As the world’s second-largest economy, China has experienced severe air pollution with unprecedentedly high levels of PM$_{2.5}$, i.e. particulate matter smaller than 2.5 µm in diameter. The Ministry of Environmental Protection of China released an air pollution monitoring report for the year 2013 for the 74 largest cities of China. The Beijing–Tianjin–Hebei (BTH) region was classified as having the poorest air quality. The annual average PM$_{2.5}$ concentration of the 13 cities in the BTH region was 106 µg/m$^3$. None of these cities met the new annual China Ambient Air Quality Standard (CAAQS), and 10.4–79.2% of the total days in 2013 met the daily CAAQS. Seven cities ranked in the top 10 with poorest air quality in the country. In January 2013, there were severe regional haze events in the BTH region, with the highest hourly PM$_{2.5}$ concentration in Beijing exceeding 900 µg/m$^3$ [1].

The deterioration of air quality is mainly because of the rapid economic growth and urbanization associated with heavy coal consumption, rapid increase in the number of vehicles, ongoing construction and high population density [2]. Economic development in the BTH region is uncoordinated and inefficient. Outdated industrial techniques and equipment are still used in many cities in Hebei Province. Inefficient fuel consumption and lagging emission control measures have led to high pollution emissions. In addition, the topography favors pollutant accumulation under weak southerly winds or stagnant weather conditions, since the region is surrounded on three sides by mountains. Major issues of PM$_{2.5}$ pollution in the region and suggested future PM$_{2.5}$ studies are illustrated in Fig. 1.

**CHARACTERISTICS OF PM$_{2.5}$ IN BTH REGION**

Typically, PM$_{2.5}$ pollution in the BTH region exhibits periodic cycles of 4–7 days [3]. Each cycle starts with a clean period when strong northerly winds blow from relatively clean mountainous regions. Particle concentration grows rapidly during the subsequent 2–4 days, when the wind turns southerly and weakens, crossing populated areas. The increase in PM$_{2.5}$ concentration can be up to 200 µg m$^{-3}$ per day in some cases [3]. Variation of PM$_{2.5}$ levels within the BTH region usually has the same trend, indicating that particle pollution is formed mainly on a regional scale [4,5].

More than 200 chemical species of PM$_{2.5}$ have been quantified to date. Secondary inorganic ions (sulfate, nitrate, and ammonium or SNA) and organic matters are the major components of PM$_{2.5}$. The fraction of secondary components increases with PM$_{2.5}$ concentration, indicating that severe particle pollution is the result of secondary formation. A higher daytime sulfate concentration is attributable to a strong formation process, whereas low temperatures and high relative humidity during the night favor the partitioning of particle-phase nitrate [5]. Black carbon concentration is higher at night owing to more diesel car emissions [6].

**PM$_{2.5}$ SOURCES IN BTH REGION**

A quantitative understanding of the sources of PM$_{2.5}$ is critical to the development of effective mediation policies. At present, two source apportionment approaches are commonly used: (1) receptor models (RMs) such as chemical mass balance model and positive matrix factorization model, and (2) chemical transport models (CTMs), such as particulate source apportionment technology. There have been several studies on PM$_{2.5}$ source apportionment...
in Beijing and Tianjin [7–9], but very few in Hebei Province. Dust (construction, windblown and road) contributes significantly to PM$_{2.5}$ year round, but its contribution in spring is greatest, owing to stronger winds and bare land. Coal combustion is the most important particle source in winter, and biomass burning contributes most in the fall and late spring. Traffic and cooking emissions make continuous contributions in all seasons, but have distinct diurnal variations.

Several studies have reported that secondary formation has become the most important contributor to PM$_{2.5}$ in the BTH region. Secondary aerosols, i.e. SNA and secondary organic aerosols (SOA), account for up to 50–90% of PM$_{2.5}$, with a greater contribution in summer and fall because of favorable meteorological conditions. Sulfate has been reported to form at the regional scale and is mainly attributed to in-cloud or aerosol droplet processes [4]. Nitrate is the oxidation product of NO$_x$ and is believed to form locally. SOA has become an important contributor to PM$_{2.5}$ in recent years. Lin et al. [6] reported that SOA contributed a large fraction to total organic aerosols in Beijing, with higher contributions in summer and lower ones in winter. Anthropogenic SOA derived from anthropogenic hydrocarbon (e.g. toluene) accounts for a larger fraction in the BTH region than elsewhere [7].

PROSPECTIVE AND FUTURE WORK

Several issues remain that are not well understood regarding the characteristics and sources of PM$_{2.5}$ in the BTH region. The mechanism of severe particle pollution formation is still unclear. Current particle formation mechanisms cannot adequately explain the rapid secondary formation in the BTH region. The secondary formation mechanisms might be a combination of several formation pathways, which may have synergistic effects, or there may be unknown formation mechanisms. Key research in the future should be undertaken regarding secondary particle formation mechanisms in complex and heavily polluted environments. Field measurements using advanced approaches are still necessary, and more laboratory and outdoor chamber studies should be conducted. Several formation mechanisms should be thoroughly investigated, e.g. fast sulfate formation from aqueous phase reactions, volatile organic compound aqueous phase oxidation, heterogeneous reactions and polymerization.

Further measurement and study of PM$_{2.5}$ sources are required, because source contributions have been changing in the BTH region owing to several new control measures. Updated source apportionment results are also essential to evaluating effectiveness of these control measures. Assessment of the accuracy of those results is difficult, since the source contributions cannot be directly measured. Even consistency between different RMs or CTMs does not indicate accuracy [10]. It has also been suggested to compare CTM results at a single receptor site with those from RM to assess their accuracy. Multiple models combining RMs and CTMs should be developed [11].

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