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Trend and Interannual Variability of Chinese Air Pollution since 2000 in Association with Socioeconomic Development: A Brief Overview

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Abstract Chinese air pollution has increased in this century along with the rapid socioeconomic development and resulting anthropogenic emissions. While recent emission control measures have shown encouraging results and have reduced the levels of sulfur dioxide and primary aerosols, the concentrations of other air pollutants continue to grow, particularly secondary pollutants including ozone and secondary aerosols. Meanwhile, a variety of intentional and unintentional socioeconomic events have temporarily changed the pace, and even the signs, of growth of air pollution. These events include the short-term emission restrictions imposed during the Sino-African Summit, the Beijing Olympics and Paralympics, the Shanghai World Exposition (Shanghai Expo), the Guangzhou Asian Olympics, and the Shenzhen Universiade, as well as the unintentional emission reductions associated with the recent economic recession and the annual Chinese New Year. This paper presents a brief overview of trends and temporary perturbations of Chinese air pollution since 2000, summarizing studies on anthropogenic emission inventories, atmospheric measurements, and inverse modeling. It concludes with recommendations for future research.

Keywords: air pollution, trend and variability, socioeconomic development, satellite measurements, bottom-up emission inventories, top-down constraints

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1 Introduction

China has become the second largest economy in the world after the United States (U. S.) due to rapid economic growth and urbanization, which in this century has resulted in an average double-digit growth rate in gross domestic production (GDP; Fig. 1). These economic gains come at the high cost of air pollution and other environmental problems. Anthropogenic emissions from a variety of air pollutants have increased dramatically (Lei et al., 2010; Lin et al., 2010a; Lu et al., 2011; Zhang et al., 2007, 2009a; Zhao et al., 2008), deteriorating air quality in both urban and rural areas (De Smedt et al., 2010; Ding et al., 2008; Guo et al., 2011; Lin et al., 2010a; Lin and McElroy, 2011; Richter et al., 2005; Wang et al., 2009; Xu et al., 2008) (see also Fig. 1).

The Chinese government has made tremendous efforts to reduce air pollution, implementing control measures in coal-fired power plants, the cement industry, urban heating facilities and transportation, and phasing out small and highly emitting devices (Lin et al., 2010a; Lu et al., 2011; Zhang et al., 2009a, b). These measures have traditionally targeted emissions of sulfur dioxide (SO_2) and particulate matter < 10 μm (PM_{10}), successfully reducing atmospheric loadings of SO_2 and PM_{10} in recent years (Li et al., 2010; Lin et al., 2010a). However, the control measures have not been effective for reducing other pollutants, including nitrogen oxides (NO_x), volatile organic compounds (VOC), ozone, and PM < 2.5 μm ($PM_{2.5}$) (De Smedt et al., 2010; Ding et al., 2008; Lin et al., 2010a; Lin and McElroy, 2011; Xu et al., 2008). Currently, the government is focused on reducing $PM_{2.5}$ and ozone over the coming years by tightening emission regulations, enhancing air quality standards, and improving environmental monitoring.

Several voluntary and involuntary socioeconomic events have had significant temporary impacts on air pollution, including the Sino-African Summit (Cheng et al. 2008), the Beijing Olympics and Paralympics (Lin et al., 2010a; Zhang et al., 2009b), the Shanghai World Exposition (Shanghai Expo) (Hao et al., 2011), the Guangzhou Asian Olympics, Shenzhen Universiade, the recent economic recession, and the annual Chinese New Year (CNY) (Lin and McElroy, 2011). These events have attracted worldwide attention, providing excellent opportunities for analyzing the characteristics of Chinese air pollution and evaluating the effectiveness of emission control strategies.

The following sections first summarize the existing anthropogenic emissions inventories for gaseous and aerosol pollutants. The analysis is switched then to atmospheric measurements inferring changes in anthropogenic emissions. Emphasis is made to evaluate the general trend of air pollution since 2000 in contrast to the temporary disruptions caused by short-term socioeconomic events. Recommendations for future research are also provided.

2 Bottom-up emission inventories

Emission trends are determined by variations in emission activity and emission factors. Over the past decade, power generation, industrial output, and vehicle numbers have increased rapidly, reflecting the economic growth of China, although these factors have been disrupted tempo-

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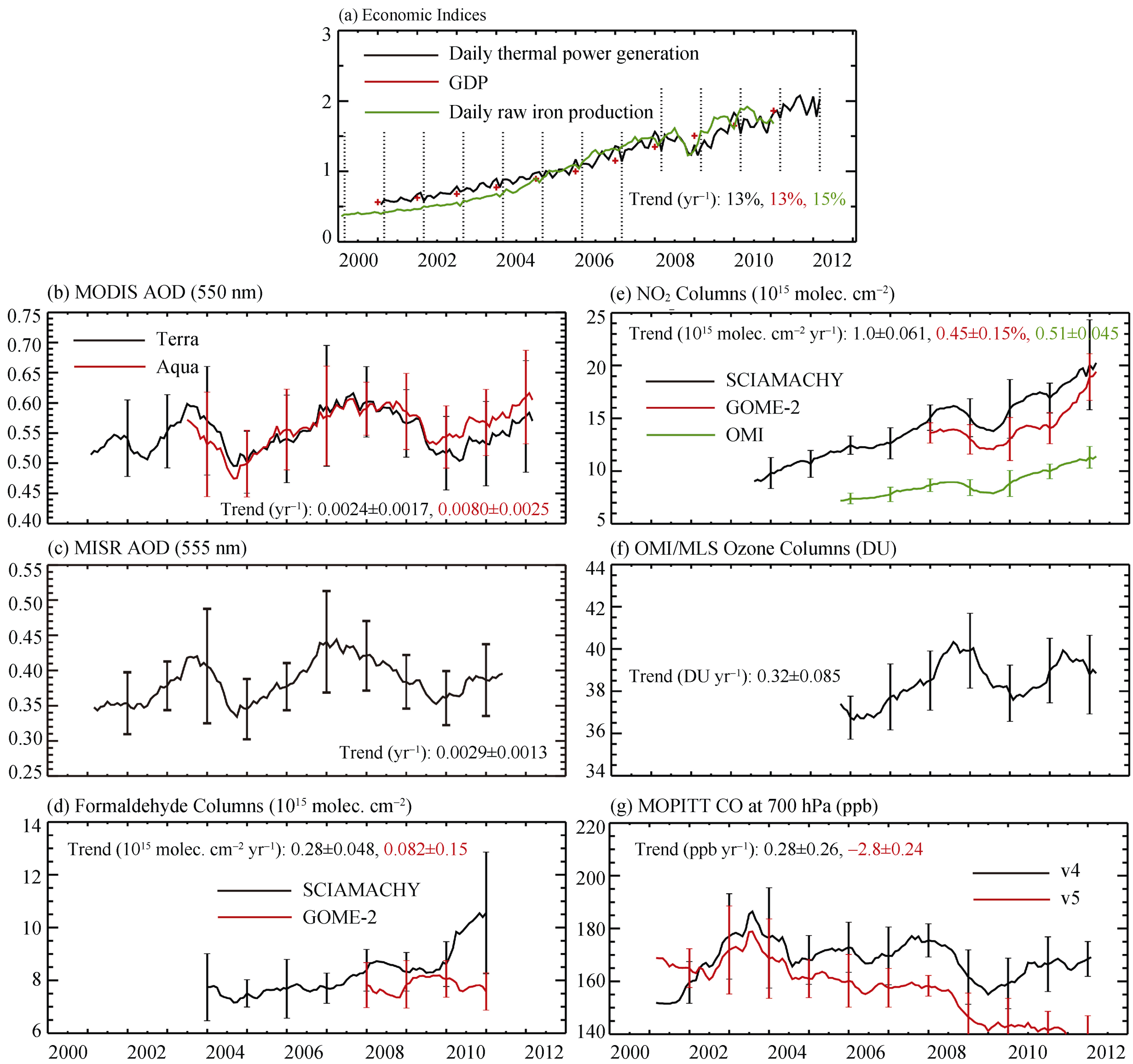

Figure 1 (a) Yearly variation of GDP and monthly variations of other economic indices of China with respective trend calculation relative to annual means in 2005. The dotted vertical lines show February when the CNY holidays occur most frequently. Note the perturbation in 2008–2009 associated with the economic downturn. Data source: the National Bureau of Statistics of China. (b–g) Monthly variations of air pollutants over northern East China (29–41°N, 110–122.25°E) detected from space: (b, c) AOD, (d) tropospheric formaldehyde columns, (e) tropospheric NO_2 columns, (f) tropospheric ozone columns, and (g) CO mixing ratio at 700 hPa. Values presented for a given month denote the means over the prior 12 months. Also shown is the trend analysis. The vertical bars indicate seasonal variability in individual years. Data source: www.temis.nl for NO_2 and formaldehyde and National Aeronautics and Space Administration (NASA) for other pollutants.

rarily by the aforementioned short-term socioeconomic events (Lin et al., 2010a; Zhang et al., 2007) (see also Fig. 1). Meanwhile, the implementation of flue-gas desulfurization (FGD) systems has significantly reduced emission factors of SO_2 in power generation, with additional benefits for primary aerosol control (Lin et al., 2010a; Zhao et al., 2009). The promotion of precalciner kilns in place of shaft kilns has increased (decreased) emission factors of NO_x (CO) in cement production due to enhanced combustion efficiency (Lei et al., 2010; Lin et al., 2010a). The revised emission standard has reduced emission factors of primary aerosols in the cement industry by up to 67%, depending on kiln types (Lei et al., 2010; Lin et al., 2010a). The phase-out of small and highly emitting devices has had a significant influence on emission factors across the heavy industries (Lin et al., 2010a; Lu et al., 2011; Zhang et al., 2009a). The rapidly strengthening vehicle emission standards have resulted in significant declines of emission factors for most pollutants (Lin et al., 2010a). In the residential sector, emission factors have also declined due to the promotion of cleaner burners replacing the previous coal/wood/grass burners (International Energy Agency (IEA), 2007; Lin et al., 2010a). The consequent emission trends are expected to differ to some extent between air pollutants due to the varying importance of individual sectors.

Chinese emission inventories accounting for trends since 2000 are available for a limited number of pollutants and years (Bond et al., 2004; Lei et al., 2010; Lin et al., 2010a; Lu et al., 2011; Zhang et al., 2007, 2009a; Zhao et al., 2008; Huang et al., 2011). According to Lu et al. (2011), anthropogenic emissions of SO_2 increased by 61% from 2000 to 2006 and then declined by 9.2% from 2006 to 2010. Emissions of black carbon (BC) and organic carbon (OC) increased by 72% and 43%, respectively, from 2000 to 2010. Zhang et al. (2007, 2009a) indicated emission growth by 13%–55% from 2001 to 2006 for SO_2, NO_x, carbon monoxide (CO), VOC, PM_{10}, $PM_{2.5}$, BC, and OC, with a larger increase in NO_x and smaller increases in CO and carbon aerosols. Results from Lu et al. (2011) and Zhang et al. (2007, 2009a) are in broad agreement with many (but not all) alternate inventories (see Zhang et al., 2009a; Lu et al., 2011 for details). More trend analyses are needed to account for the rapidly changing emissions since 2005. Of particular concern are emissions of VOC and the contribution of residential and industrial sources to various pollutants.

Bottom-up estimates are rare in directly calculating emission reductions during short-term socioeconomic events, except for the Beijing Olympics (Su et al., 2011; Wang et al., 2010). Su et al. (2011) found a reduction by about 45% in VOC emissions in Beijing in August 2008 relative to June. Wang et al. (2010) found daily emissions of SO_2, NO_x, PM_{10}, and VOC during the Olympic Games to be lower than those in June 2008 by 41%–57%. These estimates are relatively consistent pointing to the effectiveness of the short-term emission mitigation. Bottom-up analyses are needed for other socioeconomic events, especially for comparison with top-down constraints.

3 Atmospheric measurements and top-down emission constraints

Atmospheric measurements have been used widely to analyze the characteristics of Chinese air pollution and to constrain emissions. Ground based measurements are limited by spatial and temporal coverage, and aircraft measurements are rare in China. Satellite remote sensing provides an important tool for air quality analysis, although subject to retrieval errors. To reconcile the lack of sufficient ground and in situ observations, satellite measurements have been exploited extensively to analyze Chinese air pollution. Such measurements are employed here to facilitate the overview of previous studies on pollutant trends and characteristics, as shown in Fig. 1.

3.1 General trend characteristics

Vertical column densities (VCDs) of tropospheric NO_2 from a variety of satellite instruments have been employed to analyze levels, trends, and emissions of NO_x (Lamsal et al., 2011; Lin et al., 2010a; Lin and McElroy, 2011; Richter et al., 2005; Zhang et al., 2007). Richter et al. (2005) found drastic increases of NO_2 from 1995 to 2004 over East China (e.g., by ~ 9.6% per year over the Yangtze River Delta (YRD)), in contrast to the decreasing trends found over the U.S. and Europe. More recent studies indicated continuous growth of NO_x in China since 2005 (Lamsal et al., 2011; Lin et al., 2010a; Lin and McElroy, 2011) (also see Fig. 1). Lin (2012) further suggested anthropogenic emissions to be the dominant source of NO_x in China, with contributions of soil and lightning emissions not exceeding 25% even in summer. Currently, the greatest challenge for space-based emission derivation for NO_x is to constrain errors in inverse modeling to develop better comparisons to bottom-up inventories on the absolute values of NO_x emissions.

Tropospheric formaldehyde has also been retrieved from space (although more difficult than NO_2) to analyze levels and trends of VOC emissions (De Smedt et al., 2010). De Smedt et al. (2010) showed a significant increase of formaldehyde over northern China based on Global Ozone Monitoring Experiment (GOME) and SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) measurements and suggested likely drastic growth in anthropogenic VOC emissions. The trend is however not obvious from the GOME-2 data (Fig. 1), indicating significant uncertainties in satellite observations. Retrievals of glyoxal revealed a potentially dramatic underestimate (up to an order of magnitude) in bottom-up anthropogenic aromatic emissions (Liu et al., 2012); trend analyses are not available.

CO is measured by multiple space instruments, such as the Measurements Of Pollution In The Troposphere (MOPITT), SCIAMACHY, and the Infrared Atmospheric Sounding Interferometer (IASI) (Fortems-Cheiney et al., 2011; Liu et al., 2011). Based on the widely used MOPITT product version 4, Fortems-Cheiney et al. (2011) found no significant trends of CO at 700 hPa from 2000 to 2009 averaged over East and continental Southeast Asia. For China, the MOPITT version 4 product also shows no significant trends, while the version 5 product suggests that CO concentrations have declined rapidly since 2003 (Fig. 1), resulting in difficulties in inferring trends of anthropogenic CO emissions.

Tropospheric ozone has been growing gradually over East China due to growth in precursor emissions, as observed from ground measurements in Hong Kong, YRD, and Beijing (Ding et al., 2008; Wang et al., 2009; Xu et al., 2008). Satellite remote sensing is difficult for surface ozone detection due mainly to the influence of the stratosphere and upper troposphere. The measurement has, however, been used to study the effect of climate variability on tropospheric ozone (Oman et al., 2011). Figure 1 shows the apparent growth, albeit with large interannual variability, of tropospheric ozone over China since late 2004 that is consistent with increasing emissions of NO_x and VOC.

Space-based measurements are difficult for detecting anthropogenic SO_2 due to the influence of volcanic sources and tropospheric ozone. Limited data have however been used to analyze the effectiveness of sulfur control in China after 2007 (Li et al., 2010), and the results are in broad agreement with ground measurements (Lin et al., 2012b).

Chinese aerosols are under extensive studies concerning their high loadings and significant adverse environmental impacts (Guo et al., 2011; Huang et al., 2012; Lin et al., 2010a; Xin et al., 2011; Yang et al., 2011; Zhang et al., 2009b, 2012). Although under scrutiny regarding the data quality, official ground measurements for PM_{10} in tens of cities suggest declining PM_{10} concentrations in most cities, which is attributable to tightened emissions controls on primary aerosols (Lin et al., 2010a). By contrast, $PM_{2.5}$ may have increased gradually due to increasing formation from emitted precursors (Lin et al., 2010a), as indicated by the growing aerosol optical depth (AOD) (Guo et al., 2011; Lin et al., 2010a; Xin et al., 2011). Figure 1 shows gradual growth of AOD embedded in large interannual variability observed from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging SpectroRadiometer (MISR). The interannual variability is associated with variations in meteorology, natural (e.g., biomass burning) emissions, and short-term disruptions in anthropogenic emissions; the contributions of these factors have yet to be quantified.

3.2 Short-term emission controls for the Beijing Olympics and other socioeconomic events

The 2008 Beijing Olympics and Paralympics came with the strictest short-term emission control strategies in Chinese history substantially reducing emissions in Beijing and the surrounding provinces through traffic restriction and other measures (Zhang et al., 2009b). The emission disruption provided an excellent opportunity for studying the nonlinear relationship between emissions and pollution severity under the influence of varying meteorology and natural emissions (Cermak and Knutti, 2009; Gao et al., 2011; Lin et al., 2012b; Mijling et al., 2009; Shao et al., 2011; Xing et al., 2011; Zhang et al., 2009b). Top-down constraints suggested that emission reductions and favorable meteorological conditions are both critical for air quality improvement (Gao et al., 2011; Xing et al., 2011; Zhang et al., 2009b). The effect of emission control on surface ozone exhibited large horizontal inhomogeneity, with increases in urban ozone concentrations transitioning to reductions in rural areas reflecting different regimes of ozone production chemistry (Xing et al., 2011; Zhang et al., 2009b).

Prior to the Olympics, smaller-scale emission restrictions were established for the Sino-African Summit in November 2006 (Cheng et al., 2008). The success of emission mitigation for the Olympics has inspired similar actions in other Chinese cities holding major international events, including the six-month long Shanghai Expo , Guangzhou Asian Olympics, and Shenzhen Universiade. A study for Shanghai Expo showed reductions in aerosols, NO_2, and CO based on space measurements, without explicitly quantifying the effect of meteorological conditions (Hao et al., 2011). Studies for other events are yet to come.

3.3 Effects of the recent economic downturn and the CNY

China also experienced several periods of unintended emission perturbations in the past decade, including the recent economic recession (late 2008–mid 2009) and the annual CNY holidays (Lin et al., 2010a; Lin and McElroy, 2011) (see also Fig. 1). Studies on these events can help improve understanding of the characteristics of Chinese air pollution at no additional economic costs. Based on satellite measurements, Lin and McElroy (2011) found that the recession and CNY contributed, approximately equally, to a 20% reduction in anthropogenic emissions of NO_x in the month of January from 2008 to 2009. Studies on other pollutants will prove useful, given the scale of the economic recession and the annual reoccurrence of CNY.

4 Recommendations for future research

Further studies are needed on Chinese air pollution, including long-term trend characteristics and short-term variations associated with socioeconomic events. For studies on short-term emission mitigation, it is important to conduct cost-effect analyses of emission control strategies to better facilitate emission controls in the future (not just for short-term events but also for long-term endeavors to improve air quality in China).

Future research can benefit from extended ground and in situ measurements, enhanced data management-coordination, improved quantification of satellite and model errors, improved separation of the effects of changing anthropogenic emissions from the effects of varying meteorology and natural emissions, and timely update of anthropogenic emission inventories that account for the rapid emission changes.

Measurements: Current ground and in situ measurements are inadequate both for analyzing the temporal and spatial variability of air pollution and for evaluating errors in satellite data and model simulations. There is an urgent need to improve the spatiotemporal coverage of measurements. Enhancing data coordination to enable a more open data deposit and sharing system will substantially facilitate future research. A good example of such coordination lies in the U.S. where federal agencies manage and provide high-quality measurement data for researchers free of charge (e.g., http://www.epa.gov/ttn/airs/airsaqs/).

Satellite and model errors: Satellite data contain errors of both random and systematic characteristics with significant consequences for inverse modeling and other air pollution applications (Boersma et al., 2004; Lin et al., 2010b). Errors also exist in models (e.g., chemical transport models (CTMs)) associating emissions and tropospheric abundances of air pollutants (Lin et al., 2012a). These errors should be better quantified to improve the accuracy of subsequent emission inference. Aircraft measurements are important particularly for error evaluation, as they can provide pollutant information at different altitudes; they are rare in China and should be conducted more frequently in the future. To quantify model errors in the absence of pollutant measurements, an indirect approach can be taken by systematically examining meteorological and chemical parameters/processes represented in the models (Lin et al., 2012a).

Meteorology and natural emissions: Measured variations in air pollution are affected also by changes in meteorology and natural emissions (Lin, 2012). The effect of varying meteorological conditions can be analyzed with a certain set of meteorological parameters and/or by black-trajectory modeling (Ding et al., 2008; Hao et al., 2011; Lin et al., 2012b; Zhang et al., 2009b). As a more sophisticated and quantitative approach, CTMs and their adjoint models can be used to separate the effect of anthropogenic emissions from other factors by explicitly considering the non-linear processes governing the transport and transformation of air pollutants (e.g., Xing et al., 2011; Lin and McElroy, 2011; Lin, 2012).

Emission inventory: Current anthropogenic emission inventories are often not updated in time to reflect the rapid changes in Chinese emissions, and are limited mainly by lack of data availability for emission activities and emission factors. A possible solution to these challenges is to establish bottom-up inventories for a specified period of years and to use top-down (e.g., satellite-based) calculations to extend emissions to other years (Lamsal et al., 2011), provided that errors in inverse modeling can be quantified reasonably.

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