Comparisons of Asian Emissions Inventories

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ABSTRACT
Urban emissions, especially from the transport sector, have been increasing rapidly in China and India. Modelers use global and regional emissions inventories to assess temporal and spatial distribution of these emissions to estimate their impacts on regional and global air quality and climate. However, large uncertainties exist in emissions inventories and a quantification of this uncertainty is essential for better understanding of the linkage between emissions and air quality, climate, and health. We focus on this uncertainty by comparing emissions of carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matter (PM), from China, India, and Pakistan in multiple emissions inventories: from global to national. In addition to the total emissions, we also analyze emissions from four source sectors and at the provincial level. We find large discrepancies among the inventories in the domestic and transport sectors, which are very important for calculating human exposure. Regional and global emissions inventories often used in climate and chemical transport models do not necessarily reflect the spatial distribution and local peculiarities of the emissions, especially in the Asian developing countries.

INTRODUCTION
Obtaining accurate emission estimates is important in Asia, which holds five of the worst air quality countries, according to Yale's recent environmental performance index study [*Hsu et al.*, 2014]. Several emissions inventories have been developed in the past few years either specifically for a country or for larger regions that include Asia [*Garg et al.*, 2006; *European Commission and Joint Research Centre (JRC)/Netherlands Environmental Assessment (PBL)*, 2009; *Sahu et al.*, 2012; *Kurokawa et al.*, 2013; *Pandey et al.*, 2014; *Sadavarte and Venkataraman*, 2014]. In this study, we compare surface emissions of major air pollutant precursors from six different emissions inventories to highlight source

sectors or regions in three Asian countries (China, India, and Pakistan) where emissions are not well understood and need to be further constrained.

Several studies have compared emissions inventories in Asia [*Garg et al.*, 2006; *Granier et al.*, 2011]. However, most studies focus their analysis on similarities and discrepancies at the national level and do not analyze provincial scale emissions or they do not compare emissions from different source sectors. The analysis in this paper focuses on anthropogenic emissions of carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter with an aerodynamic diameter less than 10 µm (PM_{10}). Emissions inventories are analyzed to identify similarities and differences in both emissions magnitudes and temporal trends at the national and provincial levels in the three Asian countries.

BODY

Methods

The four emissions inventories analyzed in this paper were developed using similar methodology where emissions are calculated as the product of activity data, such as fuel consumption, and emission factors.

EDGAR The Emissions Database for Global Atmospheric Research (EDGAR) v4.2 [*European Commission and Joint Research Centre (JRC)/Netherlands Environmental Assessment (PBL)*, 2009] was developed by the Netherlands Organization for Applied Scientific Research and the Netherlands Environmental Assessment Agency. Recently, the European Commission's Joint Research Center has also collaborated on its development. EDGAR is a gridded emissions inventory that spans 1970-2008 at a 0.1° longitude x 0.1° latitude horizontal resolution. The present study focuses on emissions from 2000-2008.

REAS The Regional Emissions inventory in ASia (REAS) v2.1 [*Kurokawa et al.*, 2013] analyzed in this study spans 2000-2008 at a 0.25° longitude x 0.25° latitude resolution. Previous versions of REAS span a larger time period and included projections of emissions but v2.1 is based on updated activity data and parameters.

MEIC The Multi-resolution Emission Inventory for China (MEIC) is an inventory made by Dr. Qiang Zhang in Tsinghua University, Beijing, China, and provides source sector information for Chinese provinces for 2008.

Zhao et al. (2008) (hereafter **ZHAO**) A Chinese inventory made by Dr. Yu Zhao at Nanjing University is a national inventory that estimates source sector emissions for Chinese provinces for 2007 [*Yu et al.,* 2008].

Sadavarte and Venkataraman (2014) and Pandey et al. (2014) (hereafter **PANDEY**) The documentation of an Indian emissions inventory was published in two papers [*Pandey et al.*, 2014; *Sadavarte and Venkataraman*, 2014]. Sadavarte and Venkataraman (2014) presented the emissions from industry and transport sectors in India, while Pandey et al. (2014) published the complementary emissions inventory for the residential, agriculture and informal industry sectors. The resulting inventory spans 1996-2015, but this study only evaluates the 2000-2008 period.

NAGPURE An Indian national emissions inventory made by Dr. Ajay Nagpure at the University of Minnesota and Dr. Bhola Gurjar at the Indian Institute of Technology, Roorkee, provides emissions estimates for domestic and transport sectors for the 2000-2008 period.

Results

China

We find the largest discrepancy - larger than 45% - between REAS and EDGAR emissions estimates for total CO in China throughout the 2000-2008 time period. MEIC and ZHAO CO estimates fall between the two emissions inventory estimates, although they are closer to those of REAS. When we compare emissions at the seven regions within China (South Central, Southwest, Northwest, South, East, Northeast, and North), we find much larger differences than at the national level for almost all species.

For CO emissions, industry is the only source sector that increases over time in all regions. The REAS CO emissions estimates are consistently higher than those of EDGAR across all regions, and

MEIC and ZHAO CO emissions estimates generally fall between the estimates of EDGAR and REAS. The East CO emissions from the industry sector, in particular, show a high level of discrepancy, and the absolute difference more than doubles from 2000 to 2008. The EDGAR CO estimates for the transport sector in the East and the South Central regions are increasing over time, whereas those of REAS indicate the opposite. Analysis at the source sector level reveals that the majority of the differences in CO emissions among the inventories stem from the industry sector.

For PM_{10} emissions, the largest emissions discrepancy also stems from the industry sector. Industry is also the source that has an increasing PM_{10} emissions trend throughout the region for both EDGAR and REAS. We observe relatively little change in differences between EDGAR and REAS throughout the time period for all other sectors. There are, however, some interesting sector-dependent differences. For industry PM_{10} emissions, REAS estimates are always consistently higher than those of EDGAR in all regions. This is not the case for the domestic sector. In Northeast, REAS PM_{10} emissions estimates are higher than those of EDGAR. For Southwest and North, REAS emissions estimates are higher than EDGAR estimates for the period 2002-2005. What is also striking is the very small magnitude of domestic sector PM_{10} emissions estimated in MEIC, compared to other estimates.

For SO_2 emissions, we find a large divergence between EDGAR and REAS power sector emissions estimates during 2000-2008 across all regions. EDGAR estimates continues to increase over time, whereas the REAS estimates start to decrease at some point in that time range, which is not all uniform across the regions. South Central and Northwest start to deviate in 2004, South, East, and North in 2005, and Northeast and Southwest in 2006. This is most likely due to the difference in the installation timing of sulfur scrubbers in coal-fired power plants. SO_2 emissions in other sectors remain relatively constant across all regions. MEIC and ZHAO SO_2 emissions estimates are more comparable to REAS estimates for all regions.

Throughout the regions, the transport sector generally represents the largest absolute differences among the inventories for NO_x emissions between EDGAR and REAS. MEIC estimates add more discrepancies, as its estimates are higher than those of EDGAR and REAS for South Central, whereas lower than both estimates for some regions. The same applies to the power sector NO_x emissions. The industry and power sector NO_x emissions show diverging trends for regions such as the East.

India

The majority of CO emitted in India comes from the domestic sector, making up 55% and 50% of total EDGAR and REAS CO emissions from India, respectively. Although both emissions inventories show a similar increasing trend in domestic CO emissions from 2000 to 2008, each year EDGAR domestic CO emissions are consistently higher than REAS by approximately 4 Tg/yr. NAGPURE domestic CO emissions also increase over time but are much smaller than EDGAR and REAS CO emissions. On the other hand, PANDEY domestic CO emissions are within 5% of EDGAR emissions but do not increase over time.

On a regional scale, EDGAR domestic CO emissions exceed those of REAS in four regions out of nine within India, with the largest difference being 1.7 Tg/yr in southern India. REAS industrial CO emissions have gradually increased nearly linearly from 11.8 Tg/yr to 15.3 Tg/yr between 2000 and 2008, while EDGAR industrial emissions have fluctuated more with large dips in 2001 and 2008. While the transport sector is as large of a CO emitter as the domestic and industry sectors, the discrepancy between EDGAR and REAS has grown the most from 521 Gg/yr in 2000 to 6,280 Gg/yr by 2008.

Fossil fuel combustion in the power sector contributes the largest portion of SO_2 emissions in India compared to other sectors. SO_2 emissions from the power sector make up over 60% of total emissions according to EDGAR and 48% for REAS. Although the relative contributions of the power sector to total India SO_2 emissions for EDGAR and REAS differ, power sector emissions agree well for the two inventories between 2000 and 2008. Power emissions are within 10% of each other and increase by around 46% and 47% from 2000 to 2008 for EDGAR and REAS, respectively. On the other hand, PANDEY SO_2 emissions from the power sector are much less, by around 1,500 Gg yr^{-1}, than EDGAR and REAS. Industrial emissions of SO_2, on the other hand, do not show good agreement between EDGAR and REAS, although the PANDEY industrial SO_2 emissions are nearly identical to that of

EDGAR. National REAS industrial SO_2 emissions are twice as large as EDGAR and are almost as large as power emissions. Also, from 2000 to 2008 REAS industrial emissions increase by 1,580 Gg yr^{-1}, while EDGAR industrial SO_2 emissions only increase by 766 Gg yr^{-1}. The discrepancy is apparent on a regional scale in every region except the two. In the region with the highest REAS total SO_2 emissions, industrial emissions of SO_2 are over 700% of EDGAR industrial SO_2 emissions.

Total NO_x emissions from EDGAR and REAS do not show good agreement from 2000 to 2008, with REAS emissions almost twice as large as EDGAR. Although total NO_x emissions between the two are not in agreement, NO_x emissions from the power, industrial and domestic sectors are, except for industrial emissions in 2008. In particular, the increasing trend in power sector emissions from 2000 to 2008 is captured by both inventories.

The major disagreement lies in the transport sector, the largest and second largest NO_x emitter in REAS and EDGAR inventories, respectively. In 2000, REAS transport emissions are 65% larger than those of EDGAR and by 2008 over 300% larger since EDGAR does not capture the same increasing trend as REAS. PANDEY transport NO_x emissions are similar to EDGAR. NAGPURE transport NO_x emissions, however, are much larger than all the other inventories analyzed, with 23% more NO_x emissions than REAS by 2008. REAS transport NO_x emissions are higher than EDGAR in all regions, with the largest disagreement of over 500 Gg yr^{-1}. In four regions, REAS transport emissions are over twice as large as those of EDGAR.

REAS and EDGAR emissions of PM_{10} in India do not show good agreement in any of the sectors explored here. PM_{10} emissions from EDGAR are over three times as large as REAS from the power sector and REAS domestic sector emissions are more than twice as large as those of EDGAR. Although the magnitude of emissions from power and domestic sectors are different, EDGAR and REAS both show a 44% and 58% increase in power sector emissions from 2000 to 2008, respectively, and almost no change in domestic emissions of PM_{10}. On the regional scale, EDGAR PM_{10} emissions from power and domestic sectors are larger than REAS in every region. Conversely, EDGAR PM_{10} emissions from the industrial and transport sectors are much lower than REAS emissions in every region, with national average EDGAR PM_{10} emissions just 6% of REAS PM_{10} in the transport sector by 2008.

Pakistan

In Pakistan, both EDGAR and REAS emissions inventories have similar trends, with REAS having larger emissions from the domestic and industry sectors than EDGAR. The domestic sector is the largest source of CO emissions in Pakistan, with REAS having larger domestic sector emissions in all regions except the Northern Areas. Industry and transport are the second and the third largest sectors in Pakistan, respectively.

At the national level, EDGAR and REAS SO_2 emissions both have similar trends with a dip between 2002 and 2003, an increase until 2007 and another slight drop between 2007 and 2008. Both have similar magnitude of power sector emissions that have a sharp drop between 2002 and 2003, followed by a sharp increase in 2005 and 2006. The power sector emissions vary significantly at the regional level. Punjab has the largest discrepancy with REAS larger than EDGAR, while Sind has the second largest discrepancy with EDGAR larger than REAS. The industrial SO_2 sector emissions follow similar trends as those of CO, with an increase starting in 2002. REAS has a sharp increase between 2006 and 2007 that EDGAR does not. At the regional level, REAS has higher SO_2 emissions from industry than EDGAR in all regions except one. REAS also estimates larger SO_2 emissions from the transport sector than EDGAR, with a peak difference of 177% in 2008.

REAS has lower total NO_x emissions than EDGAR at the national level until 2002, after which it remains higher than EDGAR. REAS has lower transport NO_x emissions than EDGAR until 2002-2003. In 2006, EDGAR transport emissions supersede the REAS transport sector, only to decrease in 2008. At the regional level, the transport sector has the largest difference in Punjab, Baluchistan, and Sind. The REAS inventory has a slight increase in NO_x power emissions, while the EDGAR power sector shows a sharp decrease in 2002 followed by an increase in 2005. At the regional level, REAS has larger regional power sector emissions, with Punjab having the largest emissions. The NO_x emissions from the industry sector have the same trend and magnitude in both EDGAR and REAS throughout the regions. REAS has higher domestic sector NO_x emissions in each region with the difference larger than 120% in some regions.

The transport sector PM_{10} emissions have the largest discrepancy among the sectors. In 2000 there was a difference of 30% that increased to 108% in 2005. At the regional level, each area excluding Sind had a difference of over 100%. The domestic sector is the largest source of PM_{10} emissions in Pakistan. REAS shows larger industrial emissions than EDGAR in all regions except F.C.T. with the largest difference occurring in the Punjab region.

CONCLUSIONS

In this study, we compared six emissions inventories of anthropogenic air pollutant precursor emissions in China, India, and Pakistan on national and provincial scales. The EDGAR and REAS inventories have been developed and maintained for years and have been extensively used for air quality modeling in the Asian continent, while some of the national emissions inventories were recently developed and no air quality modeling studies have been published using the data at this time. This analysis reveals large discrepancies in emissions estimates among the existing inventories. Analysis of regional and sector specific emissions, as opposed to total national emissions, reveals discrepancies in emissions from certain sectors that would not be noticed upon analysis of total emissions. For instance, total EDGAR and REAS CO agree well both nationally and in most regions in India, while there were major discrepancies at the regional sector level emissions estimates.

REFERENCES

European Commission, and Joint Research Centre (JRC)/Netherlands Environmental Assessment (PBL) (2009), Emission Database for Global Atmospheric Research (EDGAR), release version 4.2, Available from: http://edgar.jrc.ec.europa.eu

Garg, A.; Shukla, P. R.: Kapshe, M. “The sectoral trends of multigas emissions inventory of India”. Atmos. Environ. 2006, 40(24), 4608–4620.

Granier, C. et al. “Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980-2010 period”. Clim. Change, 2011, 109, 163–190.

Hsu, A.; Emerson, J.; Levy, M; de Sherbinin, A.; Johnson, L.; Malik, O.; Schwartz, J.: Jaiteh, M. “The 2014 Environmental Performance Index”. 2014. Yale Center for Environmental Law & Policy, New Haven, CT.

Kurokawa, J.; Ohara, T.; Morikawa, T.; Hanayama, S.; Janssens-Maenhout, G.; Fukui, T.; Kawashima, K.: Akimoto, H. “Emissions of air pollutants and greenhouse gases over Asian regions during 2000-2008: Regional Emission inventory in ASia (REAS) version 2”. Atmos. Chem. Phys. 2013, 13(21).

Pandey, A.; Sadavarte, P.; Rao, A. B.: Venkataraman, C. “Trends in multi-pollutant emissions from a technology-linked inventory for India: II. Residential, agricultural and informal industry sectors”. Atmos. Environ., 99, 341–352.

Sadavarte, P.: Venkataraman, C. “Trends in multi-pollutant emissions from a technology-linked inventory for India: I. Industry and transport sectors”. Atmos. Environ. 99, 353–364.

Sahu, S. K.; Beig, G.: Parkhi, N.S. “Emerging pattern of anthropogenic NOx emission over Indian subcontinent during 1990s and 2000s”. Atmos. Pollut. Res., 2012. 3(3), 262–269.

Zhao, Y.; Wang, S. X.; Duan, L.; Lei, Y.; Cao, P. F.: Hao J. M. “Primary air pollutant emissions of coal-fired power plants in China: Current status and future prediction”. Atmos. Environ. 42, 8442-8452.

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