range of negative environmental effects, including crop and forest damage, visibility and quality of life degradation, acid precipitation, eutrophication of water resources and global climate change. Air quality improvement in developing cities would bring many societal benefits.

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The air quality experienced in earlier decades in many of the earlier developing cities was once comparable or even worse than that affecting today's developing cities. Particularly well-known examples are air pollution episodes that killed or sickened thousands in Donora, Penn., in 1948 [2] and London in 1952 [3]. Today the air quality in earlier developing cities in Western Europe, United States and Japan has been much improved. However, this improvement does not imply that the effort to achieve clean air has been completely successful in these cities; we will note further required improvement. Our goal in this paper is to examine the history of air quality improvement in Los Angeles, with a particular focus on aspects of that history that may provide lessons for improving the air quality in today's developing cities.

The following three sections of this paper review the temporal evolution of the ambient concentrations of primary and secondary pollutant concentrations in the Los Angeles atmosphere, discuss the air pollution control policies that have led to the clear improvements that have been observed, and briefly summarize the economic costs and benefits, and the resulting health benefits. The last three sections focus on the lessons that Los Angeles may provide for currently developing cities, as well as identifying new aspects and challenges of air pollution in these developing cities.

2 Improvement of ambient air quality in Los Angeles

Since the middle of the twentieth century, ambient concentrations of ozone and its precursors have been measured in the Los Angeles Basin by a network of measurement sites operated as a joint effort of the South Coast Air Quality Management District (SCAQMD) and the California Air Resources Board. The resultant data set provides a basis to characterize the time evolution of near-surface pollutant concentrations within the South Coast Air Basin (SoCAB). Figure 1 shows the history of maximum 1-h and maximum 8-h average measured ozone concentrations over 5 decades, and the shorter 16-year record of $PM_{2.5}$ measurements. The ozone history should be interpreted with some caution, since measurement techniques and quality control procedures evolved over that period and the monitoring network changed as individual measurement sites were added or removed from the network. In addition the spatial distribution of ozone concentrations within the SoCAB has evolved as the absolute and relative magnitudes of ozone precursor emissions changed.

The remarkable success of ozone control efforts is clear from Fig. 1. In the 1960s 1-h averages exceeded 600 ppb and 8-h averages approached 400 ppb. Since 1998, neither of these metrics has exceeded 200 ppb. The frequency of high pollution episodes has also decreased markedly. For example, there were over 100 stage "1" ozone episodes (1-h average ozone ⩾ 200 ppb) in the Los Angeles Basin each year during the 1970s, and none was observed in the last decade [4]. The number of days above the 2008 national ambient 8-h ozone standard of 75 ppb decreased from above 200 days in the 1970s to 92 days in 2014 [5]. Despite this progress, Los Angeles ozone concentrations still exceed the US and California air quality standards by a significant margin. The national design value (i.e., the metric upon which the National Ambient Air Quality Standard (NAAQS) is based) for the monitoring stations in the SoCAB was 102 ppb in 2014, while the new ozone NAAQS requires it be reduced to 70 ppb. Significant additional emission control efforts remain to be accomplished to meet this requirement.

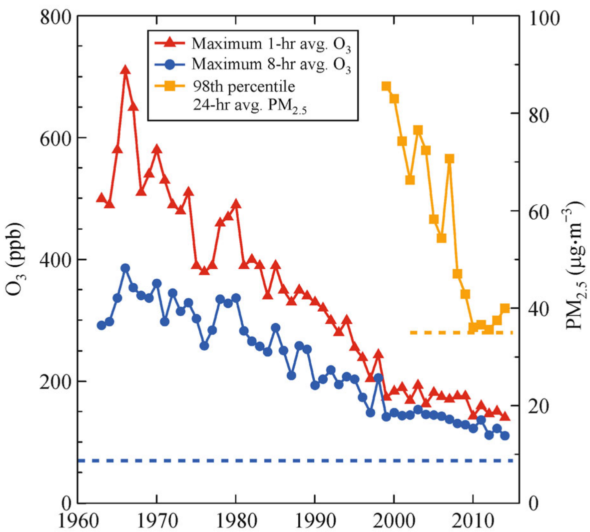

Fig. 1 History of measured ambient ozone and $PM_{2.5}$ concentrations in the SoCAB. The statistics shown (annual maximum 1-h and 8-h average ozone concentrations and 98th percentile of 24-h average $PM_{2.5}$ concentrations) provide the basis of the NAAQS. The dashed lines show the recently announced NAAQS for ozone (blue line at 70 ppb) and the current NAAQS for $PM_{2.5}$ (orange line at 35 $\mu g \cdot m^{-3}$).

One challenge facing policy makers is that not all of the ozone within the SoCAB is subject to local control; a significant fraction is transported into the region from the Pacific Ocean [6]. This "baseline" contribution to ambient ozone levels greatly reduces the margin for locally produced ozone pollution before the NAAQS is exceeded. Quantifying the magnitude of the baseline contributions is difficult. Figure 2 illustrates an approach for approximate determination through analysis of the time evolution of ambient ozone concentrations in the basin for the past 36 years (1980–2015). Consistent measurement procedures have been maintained over this period, although the number and location of measurement sites have changed.

These changes are not expected to have a large influence on this analysis.

Two issues can be addressed through the time evolution shown in Fig. 2 (this figure and much of the material in the following paragraphs is adapted from [7]). First, the period since 1980 has been one of effective implementation of ozone precursor emission controls. The decrease in ambient ozone concentrations reflects the decrease of these emissions over the period, and their effectiveness can be quantified from the measurement record. Second, the magnitude of the baseline ozone concentrations transported into the Los Angeles area from the Pacific Ocean can be quantitatively estimated from the asymptote approached by the observed concentrations. To focus on the highest summertime ozone concentrations, the maximum daily 8-h average ozone concentrations observed at any site in the basin on each day during the five-month ozone season (May through September) are selected. This selection gives 153 values (one for each day) in each year. The maximum, 90th percentile, median and 25th percentile of these 153 values are calculated for each year. The curves in Fig. 2 illustrate a conceptual model for the temporal evolution of each of these percentiles. These curves have a common functional form given by the three-parameter Eq. (1):

$$O_3 = y_0 + A \exp\{-(\text{year} - 1980/\tau), \quad (1)$$

First, y_0 is the asymptotic concentration toward which the data are approaching; it is interpreted as the ozone concentration that would be present if the basin's anthropogenic emissions were reduced to zero. Thus, y_0 is an estimate for the baseline contribution to ozone. Second, in the year 1980 ozone was elevated above y_0 by an amount equal to A; thus A represents the contribution of local and regional ozone production in 1980. Third, it is assumed that the effect of emission controls has been to exponentially reduce this local and regional ozone production with an e-folding time of τ years. The curves in Fig. 2 are least-square regression fits of Eq. (1) to the respective O_3 percentile as a function of year. Statistical uncertainties resulting from interannual variability or other "noise" about the curves prevent a precise simultaneous determination of all three parameters, so a somewhat more complicated process is used to derive best estimates of these parameters.

A best estimate for the value of τ of 22±4 years (95 percent confidence limits are indicated here and elsewhere) is first obtained. Analyses similar to that shown in Fig. 2 have been performed for all of California's heavily populated coastal air basins: San Diego, South Central Coast and San Francisco Bay in addition to the South Coast. The values of τ derived from fits to all four percentile data sets in each air basin are all consistent with this value of τ, which is a weighted average of the individual results. This e-folding time corresponds to a half-life of 15±3 years, which implies that, on average, every 15 years since 1980 emission controls have reduced anthropogenic ozone enhancements in California's heavily populated coastal air basins by half. This corresponds to a decrease in the anthropogenic enhancement of ozone of 4.4±0.8% yr^{-1}, which is a somewhat faster rate of decrease than the 2.8±0.2% yr^{-1} previously derived for the SoCAB [8]. In the analysis presented here it is assumed that ozone will eventually approach the baseline value of y_0; in contrast the previous approach [8] in effect assumed that ambient ozone concentrations would eventually approach zero. This latter assumption is not physically realistic, since transport of baseline ozone makes an important

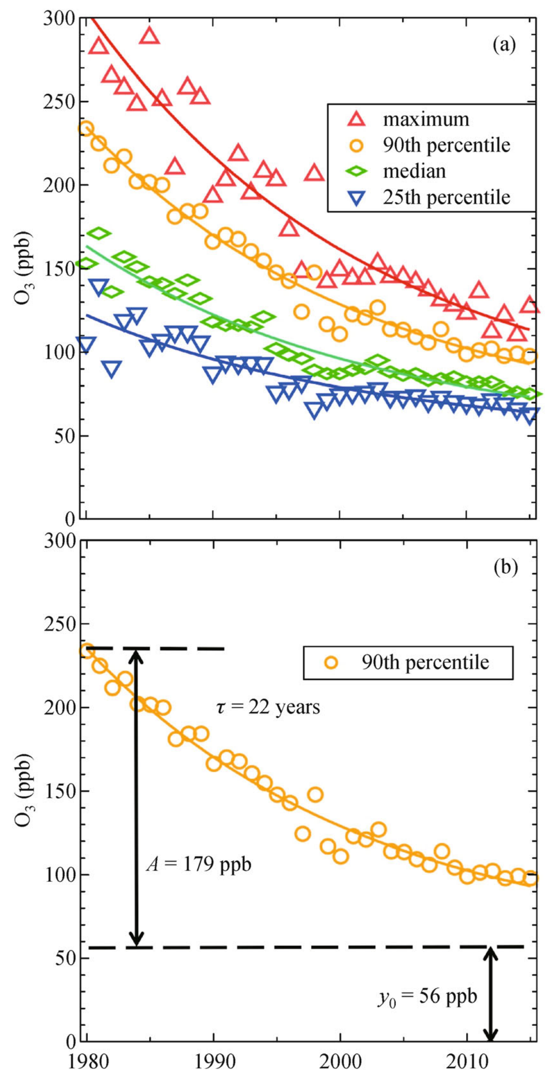

Fig. 2 Evolution of ozone concentrations over the past 35 years in the SoCAB. The data points give the indicated percentiles of the maximum daily 8-h average ozone recorded at any monitor within the basin on each day of the May–September ozone season. The curves are least-squares fits of Eq. (1) to the respective data. (b) Graphic interpretation of the parameters of Eq. (1) for the 90th percentile data. Figure adapted from [7].

contribution to ambient ozone concentrations. Notably, this 4.4% yr^{-1} rate of decrease has been sustained for the 36-year period shown in Fig. 2, resulting in anthropogenic ozone enhancements declining by a factor of nearly 5.

Least-squares regression fits with τ set to the best estimate value of 22 years allow the other two parameters in Eq. (1) (y_0 and A) to be precisely determined. Figure 2b illustrates the derived values for the 90th percentile data- A = 179±10 ppb and y_0 = 56±6 ppb. This derived value for y_0 is consistent with the upper end of the near-surface baseline ozone concentrations transported into California [9]. Figure 2b focuses on the 90th percentile data because these are the lower limits for the highest 10% of the daily maximum 8-h ozone averages recorded each year in the SoCAB, and are thus relevant for comparison with the NAAQS, which is based on the 3-yr running average of the fourth highest daily maximum 8-h ozone concentration average. It is noteworthy that in 1980 the anthropogenic ozone enhancement of 179 ppb was more than three times the baseline contribution, while in 2015 the remaining anthropogenic enhancement of ~37 ppb is only ~67% of the baseline contribution. Thus at present, baseline transport on average contributes more than half of the ozone in the SoCAB, even during most days with the largest observed ozone concentrations. These comparisons illustrate both the great success of past air quality improvement efforts, and the difficulty of achieving large future decreases in ambient ozone concentrations.

Each of the least-square regression fits of Eq. (1) to the percentiles illustrated in Fig. 2a provides a value of y_0 and A for that percentile. The set of y_0 values then defines the distribution of baseline ozone concentrations transported into the SoCAB, and the set of A values defines the distribution of ozone concentration enhancements in 1980. The curves in Fig. 2a derived from Eq. (1) then allow the calculation of the distribution of ozone concentration enhancements in any desired year.

The extensive routine atmospheric monitoring network plus focused special field studies in the Los Angeles Basin provide the basis to document the temporal evolution of the ambient concentrations of the primary pollutants that are the precursors for photochemical formation of O_3 and secondary $PM_{2.5}$. An analysis for the trends in VOC and CO concentrations over five decades in the Los Angeles Basin (Fig. 3) found a 7.5% yr^{-1} rate of decrease corresponding to a factor of 50 reduction in these concentrations during the 5 decades since 1960 [10]. Sales of motor vehicle fuel, the primary source of these species, increased by a factor of about 3 during this period [10]. These results indicate that per km traveled, modern US vehicles emit less than 1% of VOCs and CO compared to 1960 vehicles. A significantly slower rate of decrease has been found for NO_x compared to VOCs and CO [8] (Fig. 4; 2.6±0.3% yr^{-1}, or a factor of about 4 over the 5 decades), consistent with the greater initial focus of California's emissions controls on VOCs. (Note that in the semi-log plots of Figs. 3–5, the rate of decrease is quantified by the slopes of the linear fits to the log-transformed data; the intercepts reflect the relative magnitudes, so the normalizations utilized in Figs. 4 and 5 simply move the curves vertically without affecting their slopes.)

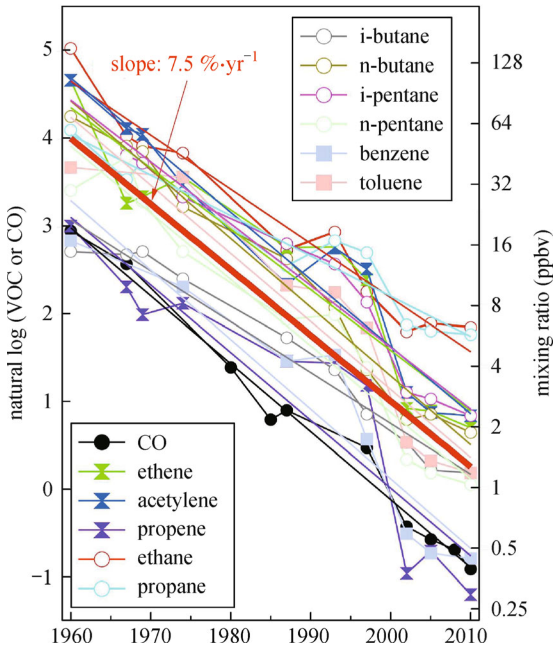

Fig. 3 Typical mixing ratios estimated from published data from various field campaigns conducted near downtown Los Angeles together with linear fits to the logarithm of the data (left axis). The solid red line indicates a 7.5% yr^{-1} decrease. Figure reproduced from [10].

The response of ozone concentrations has followed neither the VOC nor the NO_x temporal trends. Figure 4 shows that the anthropogenic enhancement of O_3 from Fig. 1 has decreased at a rate (4.4±0.8% yr^{-1}) intermediate between those of the VOCs and NO_x. In contrast, peroxyacetyl nitrate (PAN), the species identified as responsible for severe eye irritation in Los Angeles in previous decades, has decreased more rapidly (9.3±2.6% yr^{-1} or a factor of about 130 over the 5 decades) than either precursor. Since PAN has both VOC and NO_x precursors, its concentration may be expected to decrease at a faster rate than either precursor. Importantly, the ratio of VOC to NO_x emissions is often taken to be an indicator for the photochemical environment of a polluted atmosphere. The differing temporal trends of VOCs and NO_x emissions imply that this indicator ratio has decreased by a factor of ~12 within the Los Angeles Basin over the 5 decades considered. An extant challenge for the photochemical modeling community is to accurately reproduce all major aspects of this 50-year period of Los Angeles progress in reducing ambient concentrations of primary and secondary pollutants. This challenge has not been accomplished in

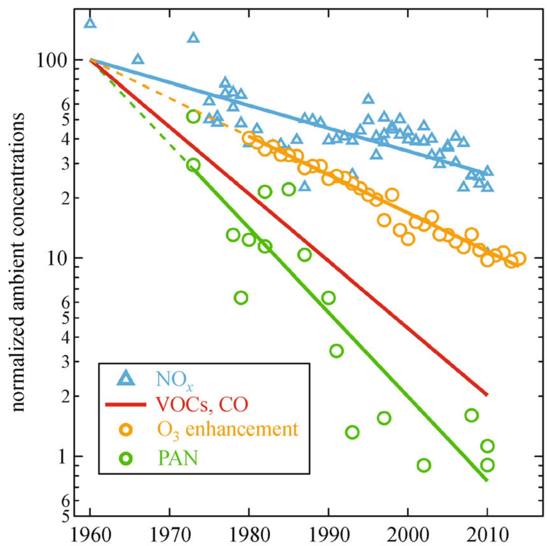

Fig. 4 Long-term trends of ambient concentrations of primary (NO_x, VOCs and CO) and secondary (O_3 and PAN) pollutants in the SoCAB. The respective lines are linear least-squares fits to log-transformed data; these lines therefore define exponential decreases of the concentrations. The data are normalized so that the linear fits intersect 100 in the year 1960. Ozone data are the anthropogenic enhancements of the 90th percentile from Fig. 2. Other data are average concentrations for summertime weekdays. For clarity, only the solid red line from Fig. 3 is shown for the VOC and CO data. Analyses and data for PAN and NO_x are from [8].

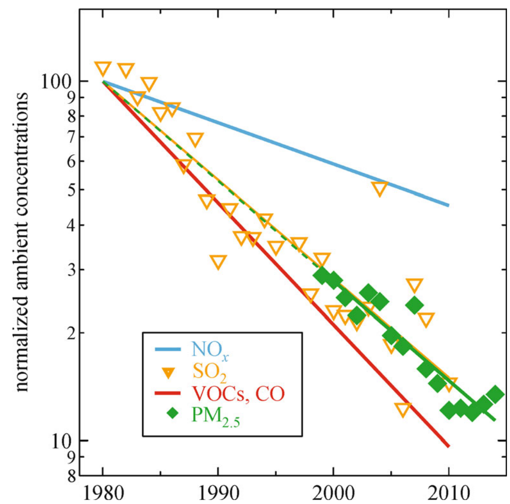

Fig. 5 Long-term trends of ambient concentrations of primary pollutants (SO_2, VOCs and NO_x) and $PM_{2.5}$ in the SoCAB in the same format as Fig. 4. Here the data are normalized so that the linear fits intersect 100 in the year 1980. The $PM_{2.5}$ data are those from Fig. 1. The SO_2 data are annual average concentrations from the North Long Beach monitoring station, where the largest SO_2 concentrations in the SoCAB are measured. The trend derived for this one station ($6.1\pm1.2\%\ yr^{-1}$) for 1980–2010 is consistent with the trend of the federal design value for the entire SoCAB ($6.2\pm0.5\%\ yr^{-1}$) for the entire 1963–2011 period.

detail, partially because of difficulties in reconstructing spatially and temporally resolved emissions inventories. Meeting this modeling challenge would demonstrate that our understanding of the controlling chemical and physical processes is complete and accurate, and thereby provide an important guide for air pollution abatement strategies in developing cities throughout globe.

The much shorter record of $PM_{2.5}$ concentration measurements in the SoCAB, which began in 1999, is included in Figs. 1 and 5. It is clear these concentrations have also decreased significantly; the relatively short measurement record beginning in 1999 indicates a decrease of $6.2\pm1.5\%\ yr^{-1}$. Since the measurement technique for $PM_{2.5}$ was implemented only recently, the concentrations of this species in previous decades are not well quantified, but extrapolation of the observed trend into the past indicates that concentrations were once much larger. Consistent with this indication are reports that 24-h-average PM_{10} concentrations exceeded 600 $\mu g\cdot m^{-3}$ [11] with annual averages near 150 $\mu g\cdot m^{-3}$ in the 1960s and 1970s [12]. PM_{10} includes larger particles than does $PM_{2.5}$, but $PM_{2.5}$ generally accounts for the majority of PM_{10}, so it is clear that $PM_{2.5}$ concentrations, like those of ozone, were once much higher than measured since 1999.

A large fraction of $PM_{2.5}$ is believed to arise from secondary formation in the atmosphere [13]. Figure 5 compares the $PM_{2.5}$ trend with the trends of three species believed to be important PM precursors: VOCs, SO_2 and NO_x. The $PM_{2.5}$ decrease ($6.2\pm1.5\%\ yr^{-1}$) is in close agreement with the observed decreases in VOCs (7.5% yr^{-1}) and SO_2 ($6.1\pm1.2\%\ yr^{-1}$), but smaller than the observed NO_x (trend = $2.6\pm0.3\%\ yr^{-1}$). A critical species for the formation of particulate matter is ammonia, whose emission trends in the Los Angeles basin have not been measured. Hence, the trends shown in Fig. 5 cannot be simply interpreted.

When viewed from the perspective of five decades, air quality improvement in Los Angeles has been quite dramatic, but this improvement has required enormous efforts. Concerted and continuous efforts have been sustained over that extended period. The following two sections will give an overview of the policies that supported those efforts and discuss their costs and benefits.

3 History of air pollution control in Los Angeles

As early as the 1900s, Los Angeles already suffered from smog and the City Council initiated several measures to combat dense smoke emissions. As the city's population, industry, and motor vehicle fleet grew, visibility declined rapidly and the first recognized episodes of smog occurred in Los Angeles in the summer of 1943. These episodes caused severe health impacts such as smarting eyes, respiratory discomfort, nausea, and vomiting [14]. In

October 1943, the Los Angeles County Board of Supervisors appointed a Smoke and Fumes Commission to study the problem, and as a result supervisors banned emissions of dense smoke and established an office of Director of Air Pollution Control in February 1945 [14]. In August 1945, a series of articles by county Health Officer Dr. H.O. Swartout suggested that smog came from many sources including smoke-belching locomotives and diesel trucks, rubbish burning in back yard incinerators and city dumps, and combustion of scrap lumber in sawmills. In addition to emissions, it was recognized that stagnation resulting from the region's mountain ranges, relatively light winds, and atmospheric temperature inversions was also a major contributor to the air pollution episodes in the Los Angeles area [14]. To deal with the air pollution problems, the City of Los Angeles established the Bureau of Smoke Control in its health department in 1945. Later, more detailed analysis by Raymond R. Tucker suggested that smog in the Los Angeles air basin was caused by multiple sources from multiple cities and that separate local efforts were ineffective against such a regional air pollution problem. Therefore, a powerful countywide air pollution agency with broad powers to adopt and enforce air pollution regulations was believed necessary. On October 14, 1947, the Los Angeles County Board of Supervisors established the Los Angeles County Air Pollution Control District. During the following decade, county supervisors activated air pollution control districts in Orange, Riverside and San Bernardino counties, and in 1976 the four county agencies were combined to form the South Coast Air Quality Management District (SCAQMD).

On a state level, in 1967, California's Legislature passed the Mulford-Carrell Act, which combined two statewide Department of Health bureaus — the Bureau of Air Sanitation and the Motor Vehicle Pollution Control Board — to establish the California Air Resources Board (CARB). Since its formation, the CARB has worked with the public, the business sector and local governments to improve California's air quality. The resulting state air quality standards set by the CARB continue to outpace the rest of the nation and have prompted the development of new antismog technology for industrial facilities and motor vehicles. CARB's mission is to promote and protect public health, welfare and ecological resources through the effective and efficient reduction of air pollutants, while recognizing and considering the effects on the state's economy.

The basis for all CARB programs is research into the causes of air pollution and their effects on public health and the environment. To understand the sources and causes of air pollution in the Los Angeles area, a network of air quality monitoring sites was established and operated by CARB and SCAQMD. Currently, the network includes 39 permanent monitoring stations and 4 single-pollutant source impact Lead (Pb) air monitoring sites. The monitoring sites were established based on comprehensive analyses of the air pollution emissions, meteorology, and topography of the area to serve several particular purposes. 1) “Background Level” monitoring is used to determine general background levels of air pollutants as they enter the SoCAB. 2) “High Concentration” monitoring is conducted at sites to determine the highest concentrations of the air pollutants in areas within the monitoring network; the network has multiple high concentration sites to account for varying meteorology year to year and longer term evolution of the spatial distribution of air pollution. 3) “Pollutant Transport” monitoring is used to assess the movement of pollutants between air basins or areas within an air basin. Mitigation of emissions in upwind areas is necessary when transported pollutants affect neighboring downwind areas. Also, pollutant transport monitoring is used to determine the extent of regional pollutant transport among populated areas and to rural areas. 4) “Population Exposure” monitoring is conducted to quantify the air pollutant concentrations to which a populated area is exposed. 5) “Representative Concentration” monitoring is conducted to represent the air quality concentrations for a pollutant expected to be similar throughout a geographical area. These sites do not necessarily identify the highest concentrations in the area for a particular pollutant. 6) “Source Impact” monitoring is used to determine the impact of significant sources or source categories of air quality emissions on ambient air quality. The air pollutant sources may be stationary or mobile. 7) “Trend Analysis” monitoring is useful for comparing and analyzing air pollution concentrations over time. Trend analyses are useful to document the progress in improving air quality for an area over a period of years. 8) “Site Comparison” monitoring is used to assess the effect on measured pollutant levels of moving a monitoring location a short distance (usually less than two miles). Some monitoring stations become no longer usable due to development, change of lease terms, or eviction. In these cases, concurrent monitoring at the old and new site for a period of at least one year is attempted in order to compare pollutant concentrations. 9) “Real Time Reporting/Modeling” is used to provide data to EPA’s AIRNOW system, which reports conditions for air pollutants on a real time basis to the general public. These data are also used to provide accurate and timely air quality forecast guidance to residents of the SoCAB.

CARB is responsible for conducting rulemaking to adopt and amend statewide regulations, and for monitoring the regulatory activity of California's 35 local air districts. CARB develops and adopts regulations through a process that allows for public input by encouraging the involvement of all stakeholders in the air quality regulatory process, and organizes Board hearings and workshops as public forums for all points of view during the rulemaking process. A wide array of emission control technologies and regulations have been developed through decades of scientific and engineering research. Efforts are focused on reducing emissions from all significantly contributing emission sources, including: 1) *Mobile sources*, such as commercial trucks and buses, passenger vehicles, motorcycles, diesel-powered off-road equipment, off-highway recreational vehicles, and off-road engines such as generators and lawn and garden equipment. The first two-way catalytic converters came into use in 1975, and the first three-way catalytic converter to control HC, NO_x, and CO emissions was introduced in 1976. In 2008, two critical regulations aimed at cleaning up harmful emissions from the estimated one million heavy-duty diesel trucks were adopted. One requires installation of diesel exhaust filters or engine replacement and the other requires installation of fuel-efficient tires and aerodynamic devices. 2) *Goods movement sources*, such as railroads, ocean-going vessels, commercial harbor craft, cargo handling equipment, drayage trucks, and transport refrigeration units. The adoption of the first-in-the-nation regulation requiring ocean-going vessels to use clean fuel when near the California coast in 2008 has been effective in reducing sulfur dioxide pollution from ships. Efforts have also been made to reduce emissions from ports by making shore power available to docked ships that previously idled their engines. More polluting drayage trucks are either removed from service or retrofitted. 3) *Gasoline, diesel and other fuels, and cargo tanks used to transport these products*. Over the years, various diesel and gasoline fuel standards were adopted including the most recent low-carbon fuel standard to reduce the carbon intensity of existing fuels, ultimately reducing the state's reliance on petroleum. 4) *Area sources* that individually emit small quantities of pollutants, but collectively are significant, including chemically formulated consumer products, aerosol coating products, and composite wood products. Standards that reduce VOCs, toxic air contaminants, and high global-warming potential compounds have been established for over 100 categories of consumer products. Consumer products regulations have resulted in estimated emissions reductions of nearly 50 percent since 1990. 5) *Industrial sources*, including power plants, refineries, manufacturing facilities, and smaller but more numerous stationary sources such as gasoline service stations, dry cleaners, and small industrial operations. Best Available Control Technology requirements have been established for these major point sources.

While the sources are numerous and diverse, common to every regulation is the basic principle that air quality goals cannot be attained unless compliance is achieved. Violations of California's air quality laws and regulations span a wide spectrum that extends from nominal breaches of the state's statutes or regulations to deliberate, criminal actions [15]. To address these varying degrees of violation and their effects on the state's health and economic welfare, the mission statement adopted by the Enforcement Division of CARB is to protect the environment and public health and to provide safe, clean air for all Californians by reducing emissions of air contaminants through the fair, consistent and comprehensive enforcement of air pollution laws, and by providing training and compliance assistance. The CARB programs are also implemented through active outreach to regulators and regulated industries through training and compliance assistance. Following is a summary of particularly important enforcement efforts: 1) Illegal engines and aftermarket parts are areas of particular concern with cars and trucks, because of the potential for exceeding emissions standards. Diesel emissions are of particular concern because they negatively affect public health through direct emissions of diesel particulate matter, a recognized toxic air contaminant, as well as emissions of ozone and $PM_{2.5}$ precursors. 2) Fuels enforcement involves inspections throughout the distribution chain, but the focus is "upstream" at import vessels and refineries in order to minimize the chance of illegal fuel reaching retail service stations. 3) Area source enforcement focuses on limiting public exposure to toxic compounds as well as preventing excess emissions of volatile organic compounds that contribute to smog formation. 4) Stationary sources are primarily the purview of local air districts. However, CARB has authority to enforce greenhouse gas regulations at facilities.

4 Economic cost and benefits, and health benefits

Over the past three decades ambient concentrations of key pollutants in the SoCAB region have decreased substantially despite a doubling of the population and tripling of vehicle use. Ozone concentrations apparently peaked in the late 1960s, and have declined impressively since then (Fig. 1). Although it still violates the NAAQS for ozone and $PM_{2.5}$, the Los Angeles basin is in compliance with the NAAQS for nitrogen dioxide and carbon monoxide, as well as sulfur dioxide and lead. It is fair to say that this megacity has gone from being one of the most polluted in the world 50 years ago to presently one of the "least polluted" cities of its size. Improvements in air quality are estimated to have saved many thousands of lives in the Los Angeles area [16,17].

From an economic perspective, it is useful to ask if the health, economic, aesthetic and other benefits justify the large costs required to effect this air quality improvement. The US Environmental Protection Agency (EPA) conducted a series of studies to answer the question: "How do the overall health, welfare, ecological, and economic benefits of Clean Air Act (CAA) programs compare to the costs of these programs"? (http://www.epa.gov/cleanairactbenefits/). The first report released in 1997 presented a retrospective analysis of costs and benefits for the period 1970 to 1990, and the following reports provided a prospective analysis for the 1990 to 2020 period. These reports underwent extensive review by panels of outside experts and by the Departments of Labor and Commerce. The EPA found that improving air quality has been costly: direct expenditures from 1970 to 1990 were estimated at \$0.52 trillion (inflation adjusted to 1990) while the central estimate of total monetized benefits of the CAA from 1970 to 1990 was \$22 trillion. Thus, the air quality improvement that resulted from the CAA from 1970 to 1990 was very cost effective with benefits exceeding costs by a ratio of approximately 42 to 1 (best estimate). The following reports found continuing large benefit to cost ratios. Additionally, as noted in the first report, "... there are social and personal values furthered by the Clean Air Act, which have not been effectively captured by the dollar-based measures ...." used in the studies. These reports can assure developing cities that investments in air quality improvement are rewarded by improved health and general well being of the urban populations. (Much of the material in this section was taken from [18]).

5 Unique problems and advantages of currently developing cities

The population growth, economic and industrial development, and rising standard of living in the large developing cities of the world will bring new problems, but these cities will also have some advantages over earlier developing cities. There are manifold challenges that accompany urban growth associated with providing food, shelter, transportation and other goods and services for an ever-increasing population. These challenges bring obvious problems that affect the health and welfare of the urban population as well as the societal and ecological environment in areas within and well beyond the urban center. At the same time, large cities are often looked upon as the economic engines of the world. As such, they also represent a concentration of resources that provide opportunities to address these challenges more efficiently than possible if the same population were dispersed in smaller cities and rural environments. Developing cities can also benefit from the knowledge accumulated as earlier developing cities dealt with air quality concerns. This section highlights some of the issues that have been identified regarding the challenges and opportunities that accompany the emergence and evolution of large urban areas.

5.1 Importance of regional pollution transport to urban pollutant concentrations

Presently, many large cities, particularly in Asia, are developing in areas that are densely populated throughout large regions (e.g., the East China plains and the Indo-Gangetic Plain), and often multiple large cities are in relatively close proximity to each other. Such cities must deal with an important new dimension to their air quality concerns – a significant, even dominant, fraction of some pollutants may be transported into the city from the surrounding region, rather than emitted or produced locally. Figure 6 compares the population density and annual average afternoon surface NO_2 mixing ratios in eastern China and western North America. Beijing is embedded within a region of high population density that extends for hundreds of km throughout eastern China, with NO_2 concentrations clearly elevated, particularly in the region around Beijing, extending south to Shanghai. Compared to Beijing, Los Angeles in western North America appears as an isolated spot in both population density and NO_2 concentration. Under the prevailing winds, Los Angeles receives clean air flowing in from the North Pacific Ocean, and seldom receives air with large concentrations of pollutants emitted elsewhere. In contrast, under winds from the south-west, which are common during the photochemically active season, Beijing receives

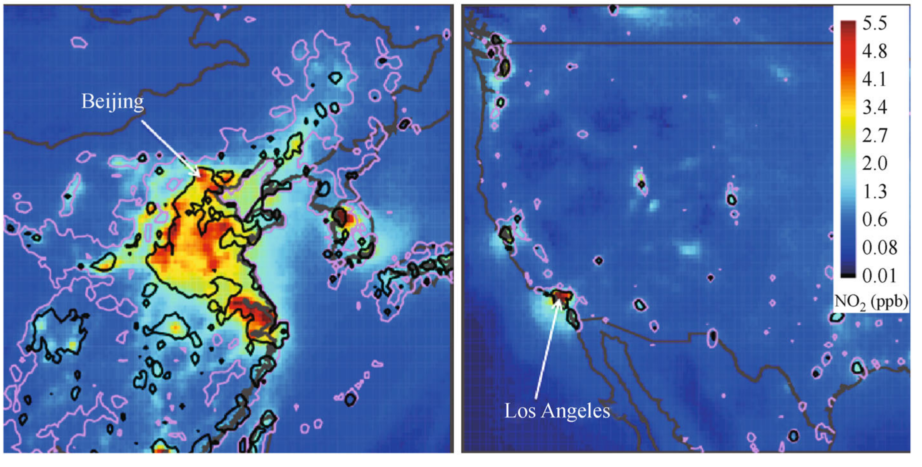

Fig. 6 Annual average afternoon surface NO_2 mixing ratios for the year 2005 binned at 0.25° × 0.25° from OMI over eastern China and western North America. Panels are on the same latitude scale. Contours represent population density data gridded at 0.25° × 0.25° resolution with 100 persons·km^{-2} (pink) and 500 persons·km^{-2} (black). Figure adapted from [19].

air that has passed over regions with very large cities and inhabited by more than 500 million people. Under these conditions, the air flowing into Beijing already contains very high concentrations of both primary and secondary pollutants.

A single urban area in a large, densely populated region cannot effectively address its air quality issues in isolation; a region-wide control strategy is required. In the 1980s the Ozone Transport Assessment Group (OTAG) [20] studied this issue in the eastern part of the US In that part of the country regional transport is significant, but it is dwarfed by the significance of regional transport in Asia. China must grapple with this daunting regional transport problem, which will become increasingly important as the country continues to develop. In effect, the entirety of eastern China is a single air basin; i.e., it can be considered to be one super megacity. This issue may be even more important in the Indo-Gangetic Plain, which encompasses much of northern and eastern India, the most populous parts of Pakistan, parts of Nepal, and most of Bangladesh with a total population of approximately 800 million people.

The atmospheric processing of primary pollutants in regions of strong regional transport, such as that surrounding Beijing, may have important distinguishing characteristics. Most of our current understanding of urban atmospheric chemistry has been informed by field measurements made in regions with relatively isolated cities. There may be important differences in atmospheric processing of fresh primary pollutants emitted into air masses with high loadings of emissions that have already been photochemically processed. The resulting large concentrations of secondary species can influence the processing of the fresh emissions in important respects. Field studies conducted in such regions may yield insights into important new features of atmospheric processing.

5.2 Economic development in cities with large current populations

In 1950 when the Los Angeles urban area first began to improve its degraded air quality, its population was approximately 4 million. During the period of air quality improvement the city grew to today's population near 13 million. To improve air quality during a period of substantial population growth is a challenge, but improving air quality in today's developing cities with populations already similar to or greater than that of present day Los Angeles is a greater challenge, since food, housing and other necessary goods and services must be continually provided to that large population. Meeting this challenge requires enormous expenditures of resources and energy, which increases pollutant emissions, and perhaps limits the resources available for air quality improvement.

Large urban population also brings more subtle challenges. Concentrating populations into relatively small urban areas implies that total health impacts increase even if the per capita pollutant emissions remain constant. Primary pollutant concentrations have been shown to grow as a power-law function of population [19]; that is, they increase as N^{b}, where N is the population size and the exponent β is between 0 and 1. Thus, the concentrations of pollutants such as NO_2 are greater over the more populated cities. Because each person is exposed to the pollutant concentration, the population integrated exposure increases roughly as N^{1+b}. To directly quantify the health effects implied by this exposure requires inclusion of the dose/response relationship of each air pollutant, but these considerations do suggest that increasing population exposed to increasing pollutant levels yields health impacts that increase rapidly with population, significantly more rapidly than directly proportional to the population. Thus, health problems related to air pollution very rapidly increase as cities grow [21], which provides strong incentives for air quality improvement.

Systems to transport people throughout urban areas are required, since people do not live, work, shop and recreate in a single location. Relatedly, systems are also needed to transport material goods throughout the urban area. Los Angeles is an example of a developed city that relies almost completely on a highway and street system to transport both people and goods and services, with only a limited public transportation system. Beijing also has an extensive highway system, but it chose to develop a much more extensive public transportation system. Beijing now has the second largest (based on system length) subway system in the world, with a total length of 554 km and a ridership of 3.4 billion passenger trips in 2014; in contrast the Los Angeles subway system has a total length of 28 km and ridership of 0.05 billion passenger trips in 2014. The people of Los Angeles primarily depend on private vehicles for transport. The design of transport systems in developing cities is a complex issue with large long-term consequences for air quality [22]; developing cities can call upon the experience of earlier developing cities in planning their public and freight transport systems. The design of a city's transport systems also has additional, subtler consequences for air quality. For example, restricting freight deliveries by heavy-duty diesel trucks to nighttime can reduce daytime highway traffic congestion. However, the atmospheric boundary layer is generally shallower and more stable during the night than the day, so shifting freight deliveries to the night may increase 24-h average ambient concentrations of diesel exhaust pollutants in many locations [23].

5.3 Developing cities are more often in tropical locations

Developing urban areas are predominately located at lower latitudes than earlier developing cities. In 2014 the United Nations [24] identified 28 megacities (i.e., urban agglomerations with populations greater than 10 million). Six of these cities are in "advanced countries" and the other 22 are in countries with "developing economies" as defined by the International Monetary Fund [25]. The former six are in Japan, Western Europe and the United States, all at northern mid-latitudes with average latitude of 41° N. The latter 22 are at an average absolute latitude of 26°, with ten in the tropics. Locations at lower latitudes experience more intense solar radiation and higher temperatures, which imply more rapid photochemistry, and a longer annual period of photochemical activity (e.g., [26]). Consequently, secondary pollutant concentrations resulting from a given amount of primary pollution are expected to be higher in developing compared to developed cities (other factors being equal) simply from the lower latitudes of the former.

5.4 Benefit from engineering developments

The scientific understanding and engineering advances that have been accrued in addressing air quality problems in developed cities are now available for immediate application in developing cities. This availability may make it possible for developing cities to more rapidly improve their air quality than was possible in earlier developing cities that had to develop the science and technology required for that improvement. Two important examples are emission controls for power plants and on-road vehicles, which have already been implemented in the Beijing region. Figure 7 shows the satellite record of the NO_2 column over north-east China, which is a good indicator of surface NO_2 concentrations. The rapid increase from the late 1990s through the decade of the 2000s has been widely discussed, and has been attributed to the rapid expansion of electrical generation plants and the on-road vehicle fleet. The NO_2 column apparently reached its maximum in 2011 and has since been decreasing so that in 2014 the NO_2 was about 25% below the maximum. Finer resolution satellite data [27] indicate that NO_2 concentrations in Beijing itself actually decreased by 10.3±13.1% over the 2005 to 2014 period, presumably due to emission controls implemented on motor vehicles, power plants and industry in that urban area. The temporal evolution of NO_2 concentrations in north-east China demonstrates the potential for air quality improvement through implementation of existing emission control technology.

6 Aspects of Los Angeles experience that can be applied to developing cities

6.1 Air pollution in developing cities – Beijing as an example

Beijing is a Chinese megacity with severe environmental problems. Beijing has a current population of about 22 million. The GDP growth rate was 7.3% in 2014 and comparable or more rapid growth rates had been maintained over the previous decade and longer. Similar economic growth has characterized the entire east China region. Environmental protection did not keep pace with this rapid economic development, resulting in serious air quality degradation in Beijing, as well as in all of east China. The Beijing area is associated with very high recent concentrations of both ozone and $PM_{2.5}$. Measured ambient ozone concentrations at a mountainous site 50 km north of Beijing in summer 2005 exceeded 120 ppb on 13 out of 39 days, with the maximum hourly average concentration reaching 286 ppb, the highest reported ozone concentration in China [28]. Hourly concentrations of $PM_{2.5}$ up to ~900 μg·m^{-3} have been reported [29]. These are remarkably high pollutant concentrations, but Los Angeles once had similarly poor air quality. Even the 286 ppb ozone concentration observed downwind of Beijing is much smaller than the highest concentrations shown for Los Angeles in Fig. 1. There is no indication that the $PM_{2.5}$

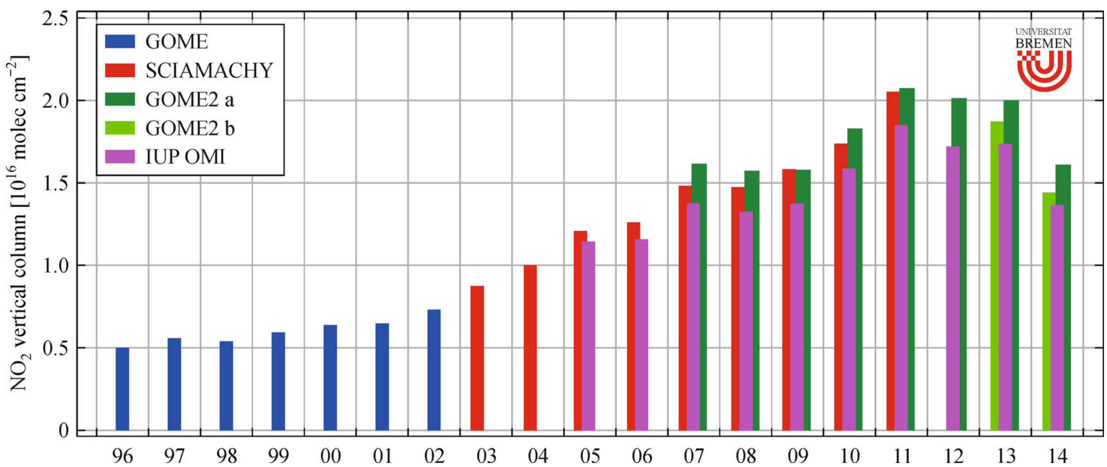

Fig. 7 Evolution of tropospheric NO_2 column over 19 years above central east China derived from several satellite measurements. Figure courtesy of A. Richter, A. Hilboll, and J. P. Burrows of University of Bremen.

concentrations ever approached 900 $\mu g \cdot m^{-3}$ in Los Angeles, but the reported annual average PM_{10} near 150 $\mu g\ m^{-3}$ [12] is similar to the highest (160 $\mu g \cdot m^{-3}$ from 2000 to 2004) reported for Beijing [30]. It is expected that Beijing can improve its air quality just as Los Angeles has done.

Efforts have already been designed and implemented to rapidly improve Beijing's air quality; this city now has some of the most stringent air pollution control programs in China. From 1998 to 2009, the Beijing municipal government has implemented 15 stages of air pollution control measures (http://govfile.beijing.gov.cn). The ambient $PM_{2.5}$ concentrations are required to drop by 25% by 2017 (2012 as the base year). The clean air measures include a wide range of actions; e.g., use of low sulfur coal and promotion of cleaner fuels, elimination of high emitters in the urban vehicle fleet, adoption of vehicle inspection/maintenance systems, upgrade of vehicular emission standards, prevention of fugitive dust from road and construction sites, and inspection of the operation of emission control devices.

These air pollution control measures in Beijing are succeeding in major respects. Inventoried SO_2 emissions have decreased substantially, from 2.24×10^5 tons in 2000 to below 0.9×10^5 tons in 2015. Annual average $PM_{2.5}$ concentrations in Beijing that ranged between 97 and 154 $\mu g \cdot m^{-3}$ before 2008, decreased to 81 $\mu g \cdot m^{-3}$ by 2015, and are expected to drop to ~60 $\mu g \cdot m^{-3}$ by the end of 2017. Based upon in situ measurements in Beijing, the emissions of NO_x and volatile organic compounds (VOC) decreased significantly between 2005 and 2011 [31]. Satellite measurements of NO_2 column [27] also find significant decreases directly over Beijing from 2005 to 2014; however, over most regions of north-east China, the NO_2 column increased over this period. This regional increase is consistent with the trend shown in Fig. 7, even considering the decrease in column NO_2 in the later years of that figure. Despite the observed decrease in VOC and NO_x emissions in Beijing, daytime average ozone concentrations increased at an annual rate of approximately 5% yr^{-1} over the 2005 and 2011 period, an increase attributed to the influence of transport of ozone and other secondary pollutants into Beijing from the surrounding region where NO_x and VOC emissions have continued to increase [31]. It is becoming increasingly clear that the major challenge for air quality improvement in Beijing is the control of secondary pollutants, i.e. ozone and secondary $PM_{2.5}$ over the entire east China region as emphasized in Section 5.1.

6.2 Lessons from Los Angeles for developing cities

While there are some significant differences in major pollution sources, meteorological conditions, and geographic settings between Los Angeles and Beijing, the principal relationships of air pollution emissions and ambient air quality and the impacts on human health and ecological system are similar. Extensive air pollution control knowledge in megacities has been gained through decades of efforts in Los Angeles, and is now available to developing cities; this can potentially speed their evolution toward improved air quality. Several key lessons learned in Los Angeles are: 1) It is important to control all pollution sources: open burning, industry, power generation, vehicle fleets, home heating, etc. 2) Controlling emissions from vehicle fleets is particularly important. 3) Unified policies over the entire airshed are vitally important. 4) Concerted action continued on at least a decadal time scale is required. 5) Consistent and effective enforcement of the air pollution control regulations and policies is critical.

6.3 Case study: Efforts to improve air quality for special events

During the 1984 summer Olympic Games in Los Angeles, the city adopted extensive measures to combat Southern California's smog. These measures aimed to reduce both vehicle and industrial emissions and resulted in significantly cleaner air during the Olympics. This experience provided strong evidence that improving air quality in the Los Angeles air basin was possible through aggressive control strategies. The clean air experienced during the Olympics pushed political leaders throughout California to further acknowledge that the serious air pollution problems were caused mainly by fossil fuel combustion and to recognize the efforts necessary to improve air quality.

Similarly, stringent air pollution control measures were implemented for the 2008 Beijing Olympic Games. China banned half the cars in the city and closed hundreds of polluting factories to avoid air pollution related medical problems during the Olympics. Mobile source NO_x and VOC emissions are estimated to have been reduced by about 50% [32] due to various emission control measures such as high-emitting vehicle restrictions, government vehicle use controls, and alternate day driving rules. Air quality in Beijing improved significantly during the Olympics as a result [33–35]. Based on measurements at Peking University in North-western Beijing, the mean $PM_{2.5}$ and PM_{10} concentrations were ~30% lower during the Olympic period compared to the non-Olympic period [33]. Observations at Miyun, a rural site 100 km downwind of the Beijing urban center, indicate that the mean daytime mixing ratio of O_3 was reduced by about 15 ppb in August 2008 [34]. During this period, temporary improvement was found in the heart function of healthy young people [36].

The Los Angeles and Beijing experiences during their respective Olympics Games demonstrated that aggressive emission control efforts could significantly improve air quality in major urban areas, although other factors such as meteorological conditions and regional pollution transport also have strong impact on the concentrations of air pollutants, especially secondary pollutants such as ozone and secondary particulate matter [37].

7 Concluding remarks

With increasing global population and extensive, ongoing urbanization, over half the world's population now resides in urban areas, and the number of urban residents is projected to nearly double, from 3.5 to 6.3 billion, by 2050 [38]. The number of megacities is expected to increase to 37 by 2025. Megacities are areas with the most intense human impact, including economic and social activities that require tremendous energy consumption. These activities concentrate emissions of air pollutants and greenhouse gases, which impact air quality and climate, as well as terrestrial and aquatic ecosystems.

The negative impact of megacities on local and regional air quality has long been recognized. This paper has reviewed the history of air quality improvement in Los Angeles with a particular emphasis on aspects of that history that may aid developing cities in improving their air quality. The experiences of developed countries show that the pronounced air quality degradation in urban areas is not inevitable. The scientific and engineering knowledge accumulated as developed megacities dealt with their air quality problems in earlier years is a significant resource for current and future megacities. Some issues that are unique to currently developing cities have also been identified. Urban areas embedded in a large region of high population density pose unique challenges to atmospheric modeling and monitoring and create a multi-disciplinary spectrum of issues, including air pollution, which need to be addressed in an integrated way.

The impact of anthropogenic emissions from megacities on regional and global climate is receiving increasing attention. This climate impact is linked to air quality through energy consumption derived from fossil fuel combustion with emissions that change the atmospheric concentrations not only CO_2, but also of short-lived species that impact both climate and human health, such as aerosols and ozone. Because of these linkages, it has been argued that megacities provide a critical opportunity to realize the co-benefits of simultaneously controlling air pollution and limiting climate change [21,39]. With the growing trend toward urbanization, understanding the role of urban areas in local to global atmospheric chemistry is critical to effectively realize these air quality and climate co-benefits.

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Speciality:
Gas-phase species < POLLUTION
Particle-phase species < POLLUTION
Sources, transport and fate < POLLUTION
Air pollution control / technology < OTHER RELATED AREAS

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