SPARTAN: A Global Network to Evaluate and Enhance Satellite-Based Estimates of Ground-level Aerosol for Global Health Applications

Abstract. Ground-based observations have insufficient coverage at the global scale to assess long-term human exposure to fine particulate matter ($PM_{2.5}$). Satellite remote sensing offers a promising approach to provide $PM_{2.5}$ exposure information at regional-to-global scales, but there are limitations and outstanding questions about the accuracy and precision with which ground-level aerosol mass concentrations can be inferred from satellite remote sensing alone. A key source of uncertainty is the global distribution of the relationship between annual average $PM_{2.5}$ and columnar aerosol optical depth (AOD), sampled at specific overpass times during cloud-free conditions. We are developing a global network of ground-level monitoring stations designed to evaluate and enhance satellite remote sensing estimates for application in health effects research and risk assessment. This Surface PARTiculate mAtter Network (SPARTAN) includes a global federation of ground-level monitors of hourly $PM_{2.5}$ situated primarily in highly populated regions and in close proximity to existing ground-based sun photometers that measure AOD.

1. Introduction, Motivation, and Problem Definition

Advancement of knowledge on the public health impact of adverse health effects of air pollution exposure at the global scale faces a troubling irony. The regions in which air pollution levels appear to be the highest, and in which the burden of disease due to air pollution is estimated to be the greatest (Lim et al, 2012), currently have limited data on ambient levels and human exposure to health-damaging particulate air pollution (Brauer et al., 2012). Such data are the basis for scientific research and risk assessment. When combined with external constraints, satellite-based remote sensing of ground-level particulate air pollution has recently emerged as a potential major contributor to addressing this problem, but the approach requires additional validation and analysis to support its wide-spread use for health-related applications. In this prospectus we describe a global Surface PARTiculate mAtter Network (SPARTAN; www.spartan-network.org) to evaluate and improve satellite-based estimates of ground-level aerosol pollution for global health applications.

$PM_{2.5}$ is a robust indicator of mortality and other adverse health effects. Research on long-term exposure to ambient $PM_{2.5}$ has documented serious adverse health effects, including increased mortality from chronic cardiovascular and respiratory disease and lung cancer (WHO 2006). The burden of disease attributable to this exposure is estimated to be substantial. The Global Burden of Disease 2010 estimated that outdoor $PM_{2.5}$ (aerosols with a median aerodynamic diameter less than or equal to 2.5 μm) caused 3.2 million deaths (3.0% of all deaths) and 76 million years of lost healthy life on a global scale in the year 2010 (Lim et al. 2012).

Research on the health effects of air pollution can only be done when population exposure can be estimated. Long-term average concentrations of $PM_{2.5}$ have been extensively measured in North America and Europe. As a result, the epidemiologic evidence cited above comes almost exclusively from studies conducted in these locations. Elsewhere in the world, in regions thought to have the highest ground-level concentrations of $PM_{2.5}$ and the largest burdens of disease attributable to air pollution, including large parts of Asia, Africa, and the Middle East, there is little or no long-term surface monitoring of $PM_{2.5}$. As a result, research on the health effects of long-term exposure to $PM_{2.5}$ in these regions has been limited (HEI 2010), and global risk assessments, such as the Global Burden of Disease (Lim et al, 2012), have had to rely on uncertain extrapolation of North American and European results to other regions where levels of air pollution are much higher. Even in developed regions of North America and Europe large measurement gaps exist.

Despite recent increases in air pollution surface monitoring in some highly-polluted locations, the ground-level measurements of particulate air pollution are still far too sparse in terms of spatial and temporal coverage to be used directly to estimate long-term exposure, or even to supplement satellite remote-sensing. Key highly populated and highly polluted areas lack $PM_{2.5}$ measurements. Existing PM_{10} measurements (e.g. Brauer et al., 2012) and airport observations of visual range (Husar et al., 2000) only partially address measurement needs for global-scale health impact assessment and epidemiologic studies focused on spatial differences in population-average long-term exposure. Global ground-based measurements of long-term exposure to particulate air pollution will be insufficient to address the needs of epidemiologic research and public health-based risk assessment in these locales for the foreseeable future.

Figure 1 shows global satellite-derived $PM_{2.5}$ averaged for the years 2001-2006 as inferred from AOD from the MODIS and MISR satellite instrument, and coincident aerosol vertical profiles from the GEOS-Chem chemical transport model, validated with CALIPSO space-based lidar vertical profile observations (van Donkelaar et al., 2010). Enhanced $PM_{2.5}$ concentrations of more than 50 $\mu g/m^3$ are apparent over broad regions of northern Africa, South Asia, and East Asia. $PM_{2.5}$ concentrations exceed 70 $\mu g/m^3$ over major industrial regions of northern India and East China. Consistent, ground-based measurements across these broad regions are needed to evaluate the quality of satellite-based estimates such as these. Our focus is on evaluating the large-scale variation of $PM_{2.5}$. Subpixel variation is being assessed through other campaigns (e.g. DISCOVER-AQ, www.nasa.gov/discover-aq).

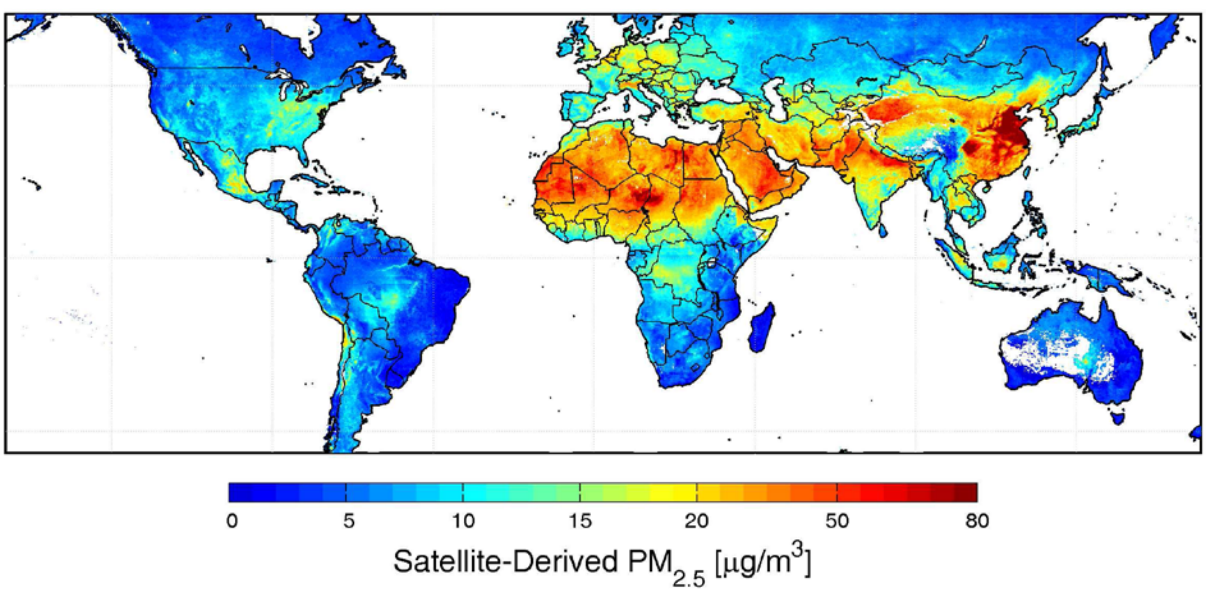

Figure 1. Global satellite-based $PM_{2.5}$ averaged over 2001-2006 (van Donkelaar et al., 2010). White space indicates water or locations containing <50 measurements.

Satellite remote sensing offers one of the most promising avenues for providing estimates of $PM_{2.5}$ exposure on a global scale, and especially for areas with limited ground-level $PM_{2.5}$ measurements. However there are outstanding questions about the accuracy and precision with which ground-level $PM_{2.5}$ mass concentrations can be inferred from satellite remote sensing (Hoff and Christopher, 2009; Paciorek and Liu, 2009). Nonetheless, satellite-based estimates have begun to be useful in both epidemiologic research and air pollution risk assessment (e.g. Crouse et al., 2012). There is a need for a network of ground-level monitoring designed specifically to evaluate and enhance satellite remote sensing estimates for application in health effects research and risk assessment. A key source of uncertainty is the relationship between satellite observations, sampled only under cloud-free conditions and at specific times-of-day, and the 24-hr annual mean $PM_{2.5}$ concentrations needed for epidemiology studies.

AERONET (aeronet.gsfc.nasa.gov; Holben et al., 1998) is a remarkably successful federation of sun photometer stations that provides global, long-term, continuous, and publicly available data, including aerosol optical depth (AOD). The AERONET network is extensively used for satellite validation, for providing temporally resolved coverage during daylight hours, and for offering 0.01 to 0.02 mid-visible AOD accuracy. Other sun photometer networks provide additional measurement locations (e.g., Kahn et al., 2004).

2. Ground-based Measurements

2.1 Instrumentation

SPARTAN is a network of ground-based instruments, targeted for measuring $PM_{2.5}$ mass concentrations and limited compositional features. Our primary focus is on $PM_{2.5}$ mass since it is the most robust indicator of mortality impacts in epidemiologic cohort studies of long-term exposure (Chen et al., 2008). PM_{10} measurements provide additional information on the particle size distribution of relevance for both aerosol optical properties and potential health effects. The cost of instrumentation and operation is an important consideration.

The SPARTAN network will include a combination of automated continuous monitoring and integrated filter samples. Continuous, optically based measurements with a nephelometer and reflectometer will monitor aerosol concentration coincident with satellite overpasses and will differentiate between measurements taken during cloudy and non-cloudy periods. As the optical (nephelometer) measurements can be affected by high relative humidity, a simple relative humidity logger is included in each measurement system. Nine-day integrated filter-based measurements of $PM_{2.5}$ and PM_{10} will be collected. They will be used to calibrate the continuous measurements and to allow for additional analysis of aerosol chemical composition. Our selected instrumentation to achieve these goals is AirPhoton Aerosol Sampling Station. This instrumentation features sealed cartridges that are robust to handling, micropore filters that allow simultaneous measurements of multiple size fractions (PM_{10} and $PM_{2.5}$), a programmable pump with the option of a duty-cycle that can avoid saturating the filter, a custom-built multi-wavelength nephelometer, and a modular design. The instruments have the capability for battery and solar power as needed.

Filters will be analyzed non-destructively for particle mass concentration of $PM_{2.5}$ and PM_{10} and particle light absorbance (a surrogate for black carbon). Subsequent destructive analysis (ion chromatography) would yield ionic species (e.g. Cl^-, NO_2^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, Ca^{2+} and Mg^{2+}) and trace metal concentrations (through inductively coupled plasma-mass spectrometry). These measurements provide the key data required to model the AOD/$PM_{2.5}$ ratio, and other information needed to assess the health effects of aerosols. Filter analysis will be performed at Dalhousie U.

2.2 Identification of Select Locations for Initial Deployment

A few key criteria influence the choice of locations for the initial measurements:

- $PM_{2.5}$ measurements are most needed in areas with high population density that do not have existing monitoring networks.
- Given the need to relate satellite AOD retrievals to $PM_{2.5}$, there would be considerable value in locating the $PM_{2.5}$ monitors in close proximity to existing ground-based sun photometers that offer high quality (level 2) measurements of AOD. Such monitor placement would yield an empirical measure of the AOD/$PM_{2.5}$ ratio and in some cases could benefit from the existing personnel and infrastructure that support the current networks.
- A third criterion is priority for locations where satellite-based $PM_{2.5}$ estimates have the highest uncertainty (taken here as the difference between the satellite-based $PM_{2.5}$ estimates and those from a GEOS-Chem simulation).
- Also of consideration is the desire for measurements that span Asia, Africa, South America, and Central America.

Figure 2 shows 20 locations that were determined from these criteria. Sites are clustered in regions with high population density and few $PM_{2.5}$ measurements. These measurement sites span a variety of regions that are not well represented by existing ground-based networks. For example, they include regions of biomass burning (e.g. West Africa, South Asia), biofuel use (e.g. South Asia), monsoonal cloud patterns (e.g. West Africa, South Asia), and mineral dust influence (e.g. North Africa, Middle East, East Asia). Sites also span a wide range of $PM_{2.5}$ concentrations from highly polluted (e.g. Beijing) to relatively clean (Kenya).

Figure 2. General priority locations of $PM_{2.5}$ monitors for initial deployment.

2.3 Partners

Partnerships are essential to the success of this project. We will explore opportunities to collocate measurements with other networks that offer additional measurement capabilities (such as LIDAR), or precise information on aerosol properties (such as Global Atmosphere Watch, or that could be used to relate these measurements to larger existing measurement programs (such as North American and European air quality networks).

Local partnership and support are critical underpinnings of this effort to monitor air quality on the ground. As alluded to earlier, human capacity and facilities are needed for air quality monitor operation, and higher-level support from government ministries and universities will determine whether such resources are available. Because the ultimate goal of this proposal is to improve research to protect public health, the monitors have dual purposes: 1) support the analysis of satellite-remote sensing air quality data, and 2) provide direct measurements for scientists and decision-makers in the cities and countries of interest to assess air pollution levels. This dual purpose means that training on air quality is a first step of SPARTAN. In light of resource limitations, training can be standardized, based on training protocols already developed, and following a train-the-trainer approach to maximize reach.

These SPARTAN measurements also offer significant co-benefits. For example, the particulate air quality measurements would be valuable to local and national air quality management agencies. More broadly, numerous studies have emphasized how the climatic effects of aerosol vary with abundance and composition. The SPARTAN in situ aerosol mass and composition measurements combined with sunphotometer measurements of AOD would yield valuable information of importance for climate research.

3. References

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