The Future of Air Quality in the Developing World

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What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

Attendees of the 2014 NASA workshop on Outstanding Questions in Atmospheric Composition identified the future of air quality in the developing world as the number one priority for tropospheric composition research over the next few decades. As noted in the workshop report [https://espo.nasa.gov/home /content/NASA_SMD_Workshop], the developing world is experiencing rapid industrialization in combination with high population density and limited emission controls, leading to serious air quality problems [*Cohen et al.*, 2005]. A recent study showed that more than 4000 people die every day in China from particulate matter (PM) exposure [*Rohde and Muller*, 2015], and given that ozone has also been linked to premature mortality [*Jerrett et al., 2009, 2015; Lelieveld et al., 2015*], the total death toll associated with air pollution is likely even higher. While China receives much of the international attention on this issue, other locations in South Asia and Africa also have dangerously poor air quality [e.g. *Tawari and Abowei*, 2012; *Liousse et al.,* 2014]. In the tropics, smoke from biomass burning is becoming a major public health issue as it affects population centers [*Pavagadhi et al.*, 2013]. Worldwide, air pollution is believed to kill more people than AIDS, malaria, breast cancer, or tuberculosis [*WHO*, 2014; *WHO*, 2012; *O'Keefe*, 2013; *Yang et al*., 2013]. Underscoring the importance of this topic, the GEO-CAPE Atmospheric Science Working Group (ASWG) endorsed it as a critical research and applications need at a recent community workshop. This ASWG represents a broad cross-section of ~35 scientists from universities and government laboratories who have contributed to pre-formulation studies for the air quality component of the GEO-CAPE mission recommended by the 2007 Decadal Survey [http://geo-cape.larc.nasa.gov/].

The 2014 NASA workshop report identified four science questions associated with air quality in the developing world, paraphrased here and listed in order of importance:

1. What are the emissions associated with major sources of pollution in the developing world and how are these emissions related to near-surface ozone and PM?
2. How will changing patterns of energy-related and agricultural emissions driven by urbanization affect local and regional air quality and what are the consequences for global tropospheric composition?
3. Can we develop a space-based observing system for global air quality, with spatial and temporal resolution relevant for determining public exposure to ozone and PM, that can be used to issue air quality warnings?
4. How do extreme air quality events form and evolve in these understudied regions and how do they affect global composition?

Why are these challenges/questions timely to address now especially with respect to readiness?

The issue of air quality in the developing world is extremely timely because the next few decades are crucial in terms of providing scientists and policy makers with the information they need to monitor, understand, and reduce air pollution in order to protect populations and to achieve concomitant short-term climate benefits. There has been much progress made in recent years toward the application of satellite measurements to air quality issues, as exemplified by the NASA AQAST team [http://acmg.seas.harvard.edu/aqast], which has pioneered new techniques and approaches for utilizing measurements from the current generation of low-Earth orbiting (LEO) satellites to aid air quality managers at the local, state, and national level. Further, advances in multispectral retrievals have demonstrated capability for near-surface measurements of carbon monoxide and ozone [*Worden et al*., 2010, 2013; *Fu et al*., 2013; *Cuesta et al*., 2013], with the potential to provide better understanding of the effects of air pollution on humans and ecosystems. Most critically, NASA (through the GEO-CAPE ASWG) and ESA have started to work with the air quality community to prepare for and exploit the expected high volume of high spatiotemporal resolution measurements of ozone, aerosols, and precursor species from the upcoming geostationary Earth orbit (GEO) missions TEMPO (NASA), GEMS (KARI), and Sentinel 4 (ESA). This "virtual constellation" has led to a set of well-defined measurement requirements for space-based observations of air quality [e.g. *Fishman et al*., 2012; *GEO-CAPE*, 2015] and is expected to revolutionize the use of satellite measurements for air quality applications and operational services. However, it will be focused on the developed regions of the Northern midlatitudes. There is a critical need for similar high spatiotemporal resolution measurements focused on developing nations in the tropics and subtropics.

Precedent for partnership between NASA and governments in the developing world has already been established through the NASA – U.S. Agency for International Development (USAID) SERVIR program [http://www.nasa.gov/mission_pages/servir/overview.html]. SERVIR provides satellite data, predictive models and science applications to help improve environmental decision-making among developing nations in parts of Africa, the Hindu-Kush region, and Southeast Asia. SERVIR strengthens the ability of governments and other stakeholders to incorporate Earth observations and geospatial technologies to respond to natural disasters, improve food security, safeguard human health, and manage natural resources. While the quantitative application of satellite data to air quality decision-making is currently out of the scope of SERVIR, the US-based input to air quality management for the Beijing Olympic Games [*Streets et al.*, 2007] provides an effective model for implementation.

Why are space-based observations fundamental to addressing these challenges / questions?

To answer the science questions described above, we must be able to quantify emissions from various sources and connect them to chemical processes and the subsequent production of ozone and PM near the surface, where they impact human health. Sparse surface measurements are insufficient for this purpose, particularly in the developing world where surface networks are rudimentary at best. Aircraft campaigns, which can be difficult to organize in developing regions, provide anecdotal data that cannot easily be generalized to larger spatiotemporal scales. Space-based measurements are thus critical because they provide the spatial coverage and long, continuous record required to address these science questions under a variety of environmental conditions.

The current generation of low-earth orbiting (LEO) satellites have provided a wealth of valuable measurements for quantifying emissions [e.g. *Jiang et al*., 2015; *Marais et al*., 2014; *Gu et al*., 2014;

Huang et al., 2014; *Ghude et al*., 2013; *Barkley et al*., 2015; *Richards et al.*, 2013; *Kim et al*., 2013] and understanding the processes controlling mid-tropospheric ozone [e.g. *Verstraeten et al*., 2015; *Neu et al*., 2014; *Huang et al*., 2015]. The GEO-CAPE pre-formulation studies, however, have shown that once-per-day LEO measurements are insufficient for monitoring and understanding air quality. These studies indicate that observations must be made multiple times a day, at horizontal resolutions of ~10 km or finer, and with as much near-surface sensitivity as possible in order to separate emissions sources at the urban scale, quantify the contribution of transported pollution, understand diurnal and day-to-day variability in emissions and chemical processing, and provide sufficient measurement statistics to enable quantitative studies in cloudy regions [e.g. *Fishman et al.*, 2012].

The TEMPO, Sentinel-4, and GEMS geostationary satellites will achieve many of the measurements needed to address these goals over the regions surrounding the United States, Europe, and Korea, respectively, but large swaths of the developing world will remain uncovered. Furthermore, none of these missions will incorporate TIR measurements that help to identify biomass burning plumes (e.g. peroxyacetyl nitrate and formic acid [*Alvarado et al.*, 2011]) and constrain agricultural emissions (e.g. ammonia [*Zhu et al.*, 2013] and, when combined with UV/VIS measurements, provide the most robust sensitivity to near-surface ozone [*Natraj et al.,* 2011; *Zoogman et al.*, 2011].

The Sentinel 5P/5, METOP, and JPSS satellites will provide global LEO coverage of many of the relevant species once per day, but will lack the spatiotemporal resolution needed to understand and quantify air pollution processes. Therefore a space-based mission is needed that measures critical air quality and biomass burning species multiple times per day, with as much coverage as possible over South and Central America, Africa, and South Asia (where many current and emerging megacities are located). There are several potential implementation approaches for such a mission, including additional GEO instruments to complement the spatial coverage of Sentinel 4, TEMPO, and GEMS; companion LEO instruments to complement the temporal coverage of Sentinel 5, METOP, and JPSS; and a set of 2 LEO orbiters in opposing near-equatorial orbits covering 30ºS-30ºN. The geostationary option offers the advantage of a hosted payload approach using planned geostationary communications satellites. Since these satellites provide commercial services, operation of air quality instruments for the benefit of the developing world could conceivably be supported by public/private partnerships including philanthropic organizations. NASA and other space agencies could partner with governments in the developing world to build native capacity for air quality monitoring and prediction featuring the operational use of these measurements.

A space-based mission to study air quality in the developing world would serve the air quality, public health, and chemistry-climate interactions communities and provide a wealth of scientific and public health-relevant information to allow us to answer the critical science questions described here. Space-based observations will foster interest in aircraft campaigns and ground-based measurements to obtain additional correlative data. While such a mission would not be focused on the US, it serves national interests by providing information that can help to improve societal and political stability around the world and can be used to quantify and help reduce the long-range transport of air pollution. With the addition of CH_4 and CO_2 measurements, it could help to identify optimal solutions for mitigating climate warming through reduction of climate forcers (see companion white paper on "Understanding the Co-Evolution of Air Quality and Climate Forcing in a Rapidly Changing World") or, when combined with ecosystem measurements, can contribute to ensuring global food security (see companion paper on "Air Quality Effects on Crop and Ecosystem Health").

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