GEO Task US-09-01a: Critical Earth Observations Priorities

Health Societal Benefit Area: Air Quality

GROUP ON EARTH OBSERVATIONS

User Interface Committee

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Group on Earth Observations

GEO Task US09-01a:
Earth Observation Priorities for Health SBA- Air Quality Sub-Area

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Summary: GEO Task US09-01a

Earth Observation Priorities for Health SBA - Air Quality Sub-Area

The primary purpose of this report is to articulate the critical Earth observation (EO) priorities for the Health Societal Benefit Area (SBA), in the sub-area of Air Quality and Health (AQH). The AQH sub-area focuses on the air pollutants that have damaging effects on human health. The EO needs of the Health SBA are also addressed in companion reports on Infectious Diseases and Aeroallergens.

The Advisory Group (AG) for this EO needs assessment consisted of 11 experts from the field of Health and Air Quality or some subset thereof. The AG includes members from seven countries and five continents, including three from developing countries. Five AG members have parallel expertise in air quality as well as human health.

As recommended by Task US-09-01a, a wide range of publicly available, potentially relevant documents were examined from geographically distributed sources. Over 110 relevant documents were selected by various methods: 11 reports recommended by the AG, 56 by the Analyst, about 30 by back- tracing from other documents and over 70 documents from web searches. The search and selection was focused on websites of international, regional, and national organizations engaged in AQH. The document selection relied heavily on expert judgment.

Standard, generally applicable methodology for establishing EO requirements currently does not exist because it depends on the SBA as well as the specific purpose of the requirements analysis. Following the encouragement from the GEO Task Leader, the analytical methodology in this report used multiple independent measures, all directed toward supporting the EO prioritization of AQ observations for Health from three perspectives: (a) which pollutants should be measured; (b) what should be the spatio-temporal coverage and (c) what aspect(s) of AQ management should the EO support.

The identification of *health-relevant air pollutants* is based on (1) scientific evidence derived from health studies; (2) current standards/guidelines for ambient pollutant concentrations near the ground; (3) bibliometric analysis of the documents for the pollutant occurrence frequency; (3) the station-frequency of pollutants that are being measured. The *Observation coverage* was assessed based the compilation of the AQ monitoring sites from the available public documents. The number of sites was aggregated over global regions: Africa, Southeast Asia, Non-Southeast Asia, Europe, and North America.

There are three general user classes of EOs for AQH: General Public, Air Quality Managers, and Scientists. The information needs of the public and managers are satisfied using data products that are derived from the raw EOs. For this report, it was decided to focus on the needs and prioritization of raw EOs, rather than on derived products.

The key outcome of this analysis is a list of priority observations for AQH. The prioritization was performed along three independent dimensions: (1) Air pollutant parameter; (2) Observation coverage, and (3) Observation utility. The prioritization of (1) and (2) was based on the gap between the desired state and the current state; the larger is the gap, the higher is the stated priority.

The list of **air pollutants** that are the main causal factors in health effects was taken from the WHO Guidelines (WHO, 2005): $PM_{2.5}$, PM_{10}, O_3, NO_2, and SO_2. These were identified as Tier 1, "essential AQH variables." Among these pollutants, $PM_{2.5}$ is assigned the highest priority because of the largest gap between the findings of recent health studies and the poor state of current/past $PM_{2.5}$ monitoring data availability.

For **observation coverage** dimension, we applied the concept of monitoring intensity (i.e., the number of AQ monitoring stations per million inhabitants). The pollutant list is identified in Tier 1. North America was taken as a reference region, with about nine monitoring stations/million inhabitants. The gap was then measured by the difference in the monitoring intensity between North America and the other regions. Monitoring priorities over Africa and Asia ranked highest because of their currently low monitoring intensity of about 0.5 air quality (AQ) stations/person.

Observation utility was determined based on the reusability of specific EOs for multiple segments of the AQ system. Columnar pollutant observations (in conjunction with surface data) of the Tier 1 pollutants have been identified as Tier 2 priority observations because they have potential application for estimating emissions and transport, as well as ambient concentrations.

This meta-analysis indicates that the per capita AQ monitoring in the developing regions of the world is 10-20 times lower than in the developed North America and Western Europe. $PM_{2.5}$, the best available indicator of health-related effects, is virtually unmonitored in the developing world, and even the existing monitoring data are typically not accessible to the broader health community. Consequently, there is a need to (1) significantly extend AQ monitoring in the developing world, particularly in the large, densely populated cities; (2) more intensely monitor and manage the concentration of $PM_{2.5}$, and (3) improve the accessibility to AQ monitoring data by the broader communities in science, AQ management, and the general public.

Table of Contents

List of Tables

List of Figures

1. Introduction

This report articulates Earth observation (EO) priorities for the Air Quality Sub-Area of the Health Societal Benefit Area (SBA) based on an analysis of over 100 publicly available documents, including documents produced by Group on Earth Observations (GEO, www.earthobservations.org), member countries, and participating organizations.

1.1 Group on Earth Observations

GEO is an intergovernmental organization working to improve the availability, access, and use of EOs to benefit society. GEO is coordinating efforts to build a Global Earth Observation System of Systems (GEOSS). GEOSS builds on national, regional, and international observation systems to provide coordinated EOs from thousands of ground, airborne, and space-based instruments.

GEO is focused on enhancing the development and use of EOs in nine SBAs: Agriculture, Biodiversity, Climate, Disasters, Ecosystems, Energy, Health, Water, and Weather.

1.2 GEO Task US-09-01a

The objective of GEO Task US-09-01a is to establish and conduct a process to identify critical EO priorities within each SBA and those common to the nine SBAs. Many countries and organizations have written reports, held workshops, sponsored projects, conducted surveys, and produced documents that specify EO needs. In addition, researchers and practitioners have also identified and recommended key EO needs in publications and peer-reviewed literature. Task US-09-01a focuses on compiling information on observation parameters from a representative sampling of these existing materials and conducting analyses across the materials to determine priority observations.

1.3 Purpose of Report

The primary purpose of this report is to articulate the critical EO priorities for the Health SBA, specifically for Air Quality and Health (AQH) (i.e., air quality [AQ] as it affects human health and well-being). Additional aspects of the Health SBA EO priorities are addressed by two companion reports within GEO Task US-0901a: Infections Diseases and Aeroallergens. The intent of this report is to describe the overall process and specific methodologies used to identify and analyze documents and determine a set of EO parameters and characteristics. The report describes the prioritization methodologies used to determine the priority EOs and also provides information on key challenges faced, offers feedback on the process, and offers recommendations for process improvements.

The primary audience for this report is the GEO User Interface Committee (UIC), which is managing Task US-09-01a for GEO. The GEO UIC will use the results of this report in combination with reports from the other eight SBAs. The GEO UIC will perform a meta-analysis across all nine SBA reports to identify critical EO priorities common to many of the SBAs. Based on the nine SBA reports, the GEO UIC will produce an overall Task US-09-01a report, including the common observations and recommendations for GEO processes to determine EO priorities in the future. The report's authors anticipate that the GEO Secretariat, Committees, Member Countries, Participating Organizations, Observers, Communities of Practice, and the broader communities associated with the Health and other SBAs are additional audiences for this report.

1.4 Scope of Report

This report addresses the EO priorities for the Health SBA. In particular, it focuses on the sub-area of Air Quality within the Health SBA (see Section 3 for more details). The report contains brief background and contextual information about AQH. However, this report is not intended as a handbook or primer on AQH, and a complete description of the AQH is beyond the scope of this report. Please consult the GEO website (www.earthobservations.org) for more information about the Health SBA and its sub-areas.

The report focuses on the EOs for AQH, independent of any specific technology or collection method. Furthermore, the report addresses the "demand" side of observation needs and priorities. It does not address the specific source of the observations or the sensor technology involved with producing the observations. Similarly, any discussions of visualization tools, decision support tools, or system processing characteristics (e.g., data format, data outlet) associated with the direct use of the observations are beyond the scope of this report.

The term "Earth observation" refers to parameters and variables (e.g., physical, geophysical, chemical, biological) sensed or measured, derived parameters and products, and related parameters from model outputs. In the context of AQH, Earth observation refers to measurements or models that help characterizing the air quality and health systems, specifically emissions, source-receptor relationship, and ambient concentrations as described in section 3.1.

The term "Earth observation priorities" refers to the parameters deemed of higher significance than others for the given SBA, as determined through the methodologies described within. The report uses the terms "user needs" and "user requirements" interchangeably to refer to Earth observations that are articulated and desired by the groups and users in the cited documents. The term "requirements" is used generally in the report to reflect users' wants and needs and does not imply technical engineering specifications.

Following this introduction, the report discusses the overall approach and methodologies used in this analysis (Section 2). Section 3 describes the Air Quality and

Health SBA and the specific sub-areas. Section 4 articulates the specific EOs on Air Quality for Health and well-being. Section 5 presents the priority observations for AQH. Sections 6 and 7 present additional findings from the analysis of the documents and any recommendations. The Appendices contain a list of the documents cited in the report, another broader list of documents cited or consulted in the preparation of the report, a list of acronyms used in this report, and a summary of the input to the Cross-SBA analysis.

2. Methodology and Process

This section documents the general process followed and describes the specific methodologies used to identify documents, analyze them, determine EO parameters and characteristics, and establish a set of priority EOs for this SBA. It (1) outlines the general task process approach, (2) identifies the Analyst and the Advisory Group (AG), and (3) describes the methodologies used for this meta-analysis, which consist of (a) document selection, (b) an approach for defining and extracting AQ EO needs, and (c) analytical methods for prioritizing EOs for AQ.

2.1 Task Process

The GEO UIC established a general, but uniform, process that is to be applied by each of the SBAs. The intent is to ensure a level of consistency across the SBAs. This general process for each SBA involves nine steps, as summarized in the following list:

Step 1: Identify Analyst and Advisory Group for the SBA
Step 2: Determine scope of topics within the SBA
Step 3: Identify documents regarding observation priorities for the SBA
Step 4: Develop analytic methods and priority-setting criteria
Step 5: Review and analyze documents for priority Earth observations needs
Step 6: Combine the information and develop a preliminary report
Step 7: Gather feedback on the preliminary report
Step 8: Perform any additional analysis
Step 9: Complete the report on Earth observations for the SBA

A detailed description of the general US-09-01a process is available at the Task website, http://sbageotask.larc.nasa.gov, or the GEO website. Some steps in the process occurred simultaneously or iteratively, such as identifying documents (Step 3), reviewing documents (Step 5), and developing priority methodology (Step 4).

2.2 Analyst and Advisory Group

The Health and Air Quality group included an “Analyst” and an “Advisory Group” to conduct the process of identifying documents, analyzing them, and prioritizing the EOs. The Analyst served as the main coordinator to manage the activities.

2.2.1 Analyst

The Analyst for this Air Quality and Health EO Requirement Report was Dr. Rudolf B. Husar (lead analyst) and Dr. Stefan R. Falke (co-analyst). Dr. Husar is a professor of Energy, Environmental and Chemical Engineering and director of the Center for Air Pollution Impact and Trend Analysis (CAPITA) at Washington University in St. Louis, Missouri. Over the past 35 years Dr. Husar has conducted parallel research in air pollution (sources, transport, transformations, effects) and environmental informatics. He has served on committees of NAS and EPA's Clean Air Scientific Advisory Committee (CASAC), as well as international advisory groups, including the World Meteorological Organization (WMO) and the International Global Atmospheric Chemistry (IGAC) Project. Recently Dr. Husar's research group has actively participated in various aspects of the evolving GEOSS, including the GEOSS Common infrastructure (GCI), the Architecture Implementation Pilot (AIP), and the GEOSS Air Quality Community of Practice (CoP). Dr. Falke is a research assistant professor of Energy, Environmental and Chemical Engineering at Washington University in St. Louis and manager of Geospatial Information Services for Energy and Environment at Northrop Grumman. Dr. Falke serves as co-chair, with Dr. Husar, of the Earth Science Information Partners Federation (ESIP) Air Quality Workgroup, which fosters interaction among satellite, aerial, surface, and modeled data producers, brokers, and consumers, and that is setting the foundation for an international GEOSS Air Quality Community of Practice. He also leads the Atmospheric Science Interest Group within the Working Group on Information Systems & Services (WGISS) in the Committee on Earth Observation Satellites (CEOS) with an initial focus on interoperability guidance for using remotely sensed atmospheric composition information across multiple countries.

In performing the document collection, analysis, and preparation of this report, Dr. Husar and Dr. Falke were supported by Ph.D. student, Erin Robinson, and Dr. Janja Husar. Collectively, they are referred to as the Analyst. The Analyst prepared this report with funding from EPA, though a subcontract with Eastern Research Group, Inc., Jan Connery, Project Manager.

2.2.2 Advisory Group

The first step in the nine-step GEO Task US-09-01a process is the formation of an expert AG that helps identify appropriate documents, provides feedback on the analysis approach, and also reviews the preliminary and final reports. For AQH, 18 potential AG members were identified. The sources of AG candidate names came from the GEO UIC, recommendations from major agencies, and individuals identified by the Analyst team. Additional AG candidates were suggested by the AG members themselves. Eleven of the invited candidates responded positively, two invitations were declined, and five candidates did not respond. Effort was made to include representatives from developing nations and to achieve a representation across geographic domains.

The current AG consists of 11 experts from the field of Health and Air Quality or some subset thereof. Table 1 shows the AG members, including: Name, GEO Member

Country or Participating Organization, Organizational Affiliation, Geographic Region, and Specialty/Area of Expertise. Overall, the AG includes members from seven countries and five continents, including three from developing countries. Five AG members have parallel expertise in air quality as well as human health.

Table 1. Advisory Group Members

Name	GEO Country or Organization	Affiliation	Region	Specialty
Jeff Brook	Canada	Env. Canada	N. America	AQ
Jack Fishman	US	NASA Langley	N. America	AQ
Barry Jessiman	Canada	Health Canada	N. America	AQH
Patrick Kinney	US	Columbia University	N. America	AQH
Jim Meagher	US	NOAA	N. America	AQ
Rashmi S. Patil	India	IIT Bombay	Asia	AQH
Leonora Rojas	Mexico	National Institute of Ecology	N. America	AQH
Paulo Saldiva	Brazil	University of São Paulo	S. America	AQH
Rich Scheffe	US	EPA OAR/OAQPS	N. America	AQ
Kjetil Tørseth	Norway	Norwegian Institute of Air Research	Europe	AQ
Michael Gatari	Kenya	University of Nairobi	Africa	AQ

The primary roles of the AG were to assist in identifying documents, assess methodologies and analytic techniques, assess prioritization schemes, review findings, and review the project report. The primary forms of communication with the AG were via e-mail and through the interactive open project wiki page. This report was prepared using an interactive wiki page on the ESIP server.[1] The members of the Analyst group used the wiki to collaboratively create the content, perform the editing and share the evolving report with the AG. The open wiki approach also provided a platform for sharing the document as it evolved and for receiving feedback from the ESIP Air Quality Work Group. The wiki, being an open and "living" document, is available for future expansion or revisions, beyond the limited period of this initial GEO task (May–November 2009).

2.3 Methodology

This section is a summary of analytic methods and approaches the Analyst used to identify and analyze documents and establish a set of priority EOs.

2.3.1 Document Selection

This section provides a general description of the process, method, and approach the Analyst used to identify documents and select a representative sampling for the analysis. Task US-09-01a methodology recommended the examination of a wide range of publicly available, geographically distributed sources for potentially relevant

[1] http://wiki.esipfed.org/index.php/GEO_User_Requirements_for_Air_Quality

documents, including: international, regional, and national documents, project reports, surveys, workshop and conference summaries, and peer-reviewed journal articles.

The candidate documents were identified using several methods: documents that were known to the Analyst; documents recommended by the AG, and documents retrieved through online searches. The documents from the Analyst's prior knowledge (6) were based on decades of experience in AQ data analysis, network assessment, and decision support for AQ management. The documents provided by the AG (11) contributed a broad range of perspectives, as well as geographic coverage and contributions from developing countries. Key documents were also identified by back-tracing from other documents (about 30). The online web searches contributed most of the documents (over 70) used in this report. The search focused on websites of international, regional, and national organizations engaged in AQH. The general search also included published articles through Google Scholar using a combination of keywords, such as “air pollution,” ”health,” and ”Africa.” It is recognized that the above selection process for qualified documents relies heavily on expert judgment and is inherently subjective.

Effort was made to select documents that discuss EOs for AQH and also contain specific statements on the EO requirements. The few documents that contain complete and directly applicable information to this report were mainly consensus reports and workshop summaries. Documents that contained information on data quality were also rare. Public documents that identify specific EO priorities were most sparse, as discussed in Section 4.3.

Documents that are considered of special significance are explicitly cited in this report and also listed in Appendix B, Table B1: Documents and References Cited. The complete listing of resources consulted for the meta-analysis are listed in Appendix B, Table B2: Documents and References Consulted.

2.3.2 Analytic Methods for Gathering EO Requirements

The analytic framework for AQH user requirements is science-based, utilizing a systems approach to the analysis. The categories of observations are based on the AQ system components (see Section 3): emissions, source-receptor relationship, and ambient concentrations. The method of gathering the user requirements, as well as the prioritization, is based on this AQ system framework.

The EO requirements methodology development began with guidance provided by the Task leader, in the form of a standard table for recording EOs from the documents. These standard tables were to be used for each SBA report and were intended for cross-SBA integration of the EO needs. During the methodology development, it became evident that, for the AQ needs and priorities, additional attributes were desirable beyond those given in the general project guidance. The metadata for each publicly available document included information about the source, form, and content of the selected document.

The metadata extraction process included the following steps: (1) once a relevant document was identified, it was assigned an ID number; (2) a hard copy was printed, and (3) a table was attached to help the Analyst record the extracted information. The table included information about the document: the title, region, and document type and AQH observation category (emission, Source-Receptor-Relationship [SRR], ambient, health). It was also recorded if the document contained "needs" for the AQH categories. If the document included measured EOs, the parameters were noted, and any information about spatial/temporal coverage and resolution, accuracy, and latency was recorded. This documented information, along with an online link to the document, was stored on a separate wiki web page devoted to each document. These document-specific pages were used to deposit both structured metadata and loose annotations on each document. These metadata were contributed by several members of the AQH Analyst group. This open wiki approach allowed both the independent verification and the evolutionary changes in this meta-analysis. The resulting online catalog of all data for this meta-analysis was created.[2]

The metadata extracted from each document were also entered into a spreadsheet[3] for further analysis, which included filtering and aggregation of the records by region, pollutants, observation category, etc. A separate spreadsheet was used to analyze the metadata for the AQ monitoring station coverage.

The documents identified in Section 2.3.1 were examined three to five times. The first scan focused on the general suitability of the document for consideration in this assessment, as outlined above. During the second more careful examination, detailed data extraction was performed and recorded into the document's metadata record. It yielded factual data regarding the observations (e.g., coverage, space and time resolution, geographic region, document type). The purpose of the third scan was to seek additional EO requirements that could only be inferred from the documents. Because the metadata extraction methodology evolved during the five-month analysis period (May–November 2009), additional document scans were performed iteratively to extract missing metadata for the evolving database.

2.3.3 Methodology for Determining EO Priorities for Air Quality and Health

The adopted method for this meta-analysis uses three independent measures to prioritize EOs for AQH: (1) the health effect potency of the pollutant; (2) spatial-temporal coverage; and (3) general utility of the observation. The overall priority is obtained by combining these three measures, weighed by subjective weight factors for each independent measure.

1. Pollutant health effect. This measure ranks the pollutants by their overall toxicity at ambient concentrations. The highest priority is assigned to those air pollutants that have been shown to have the most serious effects on human health. This prioritization is based on the scientific evidence obtained from the epidemiological studies worldwide.

[2] http://wiki.esipfed.org/index.php/GEO_User_Requirements_for_Air_Quality_Documents-CandidateDocs
[3] http://wiki.esipfed.org/index.php/GEO_User_Requirements_for_Air_Quality_Documents-CandidateDocs

The specific pollutants used are those identified in the WHO Guidelines (WHO, 2005).

2. EO spatial-temporal coverage. This measure is independent of the pollutant and ranks EOs by their ability to provide spatial and temporal characterization of air pollutants. The highest ranking is given to observations that improve the pollutant characterization most (i.e., fill in the spatial-temporal data gaps where these are most needed). This aspect of EO prioritization is aimed at reducing the uncertainty in estimating population exposure of the global population (Ostro, 2004). The priority is given to EO regions where the gap between the current AQ monitoring intensity and a desired monitoring intensity is the largest, most notably over the populous developing regions of the world that have virtually no AQ observations.

3. EO utility. This measure ranks EOs by their general utility or reusability for characterizing the air pollution system. For example, if the measured pollutant is a toxic substance, the observation provides extensive coverage and is also well-suited for emission estimation; then, it is ranked higher than an observation for single use. An iterative emission-observation-exposure-modeling reconciliation system would rate highest by the EO utility criteria.

Combining these independent measures (dimensions) of EOs was a challenge. The scale used for each of these independent measures is the ranking along the respective axes. This provides a homogeneous metric for the three independent measures. The overall priority is obtained by attaching a subjective weight factor to each of the three measures and summing the weighted ranking. Observations that rank high by each measure received the highest overall ranking.

It is understood that EO prioritization is an ill-defined problem. Developing an optimal EO prioritization is only possible if all the AQH processes and parameters and their respective spatio-temporal patterns are fully understood. Because such a full understanding is not on hand, the prioritization has to follow an iterative approach: As new understanding is gained, the prioritization needs to be reassessed.

3. Air Quality and Health Sub-Area

The Health SBA aims to understand and quantify the environmental factors affecting human health and well-being. According to the GEO 10-Year Implementation Plan (GEOSS, 2005):

"Health issues with Earth observation needs include: airborne, marine, and water pollution; stratospheric ozone depletion; persistent organic pollutants; nutrition; and monitoring weather-related disease vectors. GEOSS will improve the flow of appropriate environmental data and health statistics to the health community promoting a focus on prevention and contributing to the continued improvements in human health worldwide."

AQH, the topic of this report, is a sub-area of the Health SBA. It examines the role of outdoor air quality for human health and well-being. This particular meta-analysis is to aid GEOSS in achieving its long-term goal of facilitating the flow and provision of appropriate environmental data to the health community. The EO needs of the Health SBA are also addressed in two companion reports: Infectious Diseases and Aeroallergens.

3.1 Air Quality and Health Description

For the purposes of this analysis, the AQH sub-area is described using a well-accepted, causality-based framework. The framework is shown in the simplified, systems diagram of AQ management (Figure 1). Air pollution is caused primarily by Human Activities (HA), and through a feedback-control loop, it is also mitigated by societal actions that reduce the levels of air pollution (Bachmann, 2007; Chow et al., 2007). Figure 1 defines the system components and the scope of EOs needed for the AQH sub-area.

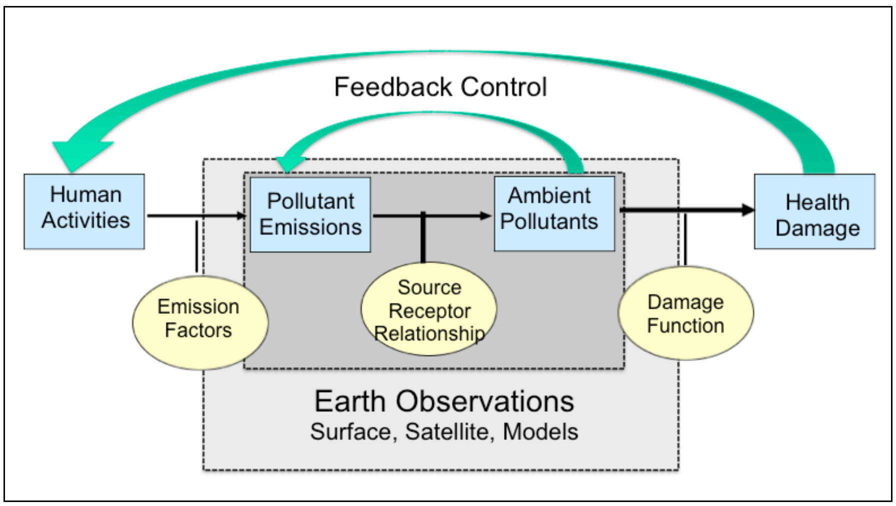

Figure 1. Framework for Categorizing Earth Observations for Air Quality and Health

In the industrial world, the overwhelming majority of air pollution *Emissions* originate from the combustion of energy-producing fossil fuels, coal, oil, and natural gas. The magnitude of the emissions is determined by the *Emission Factors (EF)* associated with human activities. The emission rates, along with the *SRR,* atmospheric dispersion, chemical transformation, and removal processes, determines the *Ambient Pollutant (AP)* concentrations. The overall global-scale *Health Damage (HD)* is the consequence of the ambient pollutant burden end exposure. Its magnitude is determined by the *Damage Function (DF)* and population density. This generalized framework is applicable to all human-induced AQ problems, regardless of the sources of the human-induced emissions and the nature of the resulting AQ damage (NARSTO, 2004; Bachmann, 2007).

Figure 1 indicates that major elements of the AQ system are quantifiable through EOs (i.e., measurements and suitably evaluated air quality models). In particular, the characterization of the ambient pollutant concentration and evaluating the SRR depends largely on EOs and the underlying atmospheric science (dark shading). The key "essential AQ variables"— ozone and $PM_{2.5}$—are secondary pollutants (i.e., most of the ambient O_3 and $PM_{2.5}$ is formed within the atmosphere through chemical reactions of their precursors). A key role of the SRR is to incorporate these chemical transformations. The SRR is generally derived from AQ models that simulate the atmospheric processes. The models themselves are developed, calibrated, and verified using EOs. Advanced AQ models are now assimilating EOs to improve their forecast performance (IGACO, 2004; USWRP, 2006). EOs can improve emission estimates and forecasting. EO-based "top-down" emission measurements are gaining increasing applicability (Dabberdt and McHenry, 2004; NARSTO, 2005).

The above systems approach yielded progress on improving air quality in many parts of the world, particularly over North America and Western Europe (NAWE). The emission reductions were motivated by scientific evidence of adverse impacts, and the progress was achieved through the implementation of science-based policies and through advances in technology (Brook et al., 2009).

The estimation of health impacts based on research conducted in NAWE is only partially applicable to developing countries. While many similarities exist regarding the constituents of air pollution around the globe, the nature of air pollution in developing regions is significantly different from those in NAWE. The human activities, emissions, and ambient concentrations are all specific to particular regions. Major cities in Asia and Africa have many diffuse, difficult-to-control sources (e.g., open burning, low-quality indoor fuels, uncontrolled small businesses and industries) (HEI, 2004; Molina and Molina, 2004). The transportation-related emissions and ambient concentrations near roadways are also region-specific. In many areas of the world, a significant fraction of the ambient pollutants originates from agricultural or domestic biomass burning, forest or savannah fires, or dust storms.

Unfortunately, the variability of AQ in the developing world is very poorly characterized. The uncertainties span all of the components of the observable AQ system: emissions, SRR, ambient concentrations, and exposure damage. Consequently, health impact estimation for the developing regions is highly uncertain (HEI, 2004; Vliet and Kinney, 2007; Cohen et. al., 2004).

In spite of these uncertainties, the World Bank has estimated the PM concentrations for all the major cities of the world (WB,1999; 1999a). WHO ventured to estimate that urban air pollution contributes each year to approximately 800,000 deaths and 4.6 million lost life-years worldwide (WHO, 2002). Particulate air pollution is consistently and independently related to the most serious effects, including lung cancer and other cardiopulmonary mortality. This amounts to about 0.8 million (1.2%) premature deaths and 6.4 million (0.5%) years of life lost. This burden occurs predominantly in developing countries; 65% in Asia alone. (Cohen et.al., 2005)

3.2 Air Quality Sub-areas

AQ itself is a sub-area of the Health SBA. For this analysis, AQ is divided into three sub-areas of the AQ system that are relevant to the prioritization of AQ EOs: (1) air pollutant parameters that are damaging to health, (2) the extent of observation coverage, and (3) observation utility.

3.2.1 Air Pollutants Parameters

The first sub-area identifies air pollutants that are considered most harmful to human health. There is firm and accumulating scientific evidence that trace concentrations of pollutant gases and particles in the ambient air affects human health (e.g. Cohen et. al., 2004). The health effects range from mild eye irritation to death. A key outcome of the air pollution health research is the identification of the key pollutants and their respective effects on human mortality and morbidity. The needs for this sub-area are determined from the available air pollution-health research, based largely on epidemiological studies that relate pollutant levels to human morbidity and mortality.

3.2.2 Air Quality Observation Coverage

The second sub-area addresses observation coverage as part of the characterization of the AQ system. AQ characterization includes documenting the spatio-temporal distribution of the ambient air pollution. Most air quality observations for health are obtained from surface-based monitoring stations. The observation coverage influences the certainty at which the pollutant concentrations can be estimated. High spatio-temporal coverage of health-related pollutant concentration reduces the uncertainty of health effect estimates.

The observation needs for this sub-area are assessed based on the regional availability of AQ observations. Ideally, the EOs should cover all areas of the world at high resolution. We selected a more practical measure. The need for EOs is measured by the gap between the current observation coverage in the developing regions and the coverage that exists over the most intensely monitored North America.

3.2.3 Air Quality Observation Utility

The third sub-area is observation utility. Observations that have application in multiple segments of the AQ system have higher utility. For instance, satellite observations have potential application for estimating emissions, SRR, and ambient concentrations (Fowler et al., 2008). EO utility is evaluated based on expert judgment.

3.2.4 Strategic Approach to Earth Observations on Air Quality and Health

The multiplicity and diversity of EOs needed for AQH requires a strategic approach to the development of effective AQH EOs. The goal of such a strategy is to satisfy the information needs for each of the system components shown in the schematic framework (see Figure 1). First, EOs are required to estimate the population exposure to harmful pollutants. This requires ambient concentration data near the surface and in geographic regions where most of the population resides. Because health damage is the result of the combined effect of multiple pollutants, the strategy needs to guide the proper allocation of multi-pollutant observations (Brook et al., 2009) while also assuring spatial-temporal coverage. Furthermore, the EO strategy needs to support the quantification of air pollutant transport and source-receptor relationship, as well as emission estimation and verification. For this purpose, observations are required that characterize the pollutant concentration pattern throughout the atmosphere. The characterization also needs to include the chemical precursors of secondary pollutants such as O_3 and $PM_{2.5}$. Comprehensive strategies for air quality monitoring are now being developed and implemented for North America (Scheffee,et al., 2009) and for Europe (EMEP, 2003). However, comprehensive monitoring strategies for the developing world are not yet available.

3.3 Document Classification

Over a hundred documents were consulted for this meta-analysis, originating from different regions of the world. Given the strong regional variation of both air pollution and population, the Analysts chose the following regions for analysis: Africa, Southeast Asia, Non-Southeast Asia, Europe, and North America. Southeast Asia includes the fast-developing and populous countries of India, Indonesia, China and Japan. Australia and South America were omitted from this meta-analysis due insufficient document sample size. Documents prepared for international organizations and covering multiple regions are assigned to the region “International”.

Table 2 shows the geographic origin of all documents analyzed and the documents used to identify the number of monitoring stations. The gray columns to the right indicate the number of total documents for each region and the number of station documents by region. The large number of consulted documents in Asia and Africa is due to the numerous documents used for the monitoring station analysis. The international reports represent mostly consensus reports.

Table 2. Document Source by Region*

	References		**Number of Documents**	
Region	**All**	**Station**	**Total**	**Station**
Africa	*1,15,23,25,31,32,52,53,54,55,56,57,58,64,67, 68,69,70,109*	*52,53,54,55,56,57,58, 64,68,69,109*	**18**	**11**
Non-Southeast Asia	*65,71,72,73,90,91*	*71,72,73,91*	**6**	**4**
Southeast Asia	*19,20,29,39,41,50,51,74, 75,76,77, 78,79,80,81,82,83,84,86, 87,88,89, 92,93,97,110*	*19,74,75,76,77,79,23,81, 82,83,84,86,87,89,92,110*	**25**	**16**
Europe	*3,4,6,9,35,37,60,61,62,63,94*	*94*	**11**	**1**

International	*2,10,11,13,14,16,17,18,21,33,34, 45,46,47,59,98,99,103,105,106,107*		**21**	
North America	*7,8,12,22,26,27,28,36,38,40, 42,43,44,95,96,100,101, 102,104*	*26*	**19**	**1**

* The italicized numbers in each row represent the document ID used in Appendix B.2: Documents and References Consulted.

3.4 Uses and Users of Earth Observations for Air Quality and Health

There are three general uses and corresponding user classes of EOs for AQH.

General Public. The general public is the broadest group of users of AQ observations. The public may be interested in AQ forecasts for planning daily activities, alerts, and action steps during air pollution events, and for learning about the general causes and patterns of AQ in their neighborhoods.

Air Quality Managers. They are responsible for the maintenance of healthy air quality by setting AQ standards, monitoring the air quality, and if necessary, initiating control actions. AQ policymakers provide general management guidance.

Scientists. They perform the research on atmospheric processes, including emissions, transport, chemical transformation, and removal processes on local, regional, and global scales (HTAP, 2007). They develop and evaluate chemical transport models that are used for forecasting and for evolution of control strategies and policies. Most importantly, epidemiological science establishes the relationship between AQ and human health effects.

The information needs of the public and managers are satisfied using derived data and information products rather than raw EOs (CDC, 2008). For instance, in providing EO to the public, multiple pollutant concentrations are combined into a derived Air Pollution Index. These information products can be derived from the raw observations using well-defined numerical or statistical procedures. Scientific users tend to require raw observations to develop and document the required scientific understanding. For assessing EO priorities it was decided to focus on the needs and prioritization of raw EOs, rather than derived products.

4. Earth Observations for Air Quality and Health

This section contains the results from the meta-analysis of the publicly available documents. The results are presented in the sections that are relevant to EO prioritization: AQ parameters, EO coverage, and EO utility.

4.1 Earth Observations by Parameter

The relevant AQ parameters may be assessed from multiple perspectives:

1. Observations identified as needed by best available health science
2. Observations required by ambient AQ Standards and Guidelines
3. Pollutant measured or estimated by current observing systems
4. AQ observations reported in the public documents

The essence of this sub-section is to demonstrate the significant gap between (1) observations required by the criteria of health science and (4) observations available through public documents or databases.

4.1.1 Air Pollutant by Severity of Health Effects

Health research has consistently and independently identified particulate air pollution, specifically $PM_{2.5}$, as the cause of the most serious health effects, including lung cancer and other cardiopulmonary mortality (Cohen, et.al., 2005). The WHO air quality guidelines (WHO, 2005) also name fine particles ($PM_{2.5}$) as one of the most dangerous pollutants for human health. Of the gaseous pollutants, sulfur dioxide and nitrogen dioxide were found to be causal factors in human health effects (HEI, 2004).

4.1.2 Air Pollutants required by Standards

The air quality parameters of highest significance to human health are encoded in the WHO Air Quality Guidelines (WHO, 2005). Table 3 identifies $PM_{2.5}$, PM_{10}, O_3, NO_2, and SO_2 as specific pollutants and indicates the maximum allowable concentration, averaging time, and the appropriate statistical measure. WHO recommends that these maximum values are not to be exceeded anywhere in order to significantly reduce the adverse health effects. The European Union directive (EC, 2008) follows the WHO 2005 Guidelines. In the United States, Canada, and other countries, the allowable levels of these pollutants are encoded in enforceable ambient air quality standards. While the specific threshold values and statistical measures may vary somewhat by country, the general level and form of these AQ standards are similar to the WHO Guidelines. For this report, WHO Guidelines are adopted as the document representing the EO needs for AQ parameters.

Table 3. WHO Guidelines for Maximum Allowable Air Pollutant Concentrations (WHO, 2005).

Pollutant	Averaging time	AQG value
Particulate matter		
$PM_{2.5}$	1 year 24 hour (99[th] percentile)	10 μg/m^3 25 μg/m^3
PM_{10}	1 year 24 hour (99[th] percentile)	20 μg/m^3 50 μg/m^3
Ozone, O_3	8 hour, daily maximum	100 μg/m^3
Nitrogen dioxide, NO_2	1 year 1 hour	40 μg/m^3 200 μg/m^3
Sulfur dioxide, SO_2	24 hour 10 minute	20 μg/m^3 500 μg/m^3

4.1.3 Air Pollutants by Bibliometric Analysis

In order to assess the attention given to individual air pollutants, the documents were examined for particular AQ parameters. The rationale for this tabulation is that pollutants for which observations are more important would be reported more frequently in the consulted documents. The resulting bibliometric analysis of the consulted documents is given in Table 4. For each pollutant, the italicized numbers are the references consulted (Appendix B.2). The far right column in Table 4 indicates the number of documents that measured a given pollutant. As indicated for Table 2, the large number of documents for Asia and Africa is due to the documents used primarily for the monitoring station analysis.

Table 4. Documents With EO Measurements by Pollutant*

	Africa	Non-Southeast Asia	Southeast Asia	Europe	International	N. America	Number of Docs
SO_2	*32,52,53,56, 57,58,64,68, 69*	*65,73,90,91*	*19,39,50,51, 74,75,76,77, 78,79,80,81, 83,84,86,88, 89,92*	*4,6,60,61, 94*	*18*	*8,22,26,27, 28,43 ,95*	44
NO_2	*32,52,53,56, 58,64,68*	*65,71,90*	*19,39,50,51, 74,75,76,77, 78,79,80,81, 84,86,88*	*4,6,60,61, 94*	*18*	*8,22,26,27, 28,43,95*	38
NOx	*32,58,69*	*73,91*	*19,39,75,83, 89,92*	*6,60,61,94*	*18*	*27*	17
CO	*15,32,52,58, 64,68,69*	*65,71,73,90, 91*	*19,39,50,74, 75,76,77,79,*	*6,60,61,94*	*18*	*8,26,27,43, 95*	37

			80,81,83,84, 88,89,92				
O_3	*15,32,52,58, 64*	*71,73,90,91*	*19,39,74,75, 76,77,78,79, 80,81,83,84, 89*	*6,60,61,94*	*13,18*	*8,12,22,26, 27,28,43*	35
VOC	*15,32,52,58, 69*	*73,91*		*6,60,61,94*			11
PM10	*32,52,56,64*	*71,73,90,91*	*19,50,51,75, 76,77,78,79, 80,89,93*	*4,6,60,61, 94*	*13,17,18*	*8,22,26,27, 44*	32
PM2.5	*56*	*73,91*	*80*	*4,6,60,61, 94*	*14,17,18*	*8,12,26,27, 28,44*	18
Lead	*64*	*72*	*19,39,75,80, 83*	*37,94*		*26*	10
Aer. Carbo n	*68*		*83*	*4*	*14*	*26*	5
TSP	*53,57*	*65*	*39,74,75,77, 80,81,82,83, 84,86,88,92, 93*				16
AOD				*61*		*26,44*	3
HNO3				*6*		*27*	2
POPs				*6,62,94*			3
HCHO						*43*	1
AQI				*61*			1
Weath er		*91*	*84*			*12*	3

* The italicized numbers in each row represent the document ID used in Appendix B.2: Documents and References Consulted.

Figure 2 shows the key results of Table 4. The six pollutant parameters to the left (blue) are gaseous pollutants while the next six parameters (red, yellow) are different measures of particulate air pollution. The remaining parameters to the right (green, light blue) fall in the miscellaneous category. The most frequently reported pollutants were SO_2, NO_2, CO, O_3, and PM_{10}. This is expected, as each has been implicated in health effects and also identified in National Air Quality Standards and WHO AQ Guidelines.

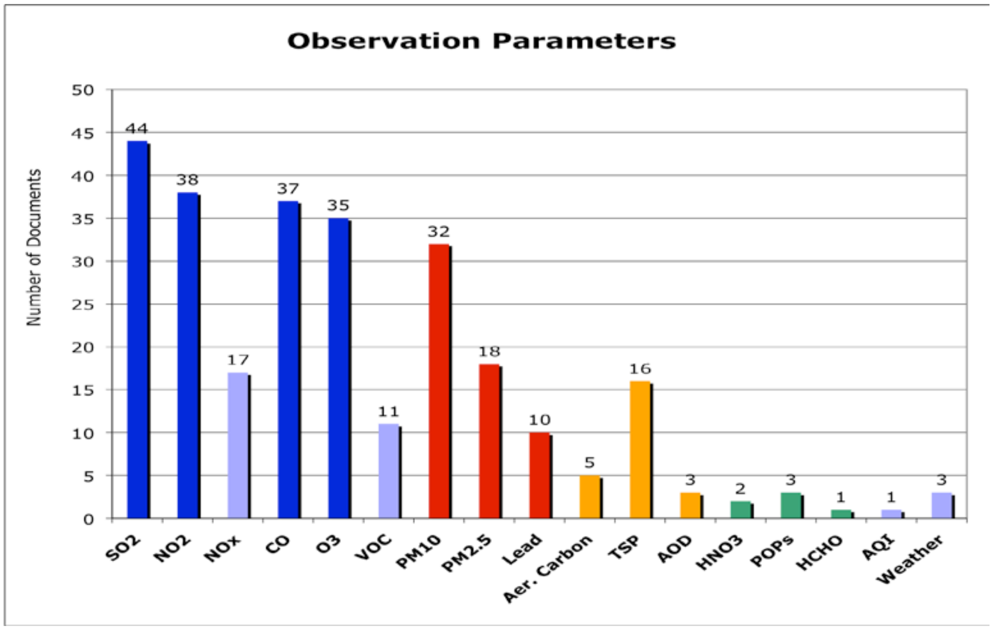

Figure 2. Bibliometric Frequency of Air Pollutants Observations

PM_{10} is the mass concentration for aerosol particles below 10 micrometers, while $PM_{2.5}$ is the particle mass below 2.5 microns. Each of the discussed pollutants has been identified through epidemiological studies as causal factors in human morbidity or mortality.

The top list of the six referenced pollutants: SO_2, NO_2, O_3, CO, PM_{10}, $PM_{2.5}$ constitute the short list of 'essential air quality variables'. These are analogous to the "essential climate variables" identified in the report on EO priorities for Climate. The intense attention to this list can be explained by the fact that these pollutants are societally regulated by environmental laws in many countries of the world (i.e., the emissions and/or the ambient concentrations are subject to enforceable and mandatory standards).

Nitrogen oxides (NO_x=NO+NO_2) and Volatile Organic Compounds (VOCs) are both precursors of ozone, which is formed in the atmosphere through photochemical reactions of NO_x and VOCs. The observation of these compounds is necessary for understanding behavior and controlling the sources of tropospheric ozone.

Lead (Pb), a toxic substance, is referred to less frequently, presumably because the main source of ambient Pb (i.e., automotive gasoline) is being phased out worldwide. The next three observed AQ parameters are Aerosol Optical Depth (AOD), Carbonaceous Aerosols, and Total Suspended Particles (TSP). These are different measures of aerosols that are useful for the understanding of aerosol sources, transport, and vertical aerosol burden, or may serve as surrogates for PM_{10} or $PM_{2.5}$. Nitric acid (HNO_3) is a reaction product of NO_x and formaldehyde (HCHO) and is an indicator of natural organic emissions. Persistent Organic Pollutants (POPs) are long-lived toxic substances arising primarily from pesticide use. The air quality index (AQI) is a derived variable from the combination of the essential air quality variables. Weather parameters (temperature, humidity, precipitation, visibility) are observed along with the pollutants. There are numerous other gaseous and aerosol composition parameters that are useful for research or specialized applications. For the source apportionment and for health effect research, highly speciated aerosol measurements are used.

4.1.4 Air Pollutants by Monitoring Stations

This analysis presents the number of monitoring sites that are reported for each air pollutant. Table 5 shows the number of monitoring stations over NAWE and the developing countries separately in order to indicate the difference.

Table 5. References and Number of Stations for NAWE and Developing Countries

	References		Number of Stations	
	NAWE	**Dev_World**	**NAWE**	**Dev_World**
SO_2	*94,26*	*52,53,56,57,58,64,68,69,73,91,19,74,75,76,77,79,23,81, 83,84,86,89,92,*	5634	3380
NO_2	*94,26*	*52,53,56,58, 64,68,71,19,74,75,76,77,79,23,81,84,86*	6120	3483
NO_x	*94*	*58,69,73,91,19,75,23,83,89,92*	5200	904
CO	*94,26*	*52,58,64,68,69,71,73,91,19,74,75,76,77,79,23,81,83,84, 89,92*	4596	1976
O_3	*94,26*	*52,58,64,71,73,91,19,7475,76,77,79,23,81,83,84,89*	5398	2672
VOC	*94*	*52,58,69,73,91,23*	1210	382
PM_{10}	*94,26*	*52,56,64,71,73,91,19,75,76,77,79,23,89*	5653	1402
$PM_{2.5}$	*94,26*	*56,73,91,23*	4100	101
TSP	*26*	*53,57,74,75,77,23,81,82,83,84,86,92*	111	3272
Pb	*94,26*	*64,72,19,75,23,83*	3731	612

* The italicized numbers in each row represent the document ID used in Appendix B.2: Documents and References Consulted.

Figure 3 graphically presents the number of stations measuring pollutants for NAWE and the developing world. Note that almost all $PM_{2.5}$ monitoring occurs in NAWE. Also note that the developing world still conducts significant monitoring for TSP, while NAWE do not. This is indicative of the time lag in switching from the older TSP measurement to the more health-related $PM_{2.5}$ and PM_{10} measurements, which were introduced over time in the late 1990s.

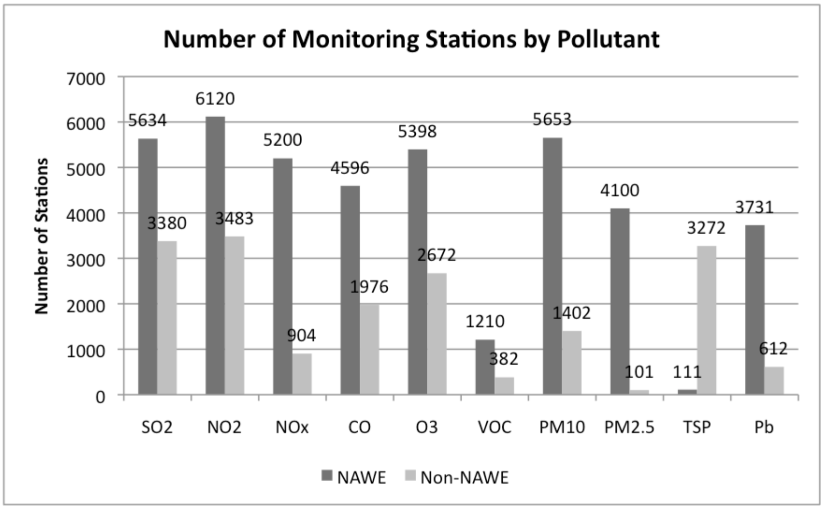

Figure 3. Monitoring by Parameter for Developing and NAWE Countries

4.2 Earth Observations by Coverage

This section describes the results of the global ambient AQ monitoring coverage as compiled from the available public documents. The description includes the main sources used and comments on the regional characteristics. The number of sites is aggregated over the six global regions.[4] The specific documents used in this monitoring coverage analysis are listed in Table 6 along with the monitoring stations by region.

Table 6. References for Number of Stations and Number of Stations for Each Region

Region	Reference	Number of Stations
Africa	*52,53,54,55,56,57,58,64,68,69,109*	419
Asia, Southeast	*71,72,73,91*	3407
Non-Southeast Asia	*19,65,74,75,76,77,79,23,81,82,83,84,86,87,89,92,110*	191
Europe	*94*	3418
N. America	*26*	3904

* The italic numbers in each row represents the document ID used in Appendix B.2 Documents and References Consulted.

For North America, the Survey on AQ Monitoring by the Committee on Environmental and Natural Resources Research and the Air Quality Research Subcommittee (CENR, 2009) was used to estimate the number of stations for Canada, Mexico, and the United States. This recent survey also contained extensive information on other aspects on

[4] South America and Australia are not covered due to the paucity of data and insufficient time for this report.

the status of the North American AQ monitoring, including measured parameters, lead agency, and year the monitoring began. For North America, a total of 3,904 monitoring sites were reported, mostly operated by environmental agencies in the United States (3,485), Canada (308), and Mexico (111).

The European Monitoring Exchange Network (AirBase, 2007; Mol et al., 2007) reports the number of monitoring stations for each pollutant parameter for 33 countries in Europe including 27 EU member countries. The breakdown for each pollutant also classifies station type for each pollutant measured (i.e., traffic, urban background). For countries of the former Soviet Union, which include the Russian Federation, the ambient monitoring information was obtained from the reports of a WHO Workshop (WHO, 2003). For Europe, there are 3,418 reported stations, operated mostly by the environmental agencies mostly in Western Europe. Russia (681), Italy (549), France (521), and Germany (467) contributed 65% of the European Stations.

For Africa, the Air Pollution Information Network for Africa (APINA, 2009) fact sheets for individual countries contained the information on the number of monitoring sites in the countries: South Africa, Mozambique, Zambia, Malawi, Botswana, and Zimbabwe. For Egypt, the environmental ministry website contained detailed information on monitoring sites. For Tunisia, Morocco, and Tanzania, the station data were obtained from environmental organization websites. For the remaining African countries, no monitoring information was found. The total number of reported/found stations in Africa is 419, virtually all in four countries: South Africa (266), Mozambique (53), Egypt (42), and Botswana (17).

For the populous Southeast Asia, a unified catalog of monitoring station information was not found. However, the Clean Air Initiative (CAI-Asia, 2009) website provided links to the websites of environmental ministries and departments that contained such information. A total of 3,407 monitoring stations were identified in the 14 countries of Southeast Asia, stretching from India to Japan/Philippines. A surprisingly high number of the stations are reported for Japan (1,910). China (559), India (290), and South Korea (271) are all further key contributors the AQ monitoring in Southeast Asia.

For the remaining, less populous Non-Southeast Asia (Asia NSE), the meager station count data was obtained from two sources. The stations count for Afghanistan, Iran, Jordan, and Iraq was obtained from (CAI-Asia, 2009) or through Google searches.

Below are several comments and concerns regarding the monitoring station coverage data. The number of stations reported here are those extracted from the publicly available documents or other meta-analyses. An independent verification of these numbers was not possible, but the Analyst speculates that the given numbers are too high. Also, the majority of the monitoring systems reported for Africa and Asia have been installed since about 2005.

Having monitoring sites (announced or operated) by a national agency does not mean that monitoring data are publicly available. In fact, there is very little evidence that the

AQ monitoring data from the developing countries are accessible to the global public health community. A review of the literature shows that only a small fraction of the potentially useful monitoring data is publicly accessible. A recent meta-analysis by HEI (HEI, 2004) reinforces this poor data availability. The study shows that in developing countries of Asia, there were 138 health studies conducted, 44 studies in China alone. In order to perform the health effect studies, air pollutant measurements were necessary along with the health indicators. Frequently, the AQ monitors were set up and operated for short periods of time. However, these monitoring data are not available for verification or reuse (Vliet and Kinney, 2007; UN, 2001).

Monitoring data for PM_{10}/TSP are available for only 304 cities of the world. Of these, 268 (88%) are located in NAWE where only 20% of the global population resides. The bulk of the global population (80%) has only has data for 36 cities (Cohen et. al., 2004). This indicates a disparity of a factor of 30 in the per person data availability between the developed and developing counties. The paucity of the accessible AQ data in the non-NAWE world reinforces the need for clearly separating AQ monitoring and data availability statistics.

A summary of the regional station coverage data is shown in Figure 4. For each region, the bar height depicts the number of monitoring sites per person. The highest station coverage is in NAWE, averaging respectively about nine and five stations per million persons for North America and Europe, respectively. On the other extreme, Africa and Non-Southeast Asia average about 0.5 stations per million persons. Southeast Asia has about 1 station for each million persons, but if one excludes the 2,000 stations in Japan, the remainder of Southeast Asia is again at about 0.5 stations/million persons. This analysis provides quantification of the needs/requirement for AQ monitoring over the developing regions, particularly in areas of high population density. In particular, it highlights the factor of 10-20 disparity in regional monitoring between the developed and developing regions.

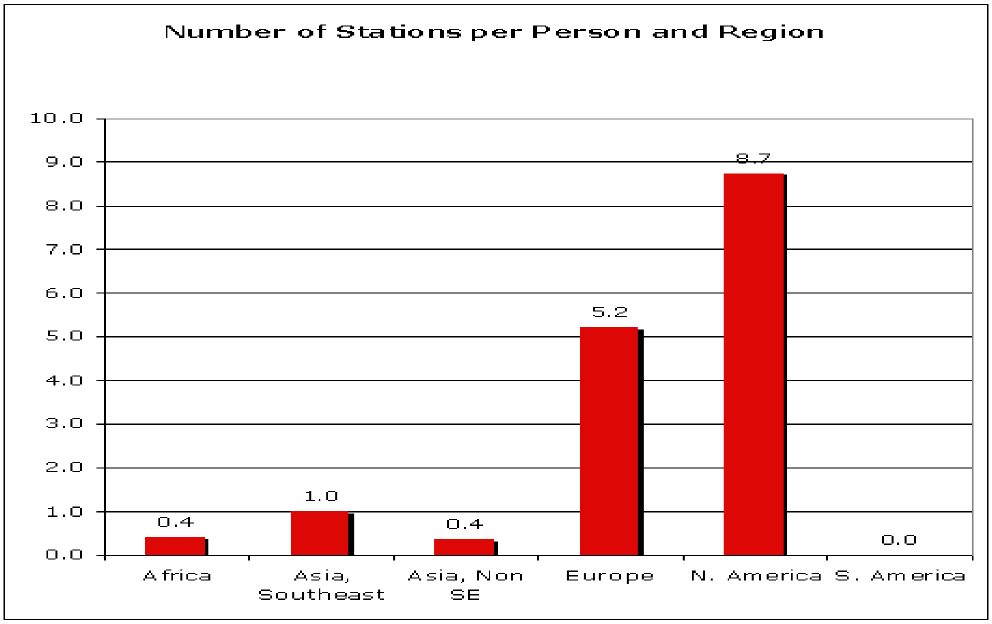

Figure 4. Number of Stations per Million People for Each Region

4.2.1 Vertical Column and Profile Observations

Surface observations are necessary to estimate the population exposure to air pollutants. However, surface observations characterize only a small fraction, a thin horizontal slice of the AQ system. Although breathing zone monitoring is a rich data source, most pollutant mass resides beyond the reach of surface stations. Since virtually all the atmospheric processes are taking place aloft, vertical column and profile observations are key to a complete characterization of the AQ system for the purposes of AQ management and protection of public health (Edwards et al., 2006; EC/ESA, 2006; Fishman et al., 2008) .

Column observations from remote sensors have the potential to cover broad spatial areas, in fact, global coverage at relatively high spatial resolution. Collectively, the remote sensing techniques exists for measuring columns and/or profiles of aerosols (AOD), O_3, CO, CO_2, CH_4, SO_2, nitrogen oxides, CFCs, other pollutants, and atmospheric parameters such as temperature and H_2O.

Remotely sensed, interpreted, columnar observations can complement existing surface networks and support the air quality assessment processes in multiple ways: (CENR, 2009)

1. Providing direct observational evidence of regional and long-range transport
2. Emission inventory improvements through inverse modeling,
3. Evaluation of Air Quality Models,
4. Tracking emission trends (accountability)
5. Complementing surface networks through filling of spatial gaps.

Columnar observations from remote-sensing satellites can be used to determine the spatial and temporal pattern of pollutants. These observations can provide global-scale data in an internally consistent manner in time (i.e., across days, weeks, or months) and space (globally at high spatial resolution). Such consistency could provide significant improvement of chronic exposure across large regions and among different countries. (Craig et al., 2008). However, a better understanding of spatial, temporal, and measurement limitations is necessary to determine how these column observations can complement ground-based networks in support of AQH needs (Hoff et. al, 2009; Hidy et. al, 2009).

4.3 Earth Observations by Process Category

The content of the documents was classified by the AQH process that the document addressed (Table 7). Documents dealing with EOs for purposes of supporting emissions are labeled, or tagged, “Emission.” Similarly, documents dealing with SRR are tagged “SRR,” and those addressing observations on health and ambient air quality were tagged “Health.” Given the rich bibliographic resource, it was possible to provide bibliometric analyses of the frequency at which specific pollutants have been reported.

The observation categories are Emissions, Source-Receptor Relationship, Ambient Concentrations, and Health, as defined in Section 3.1 Table 7 lists the documents consulted for each observation category. Table 8 lists those documents that contain explicit or implicit information about observation needs. At the bottom of both tables, the total number of documents for each observation category is given.

Table 7. Documents by Observation Category and Region*

	References			
	Emission	**Source-Receptor**	**Ambient**	**Health**
Africa	*23*	*23*	*15,23,52,64,67,68,69,109*	
Asia Non SE			*65,71,72,73,90,91*	
Asia Southeast	*19*		*19,50,51,74,75,76,77,78,79,80,81,82,83,84,86,88,89,92,93,110*	*41,51*
Europe	*6*	*6*	*6,60,61,62,94*	
International			*13,14,18*	*13,14*
N. America	*43,44,95*	*43*	*8,22,26,27,28,43,44*	*8,22,28*
Number of Documents	**6**	**3**	**49**	**7**

* The italicized numbers in each row represent the document ID used in Appendix B.2: Documents and References Consulted.

Table 8. Needs by Region Emission Transport Ambient Health*

	References			
	Emission	**Source-Receptor**	**Ambient**	**Health**
Africa		*15*	*1,25,31,52,53,56,57,70*	*25*
Asia Non SE			*72,73*	
Asia Southeast	*20*	*19,20,74,84,86,87, 88,89*	*20,29,39,41,50,74,82,86,87, 88,92,93*	*20,29,41,84*
Europe	*9,62,94*	*6,9,60,61,62,94*	*3,4,6,9,35,37,60,61,62,63*	*3,4,9,35*
International	*10,11,17,18,34,45,59*	*11,13,17,18,34,45,59*	*2,10,11,14,17,18,33, 34,45,59*	*2,10,11,14,33,34,59*
N. America	*7,26,36,38,40,95*	*7,26,38,40,42,95*	*7,8,12,26,36,38,40,42*	*7,8,12,26,36*
Number of Documents	**18**	**28**	**50**	**21**

* The italicized numbers in each row represent the document ID used in Appendix B.2: Documents and References Consulted.

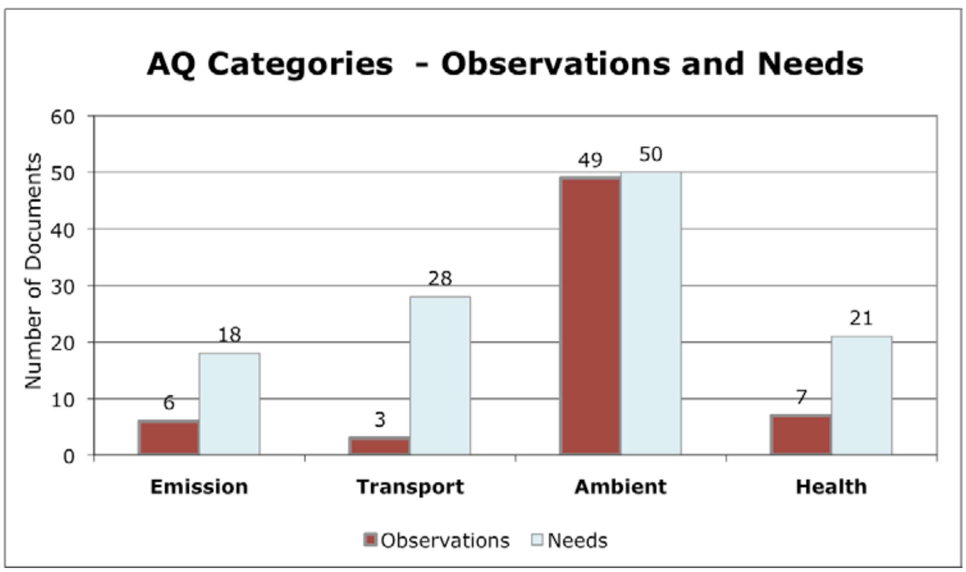

Figure 5. AQ Observation and Needs by Category

Figure 5 indicates that the majority of the consulted documents contain information on ambient observations or observation needs. Documents addressing emissions, SRR, and AQ health were less frequented. In all process categories, the documents expressing observation needs exceeded those that reported actual AQ observations.

5. Priority Earth Observations for Air Quality and Health

The primary purpose of this section is to prioritize the critical EOs for AQH. Priority observations for AQH are summarized in Table 9. The use of this standardized table was recommended for each SBA report. However, the method of prioritization was left to the discretion of the Analysts and the AG.

5.1 General Description

Observations for AQH are prioritized using three independent dimensions: (1) air pollutant parameter; (2) observation coverage and (3) observation utility. The method used for the prioritization of (1) and (2) was gap analysis. The gap is determined based on the difference between the desired state and the current state. The larger the gap, the higher the priority. The meta-analysis presented in section 4 is aimed to support the prioritization given below. The EO priorities along the third dimension, EO utility, were determined subjectively.

The first prioritization dimension is by air pollution parameter. The list of air pollutants is composed of those atmospheric constituents that represent the main causal factors in health effects. This list is taken from the WHO Guidelines (WHO, 2005). The current state of observations is obtained from the survey of global air pollutant monitoring, shown in Table 5 and Figure 3. Both the health research and the WHO Guidelines highlight $PM_{2.5}$ as the main causal factor in health effects. On the other hand, the current observations are strongly skewed toward SO_2 and other gaseous pollutants. The gap is in the relative attention and importance given to past monitoring priorities compared to the needs highlighted by more recent developments. Because of this gap, observations of $PM_{2.5}$ are given the higher priority than any other air pollutant. $PM_{2.5}$ constitutes a Tier 1. pollutant. The remaining Tier 1. pollutants in Table 9 are those listed in the WHO Guidelines.

The second prioritization dimension is by observation coverage. The desired state of observation coverage is hard to quantify. However, the current state of AQ monitoring over North America offers a reference for comparison with other less monitored regions. Figure 4 and Table 6 show that monitoring in North America involves about nine stations per million people compared to about 0.5 stations per million people for the developing areas. The gap can be measured by the difference in the monitoring intensity between North America and the developing regions. In fact, the monitoring intensity in North America is about 20 times higher than that in the developing world. Based on the above criteria, in Table 9, the highest priority is given for the monitoring coverage over Africa and Asia.

The third prioritization dimension is by observation utility. Observations that can be used to characterize multiple components of the air pollution system are given higher priority. Column concentration measurements, when properly combined with surface observations, can contribute to ambient concentration measurements for areas that are not covered with surface monitors. Column concentration measurements can also be used to estimate pollutant emissions. In the presence of surface-based and column measurements, the column observation may help with crude estimation of pollutant elevation.

The observation prioritization by coverage and utility defines Tier 2 observations, which represent the column observations of the parameters listed in Tier 1. Tier 2. EOs contribute to multiple aspects of air pollutant characterization.

5.2 Priority Observations

The priority observations listed in Table 9 constitute the key outcomes of this meta-analysis. The priority observations are grouped into three tiers. Tier 1 observations are surface measurements for five "essential AQH variables" over the areas of high population density in Asia and Africa. These EOs have the highest ranking in both health and coverage dimensions of EO needs. Tier 2 observations include the column concentration EOs of the essential AQ variables. Tier 2. EOs need to have global coverage. Columnar EOs are required for the verification of emissions and SRR, and also support the improved spatial-temporal coverage.

Tier 3 observations constitue a mixture of EOs that are vital for different aspects of the AQH system. Population density is required to estimate the total health impact on humans. VOCs are precursors of ozone and are required to estimate the ozone production in the atmosphere. $PM_{2.5}$ composition reveals the multiple source types that contribute to the $PM_{2.5}$ mass concentration. Both VOCs and $PM_{2.5}$ composition EOs support the quantification of the SRR, and they are aggregate variables that include multiple pollutants. This signifies that the AQH sub-area explicitly focuses on human health and welfare.

Table 9. Priority Observations

GEO Task US-09-01a: Priority Earth Observations for Air Quality and Health Sub-Area							
			Aggregated Characteristics of Priority Observation Parameters				
Observation Category	**Parameter**	**Spatial Priority**	**Spatial Resolution**	**Temporal Resolution**	**Accuracy**	**Latency**	**Other**
Tier 1							
Ambient	$PM_{2.5}$	Africa, Asia	1 km city 10 km rural	1-hr	10-20%	Obs:1hr For Record: 1-3 days	
Ambient	SO_2	Africa, Asia	1 km city 10 km rural	1-hr	10-20%	1-3 hours	
Ambient	NO_2	Africa, Asia	1 km city 10 km rural	1-hr	10-20%	1-3 hours	
Ambient	O_3	Africa, Asia	1 km city 10 km rural	1-hr	10-20%	1-3 hours	
Ambient	PM_{10}	Africa, Asia	1 km city 10 km rural	1-hr	10-20%	1-3 hours	
Tier 2							
Ambient, Emissions, SRR	Column $PM_{2.5}$	Global	1-10 km	1-hr	20%	1-3 hours	
Ambient, Emissions, SRR	Column SO_2	Global	1-10 km	1-hr	20%	1-3 hours	
Ambient, Emissions, SRR	Column NO_2	Global	1-10 km	1-hr	20%	1-3 hours	
Ambient, Emissions, SRR	Column O_3	Global	1-10 km	1-hr	20%	1-3 hours	
Ambient	PM_{10}	Global	1-10 km	1-hr	10-20%	1-3 hours	
Tier 3							
Exposure	Population	Global	1 km city 10 km rural	1 year	20%		
Ambient, Emissions, SRR	$PM_{2.5}$ Composition	Global	1-10 km	1-hr to 1-day	10-20%	1-3 weeks	
Emission, SRR	VOCs	Global	1-10 km	1-hr	10-20%	1-3 weeks	

In summary, this meta-analysis indicates that (1) the per-capita AQ monitoring in the developing regions of the world is 10–20 times lower than in the developed NAWE; (2) the monitoring of $PM_{2.5}$, the best available indicator of health-related effects, is virtually unmonitored by surface networks in the developing world; and (3) the existing monitoring data from developing regions is less publicly accessible to the broader health community. Consequently, there is a need for (1) significantly extended AQ monitoring in the developing world, particularly in the large, densely populated cities; (2) more intense monitoring of $PM_{2.5}$ concentrations; and (3) improving the accessibility to AQ monitoring data by the broader communities in science, AQ management, and the general public.

6. Additional Findings

The review of the public documents established that AQH is closely linked to other SBAs. On the causal side, the most significant connection is with the **Energy** SBA, because the overwhelming majority of anthropogenic air pollutants are caused by fossil fuel combustion. Forest fires and dust storms are major causes of air pollution events with extreme concentrations of smoke and dust particles and ozone precursors, which links AQH to the **Disasters** SBA. **Weather,** in particular atmospheric ventilation, is also a significant factor in the dispersion of air pollutants. In addition to the effects on human health, air quality has impacts in other SBAs. Air pollutants, especially aerosols, perturb the Earth's radiative balance (i.e., the link to **Climate)**, but the magnitude and even the direction of the perturbation (i.e., heating or cooling) is uncertain. In fact, the main uncertainty in climate impact assessment is due to the uncertainty of radiative forcing from natural and anthropogenic aerosols. Deposition of acidic air pollutants contributes to the acidification of terrestrial and aquatic **Ecosystems** and also is a major source of terrestrial and aquatic nutrients**.** Ambient ozone is known to produce damage to **Agricultural** plant growth.

An additional finding of this meta-analysis is the poor accessibility to existing AQH-relevant EOs. This means that EOs that are already collected are not necessarily available for reuse.

7. Analysts Comments and Recommendations

This section contains Analyst comments and recommendations regarding the US-09-01a Task process and methodologies. Inherently, this section is more subjective.

7.1 Process and Methodology

A detailed description of the general US-09-01a process and the guidance provided by the Task Lead, Lawrence Friedl, was helpful for harmonizing this meta-analysis with those prepared for other SBAs. Also, access to EO Prioritization Reports by other SBAs was beneficial. Because no standard approaches are available for establishing EO requirements and priorities applicable to all SBAs, the GEO Task Lead has encouraged the Analysts of each SBA to be innovative and to consider multiple approaches toward developing their respective methodologies. However, strong emphasis was placed on the need to describe and document the chosen methodologies. The Analyst has taken the liberty of adopting a science-based prioritization method.

7.2 Challenges

Gathering the feedback and comments from the AG is still incomplete. We anticipate that over the January–February 2010 period, more extensive feedback from the Task Lead and AG can be incorporated in this report.

Most public documents refer to AQ EO needs in general terms (e.g., need more monitoring stations, better emission inventories, or the incorporation of satellites and models). Very few documents made explicit statements regarding specific AQ EO parameters, spatial and temporal coverage, resolution, or accuracy. On the other hand, scientific research groups tend to list their EO needs so broadly that it included virtually all EOs. Consequently, identifying the EO priorities has to be done mainly through inference and Analyst judgment, not by explicit formulation by the consumers of EOs.

In this report we have pursued gap analysis (i.e., the difference between the desired and the current state) as the main prioritization method. Implicit in this approach is the requirement to establish the current state of observations. Clearly, full quantification of the current state of AQH-relevant EOs was beyond the scope of this initial assessment.

The number of stations reported here are those extracted from the publicly available documents or other meta-analyses. An independent verification of these numbers was not possible, but the Analyst speculates that the numbers given are too high. Also, the majority of the monitoring systems reported for Africa and Asia have been installed since about 2005.

7.3 Recommendations

As a recommendation, the next stage of work on this project could benefit from more extended gap analysis (i.e., establishing currently available AQ-relevant EOs and assessing the gap between the currently available EOs and the “needs” assembled in this report).

Given the continuous evolution of the user needs and of the available EOs, it would be desirable to modify the GEO Task US-09-01a so that it facilitates periodic updates.

The current process of requirement analysis was performed primarily the Analyst and the AG. Future requirement analyzes should incorporate a broader community of stakeholders, preferably through an open process. The GEO Air Quality Community of Practice would be a natural forum for such a process.

Appendix A: Acronyms

Abbr	Full Name
AG	Advisory Group
AIP	GEOSS Architecture Implementation Pilot
AOD	Aerosol Optical Depth
AP	Ambient Pollutant
AQ	Air Quality
AQH	Air Quality and Health
AQI	Air Quality Index
Asia_NSE	Asia Non-Southeast
Asia_SE	Asia Southeast
CAPITA	Center for Air Pollution Impact and Trend Analysis
CASAC	Clean Air Scientific Advisory Committee
CDC	Center for Disease Control
CEOS	Committee on Earth Observation Satellites
CFCs	Chlorofluorocarbon
CH4	Methane
CO	Carbon Monoxide
CO2	Carbon Dioxide
CoP	Community of Practice
Dev_World	Developing World
DF	Damage Function
EF	Emission Factor
EO	Earth Observation
EPA	Environmental Protection Agency
ERG	Eastern Research Group
ESA	European Space Agency
ESIP	Earth Science Information Partners
GCI	GEOSS Common Infrastructure
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
H_2O	Water
HA	Human Activities
HCHO	Formaldehyde
HD	Health Damage
HEI	Health Effects Institute
HNO_3	Nitric Acid
IGAC	International Global Atmospheric Chemistry
NAM	North America
NAS	National Academy of Science
NASA	National Aeronautics and Space Administration
NAWE	North America and Western Europe
NH_3	Ammonia
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides
O_3	Ozone
Pb	Lead
PM	Particulate Matter
PM_{10}	PM less than 10 µm in diameter
$PM_{2.5}$	PM less than 2.5 µm in diameter
POPs	Persistant Organic Pollutants
SBA	Societal Benefit Area
SO_2	Sulfur Dioxide

SRR	Source-Receptor Relationship
TSP	Total Suspended Particulates, PM of any size
UIC	User Interface Committee
VOC	Volatile Organic Compounds
WGISS	Working Group on Information Systems & Services
WHO	World Health Institute
WMO	World Meteorological Institute

Appendix B: Bibliography and References

B.1 Documents and References Cited

109. (APINA) Air Pollution Information Network for Africa, 2009, Country Fact Sheets, http://apinanet.org/facts/

121. AirBase database. *AirBase - the European Air quality dataBase*. 2007 Available at: http://air-climate.eionet.europa.eu/databases/airbase/ [Accessed December 22, 2009].

120. Bachmann, J., 2007. Will the circle be unbroken: A history of the U.S. National ambient Air Quality Standards. *Journal of the Air & Waste Management Association*, 57(6), 652-697.

36. Brook, Jeffrey R., Kenneth L. Demerjian, George Hidy, Luisa T. Molina, William T. Pennell, and Richard Scheffe. 2009. New Directions: Results-oriented multi-pollutant air quality management. Atmospheric Environment 43, 2091-2093.

93. (CAI-Asia) Clean Air Initiative for Asian Cities, 2009, http://www.cleanairnet.org/caiasia/1412/articles-72696_AR2008.pdf.

12. (CDC) Centers for Disease Control and Prevention, 2008, Recommendations for Nationally Consistent Data and Measures within the Environmental Public Health Tracking Network, http://ephtracking.cdc.gov/docs/CDC_NCDM_Pt1_1.3.pdf

102. Chow, Judith C, John G Watson, Howard J Feldman, Janice E Nolen, Barry Wallerstein, George M Hidy, Paul J Lioy, et al., 2007, Will the circle be unbroken: a history of the U.S. National Ambient Air Quality Standards, Journal of the Air & Waste Management Association, 57, 1151-1163.

107. Cohen, A. J, H. R Anderson, B. Ostro, K. D Pandey, M. Krzyzanowski, N. Künzli, K. Gutschmidt, et al., 2004, Urban air pollution. in WHO Nonserial Publication "Comparative Quantification of Health Risks", M. Ezzan, Lopez A.D., Rogers A.and Murray C.J.L, (eds)http://www.who.int/healthinfo/global_burden_disease/cra/en/index.html

111. Cohen Aaron J. C, H. Ross Anderson, Bart Ostra, Kiran Dev Pandey,Michal Krzyzanowski, Nino Künzli, Kersten Gutschmidt, Arden Pope, Isabelle Romieu, Jonathan M. Samet, Kirk Smith, 2005, The Global Burden Of Disease Due to Outdoor Air Pollution, Journal of Toxicology and Environmental Health, Part A, 68,1–7.

26. (CENR) Committee on Environment and Natural Resources, 2009, Survey of Air Quality Monitoring, Draft, Prepared for the, Air Quality Research Subcommittee, May. http://wiki.esipfed.org/images/b/b9/Complete_Report_with_appendices_Air_Quality_Monitoring_051909_JAT-rs.pdf

11. Craig, L., J. Brook, Q. Chiotti, B. Croes, S. Gower, A. Hedley, D. Krewski, et al., 2008, Air pollution and public health: a guidance document for risk managers. Journal of Toxicology and Environmental Health Part A, 71, 588–698

18. Dabberdt, W. F., McHenry, J. N. , 2004, Global Earth Observation System (GEOS), System Capabilities and the Role for U.S. EPA Final GEOSS Task A Report, 31 July. http://www.cgrer.uiowa.edu/people/carmichael/GURME/Final_GEOSS_Task_A_Report_31July2004.pdf.

40. Edwards, D., P.DeCola, J.Fishman, D.Jacob, P.Bhartia, D.Diner, J.Burrows, and M.Goldberg.

2006. Community input to the NRC decadal survey from the NCAR Workshop on Air Quality Remote Sensing From Space: Defining an Optimum Observing Strategy. Community Workshop on Air Quality Remote Sensing from Space: Defining an Optimum Observing Strategy, February 21–23, 2006, National Center for Atmospheric Research, Boulder, Colo. Available at http://www.acd.ucar.edu/Events/Meetings/Air_Quality_Remote_Sensing/Reports/AQRSinputDS.pdf.

37. (EC) European Commission, 2008, Air Quality Framework Directive-EU http://ec.europa.eu/environment/air/quality/legislation/existing_leg.htm.

60. (EC/ESA) European Commission and European Space Agency, 2006, PROtocol Monitoring for the GMES Service Element (GSE), PROMOTE-2, Atmospheric Monitoring Services, Stage 2 of the Earthwatch GMES Services Elements 29/11/2006 http://www.oma.be/PROMOTE_validation_office/Documents/C5%20Service%20Validation%20Protocol%20%28v1issue02%29.pdf.

6. EMEP, 2003, Monitoring Strategy 2004-2009; Background Document with Justifications and Specification on the EMEP Monitoring Programme 2004-2009. August. http://tarantula.nilu.no/projects/ccc/reports/cccr9-2003.pdf.

43. Fishman, J., K. W. Bowman, J. P. Burrows, A. Richter, K. V. Chance, D. P. Edwards, R. V. Martin, et al., 2008. Remote Sensing of Tropospheric Pollution from Space. Bulletin of the American Meteorological Society 89, 805-821.

59. Fowler, D., M. Amann, R. Anderson, M. Ashmore, M. H. Depledge, D. Derwent, P. Grennfelt, et al., 2008, Ground-level ozone in the 21st century: future trends, impacts and policy implications. Royal Society, London, UK, Science Policy Report15/08, October. http://www.royalsociety.org

47. (GEOSS) Global Earth Observation System of System 10-Year Implementation Plan, 2005, http://www.earthobservations.org/documents/10-Year%20Implementation%20Plan.pdf.

29. HEI, 2004, Health Effects of Outdoor Air Pollution in Developing Countries of Asia, Special Report 15, Executive Summary, April. http://pubs.healtheffects.org/getfile.php?u=12

122. Hidy, G. et al., 2009. Introduction to the A&WMA 2009 Critical Review -- Remote Sensing of Particulate Pollution from Space: Have We Reached the Promised Land? *Journal of the Air & Waste Management Association*, 59(6), 644, 642.

123. Hoff, R.M. & Christopher, S.A., 2009. Remote Sensing of Particulate Pollution from Space: Have We Reached the Promised Land? *Journal of the Air & Waste Management Association (1995)*, 59(6), 645.

105. (HTAP) United Nations (UN), 2007, Economic Commission for Europe, Geneva, Hemispheric Transport of Air Pollution, Air Pollution Studies, No. 16, 2007, ISBN 978-92-1-116984-3.

106. IGACO, 2004, The Integrated Global Atmospheric Chemistry Observation, For Monitoring of the Environment from Space and from Earth, The Changing Atmosphere, An integrated Global Atmospheric Chemistry Observation Theme for IGOS Partnership. ESA SP-1282, September 2004Report GAW No. 159 (WMO TD No. 1235), September.

94. Mol, W., van Hooydonk, P. & de Leeuw, F. European exchange of monitoring information and state of the air quality in 2007. ETC/ACC Technical paper 2007/1. (2007).

103. Molina, M. J, and L. T Molina, 2004, Megacities and Atmospheric Pollution,. Journal of the Air & Waste Management Association, 54, 1096-2247.

104. NARSTO, 2004. Particulate Matter Assessment for Policy Makers: A NARSTO Assessment. P. McMurry, M. Shepherd, and J. Vickery, eds. Cambridge University Press, Cambridge, England. ISBN 0 52 184287 5.

95. NARSTO, 2005, Emission Inventory Assessment Team, Improving Emission Inventories for Effective Air Quality Management across North America, a NARSTO Assessment, ftp://narsto.esd.ornl.gov/pub/EI_Assessment/Improving_Emission_Index.pdf

2. Ostro, B., 2004, Outdoor air pollution: assessing the environmental burden of disease at national and local levels, WHO, ISBN 92 4 159146, http://www.who.int/quantifying_ehimpacts/publications/ebd5/en/index.html.

27. Scheffe, R. D, P. A. Solomon, R. Husar, T. Hanley, M. Schmidt, M. Koerber, M. Gilroy, et al., 2009, The National Ambient Air Monitoring Strategy: Rethinking the Role of National Networks. Journal of the Air & Waste Management Association, 59, 579-590.

31. (UN) United Nations, 2001, Economic and Social Council, Economic Commission for Africa State of the Environment Africa. http://www.uneca.org/water/State_Environ_Afri.pdf.

45. USWRP, 2006, Workshop on Air Quality Forecasting; Meeting Summary, February 2006, http://ams.allenpress.com/archive/1520-0477/87/2/pdf/i1520-0477-87-2-215.pdf.

1. Vliet, E. D. S. van, and P. L. Kinney, 2007, Impacts of roadway emissions on urban particulate matter concentrations in sub-Saharan Africa: new evidence from Nairobi, Kenya. Environmental Research Letters, 2, 4, 045028.

98. (WB) World Bank, 1999, Sustainable Rural and Urban Development, Ranking the cities above 100,000 population by estimated PM10 levels (quintiles), based on AQ in 1999. http://go.worldbank.org/IM6FRGJGL0

99. (WB) World Bank, 1999a, Research at the World Bank, Urban population weighted average PM10 concentrations (micro grams per cubic meter) in residential areas of cities larger than 100,000), http://go.worldbank.org/3RDFO7T6M0

10. (WHO) World Health Organization, 2005, Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide; Global Update. http://whqlibdoc.who.int/hq/2006/WHO_SDE_PHE_OEH_06.02_eng.pdf.

65. (WHO) World Health Organization Europe, 2003, Health in Eastern Europe, Caucasus and Central Asia. In Report on the WHO Workshop St. Petersburg, Russian Federation, October 13-14. http://www.euro.who.int/document/E82809.pdf

110. (WHO) World Health Organization, 2002, World Health Report, http://www.who.int/whr/2002/en/whr02_en.pdf

B.2 Documents and References Consulted

1. Vliet, E. D. S. van, and P. L. Kinney, 2007, Impacts of roadway emissions on urban particulate matter concentrations in sub-Saharan Africa: new evidence from Nairobi, Kenya. Environmental Research Letters, 2, 4, 045028.

2. Ostro, B., 2004, Outdoor air pollution: assessing the environmental burden of disease at national and local levels, WHO, ISBN 92 4 159146, http://www.who.int/quantifying_ehimpacts/publications/ebd5/en/index.html.

3. Krzyzanowsky M., 2005. Health effects of transport-related air pollution: summary for policy-makers, WHO Regional Office for Europe, http://www.euro.who.int/InformationSources/Publications/Catalogue/20050601_2.

4. Beelen, R.Gerard Hoek, Piet A. van den Brandt, R. Alexandra Goldbohm, Paul Fischer, Leo J. Schouten, Michael Jerrett, Edward Hughes, Ben Armstrong, and Bert Brunekreef, 2008, Long-Term Effects of Traffic-Related Air Pollution on Mortality in a Dutch Cohort (NLCS-AIR Study) Environ Health Perspect; 116(2): 196–202. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2235230/.

6. T\orseth, K., and \O Hov. 2003. The EMEP Monitoring strategy 2004–2009. EMEP-CCC-Report 9: 2003.

7. HEI, 2003, Accountability Working Group. Assessing the Health Impact of Air Quality Regulations: Concepts and Methods for Accountability Research. January . http://pubs.healtheffects.org/view.php?id=153.

8. Miller, Kristin A., David S. Siscovick, Lianne Sheppard, Kristen Shepherd, Jeffrey H. Sullivan, Garnet L. Anderson, and Joel D. Kaufman. 2007. Long-Term Exposure to Air Pollution and Incidence of Cardiovascular Events in Women. N Engl J Med 356, no. 5 (February 1): 447-458. doi:10.1056/NEJMoa054409.

9. World Health Organization (WHO), 1999, Monitoring ambient air quality for health impact assessment, http://www.euro.who.int/document/e67902.pdf

10. World Health Organization (WHO), 2005, Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide; Global Update. http://whqlibdoc.who.int/hq/2006/WHO_SDE_PHE_OEH_06.02_eng.pdf.

11. Craig, L., J. Brook, Q. Chiotti, B. Croes, S. Gower, A. Hedley, D. Krewski, et al., 2008, Air pollution and public health: a guidance document for risk managers. Journal of Toxicology and Environmental Health Part A, 71, 588–698.

12. Centers for Disease Control and Prevention (CDC), 2008, Recommendations for Nationally Consistent Data and Measures within the Environmental Public Health Tracking Network, http://ephtracking.cdc.gov/docs/CDC_NCDM_Pt1_1.3.pdf

13. Estimations of the Health Impact of Urban Air Pollution in World Cities in 200 and 2030. http://www.baq2008.org/sw26-deleeuw.

14. Kinney, Patrick, Assessing Health Impacts of Major Air Pollution. 2008 Presentation PPT http://www.unep.org/urban_environment/PDFs/EABAQ2008-HealthImpactsPatrickKinney.pdf.

15. Zunckel, M., A. Koosailee, G. Yarwood, G. Maure, K. Venjonoka, A.M. van Tienhoven, and L. Otter. 2006. Modelled surface ozone over southern Africa during the Cross Border Air Pollution Impact Assessment Project. Environmental Modelling & Software 21, no. 7 (July): 911-924. doi:10.1016/j.envsoft.2005.04.004.

16. WRI Final Summary Report: Climate, Air Pollution and PublicHealth: Estimating Morbidity and

Mortality from Fossil FuelConsumption in Major Urban Areas in Developing Countries, 2004 http://www.epa.gov/ies/pdf/general/wrireport.pdf.

17. WMO Sand and Dust Storm Warning Advisory and Assessment System, SDS WAS_draft implementation plan. 2009, http://www.wmo.int/pages/prog/arep/wwrp/new/documents/SDS_WAS_draft_implementation_plan.pdf.

18. Dabberdt, W. F., McHenry, J. N. , 2004, Global Earth Observation System (GEOS), System Capabilities and the Role for U.S. EPA Final GEOSS Task A Report, 31 July. http://www.cgrer.uiowa.edu/people/carmichael/GURME/Final_GEOSS_Task_A_Report_31July2004.pdf.

20. Nepal Air Pollution Impact Assessment. http://www.rrcap.unep.org/male/baseline/ActnPlan/Nepal/NEPCH-B.htm.

21. Minjares, R.J, Rutherford, D. Maximising the co-benefits of light-duty dieselisation in Asia Submitted to Institute for Global Environmental Strategies (IGES), 2009, http://wiki.esipfed.org/images/f/f0/ICCT_CoBenefits_v5_in_press.pdf

22. Rojas-Martinez, R., R. Perez-Padilla, G. Olaiz-Fernandez, L. Mendoza-Alvarado, H. Moreno-Macias, T. Fortoul, W. McDonnell, D. Loomis, and I. Romieu. 2007. Lung function growth in children with long-term exposure to air pollutants in Mexico City. American journal of respiratory and critical care medicine: 200510.

23. Tienhoven. APINA – Progress Towards A Regional Policy On Transboundary Air Pollution. Presented at CEMSA Conference, August 27-30, 2002 . http://dbn.csir.co.za/capia/documents%5CConference_publications.pdf.

25. Clean Air Initiative: Sub-Saharan Africa-Road Ahead for 2005-2007. http://www.cleanairnet.org/ssa/1414/article-70815.html.

26. Committee on Environment and Natural Resources (CERN), 2009, Survey of Air Quality Monitoring, Draft, Prepared for the, Air Quality Research Subcommittee, May. http://wiki.esipfed.org/images/b/b9/Complete_Report_with_appendices_Air_Quality_Monitoring_051909_JAT-rs.pdf

27. Scheffe, R. D, P. A Solomon, R. Husar, T. Hanley, M. Schmidt, M. Koerber, M. Gilroy, et al. 2009. The National Ambient Air Monitoring Strategy: Rethinking the Role of National Networks. Journal of the Air & Waste Management Association (1995) 59, no. 5: 579.

28. Krewski, D. Extended Analysis of the American Cancer Society Study of Particulate Air Pollution and Mortality. HEI Publications. Research Report #140.

29. HEI, 2004, Health Effects of Outdoor Air Pollution in Developing Countries of Asia, Special Report 15, Executive Summary, April. http://pubs.healtheffects.org/getfile.php?u=12

31. (UN) United Nations, 2001, Economic and Social Council, Economic Commission for Africa State of the Environment Africa, November 1. http://www.uneca.org/water/State_Environ_Afri.pdf.

32. State of the Environment South Africa Emerging issues Atmospheric pollution. http://soer.deat.gov.za/themes.aspx?m=496.

33. McGranahan, Gordon, and Frank Murray. 2003. Air pollution and health in rapidly developing countries. Earthscan, May. 2003

34. A Methodology for Cost-Benefit-Analysis of Ambient Air Pollution. Final Report, January 2009, http://www.environment.gov.au/atmosphere/airquality/publications/pubs/cost-benefit-analysis.pdf.

35. WHO, Air Quality Guidelines for Europe, WHO Regional European Series Publication No 91, 2000, http://www.euro.who.int/document/e71922.pdf

36. Brook, Jeffrey R., Kenneth L. Demerjian, George Hidy, Luisa T. Molina, William T. Pennell, and Richard Scheffe. 2009. New Directions: Results-oriented multi-pollutant air quality management. Atmospheric Environment 43, no. 12 (April): 2091-2093. doi:10.1016/j.atmosenv.2008.12.041.

37. European Commission (EC), 2008, Air Quality Framework Directive-EU http://ec.europa.eu/environment/air/quality/legislation/existing_leg.htm.

38. Board, S. S. 2007. Earth science and applications from space: National imperatives for the next decade and beyond. National Academy of Sciences, Washington, DC.

39. World Bank. 2001. China. World Bank Publications.

40. National Research Council (NRC), 2006, Community Input to the NRC decadal Survey from the NCAR Workshop on Air Quality Remote Sensing from Space: Defining an Optimum Observing Strategy. http://www.acd.ucar.edu/Events/Meetings/Air_Quality_Remote_Sensing/Reports/AQRSinputDS.pdf.

41. Smith, K. R. 2008. Comparative Environmental Health Assessments. Annals of the New York Academy of Sciences 1140, no. 1: 31–39.

42. Dabberdt, W. F, M. A Carroll, D. Baumgardner, G. Carmichael, R. Cohen, T. Dye, J. Ellis, et al. 2004. Meteorological Research Needs for Improved Air Quality Forecasting: Report of the 11th Prospectus Development Team of the US Weather Research Program*. Bulletin of the American Meteorological Society 85, no. 4: 563–586.

43. Fishman, Jack, Kevin W. Bowman, John P. Burrows, Andreas Richter, Kelly V. Chance, David P. Edwards, Randall V. Martin, et al., 2008. Remote Sensing of Tropospheric Pollution from Space. Bulletin of the American Meteorological Society 89, 805-821.

44. Al-Saadi, Jassim, James Szykman, R. Bradley Pierce, Chieko Kittaka, Doreen Neil, D. Allen Chu, Lorraine Remer, et al. 2005. Improving National Air Quality Forecasts with Satellite Aerosol Observations. Bulletin of the American Meteorological Society 86, no. 9 (September 1): 1249-1261 .

45. Walter F. Dabberdt, M. A. Carroll, W. Appleby, D.Baumgardner, G. Carmichael, P. Davidson, J.. C. Doran, T. S. Dye, S. Grimmond, P. Middleton, W. Neff, and Y. Zhang , USWRP , 2006, Workshop on Air Quality Forecasting; Meeting Summary, February 2006, http://ams.allenpress.com/archive/1520-0477/87/2/pdf/i1520-0477-87-2-215.pdf.

46. Global Earth Observation System of System (GEOSS)10-Year Plan Reference Document, GEO 1000R, 2005 http://www.earthobservations.org/documents/10-

Year%20Plan%20Reference%20Document.pdf.

47. Global Earth Observation System of System (GEOSS) 10-Year Implementation Plan, 2005, http://www.earthobservations.org/documents/10-Year%20Implementation%20Plan.pdf.

48. Conceicao, G. M., S. G. Miraglia, H. S. Kishi, P. H. Saldiva, and J. M. Singer. 2001. Air pollution and child mortality: a time-series study in S\ ao Paulo, Brazil. Environmental Health Perspectives 109, no. Suppl 3: 347.

50. Chan, C. K, and X. Yao. 2008. Air pollution in mega cities in China. Atmospheric Environment 42, no. 1: 1–42.

51. Kan, H., B. Chen, and C. Hong. 2009. Health Impact of Outdoor Air Pollution in China: Current Knowledge and Future Research Needs. Environmental Health Perspectives 117, no. 5: A187.

52. APINA Country Fact Sheet South Africa. http://apinanet.org/facts/FS_South%20Africa_20080229.pdf.

53. APINA Country Fact Sheet Zimbabwe. http://apinanet.org/facts/FS_Zimbabwe_20080229.pdf.

54. APINA Country Fact Sheet Zambia. http://apinanet.org/facts/FS_Zambia_20080229.pdf.

55. APINA Country Fact Sheet Tanzania. http://apinanet.org/facts/FS_Tanzania_20080229.pdf.

56. APINA Country Fact Sheet Mozambique. http://apinanet.org/facts/FS_Mozambique_20080229.pdf.

57. APINA Country Fact Sheet Malawi. http://apinanet.org/facts/FS_Malawi_20080229.pdf.

58. APINA Country Fact Sheet Botswana. http://apinanet.org/facts/FS_Botswana_20080228.pdf.

59. Fowler, D., M. Amann, R. Anderson, M. Ashmore, M. H. Depledge, D. Derwent, P. Grennfelt, et al. 2008. Ground-level ozone in the 21st century: future trends, impacts and policy implications. Royal Society, London, UK.

60. European Commission and European Space Agency (EC/ESA), 2006, PROtocol MOnitoring for the GMES Service Element (GSE), PROMOTE-2, Atmospheric Monitoring Services, Stage 2 of the Earthwatch GMES Services Elements 29/11/2006. http://www.oma.be/PROMOTE_validation_office/Documents/C5%20Service%20Validation%20Protocol%20%28v1issue02%29.pdf.

61. GMES Service Element Promote User U5 User Needs Dossier. http://www.gse-promote.org/docs/Core_User_Needs_Dossier.pdf.

63 . EMEP Monitoring Strategy & Measurement Programme for 2010-2019. Third Draft, 2008, http://unece.org/env/documents/2008/EB/ge1/Informal%20docs/No.1_Draft%20EMEP%20Monitoring%20Strategy%20&%20Measurement%20Programme%20for%202010.pdf.

64. Egypt Environmental Affair Agency Air Quality. http://www.eeaa.gov.eg/english/main/accomp1.asp.

65. World Health Organization Europe ((WHO), 2003, Health in Eastern Europe, Caucasus and Central Asia. In Report on the WHO Workshop St. Petersburg, Russian Federation, October 13-14. http://www.euro.who.int/document/E82809.pdf

66. Assunção, J.V. de, Sao Paulo Metropolitan Area Air Quality in Perspective, Presented at the International Seminar Urban Air Quality Management, Sao Paulo, Brazil – 21st –23rd October 2002, http://www.iuappa.com/seminar/Assuncao.doc

67. Morocco to generalise pollution control to big cities by 2012, official. http://www.map.ma/eng/sections/economy/morocco_to_generalis/view.

68. Tunisia, South Korea partner to monitor air quality - SciDev.Net. http://www.scidev.net/en/agriculture-and-environment/air-pollution/tunisia-south-korea-partner-to-monitor-air-quality.html?utm_source=link&utm_medium=rss&utm_campaign=en_agricultureandenvironment_airpollution.

69. Air Quality Management in Lagos Nigeria. http://www.uwe.ac.uk/aqm/files/Air_Quality_Management_in_Lagos_Nigeria.pdf.

70. Tanzania An Overviewof Air Pollution. http://www.unep.org/pcfv/PDF/DART-OVERVIEWAIRPOLLUTION.pdf.

71. Sri Lanka. CEA - Air Quality Monitoring. http://www.cea.lk/lab_air_quality_monitoring.php.

72. Jordan to install air pollution monitoring devices in big cities - Arab Environment Watch. http://www.arabenvironment.net/archive/2007/10/357067.html.

73. Iran Technical Specifications air Quality Monitoring. http://www.cleanairnet.org/cai/1403/articles-60109_resource_1.pdf.

74. Japan Air Pollution Monitoring in East Asia http://www.nistep.go.jp/achiev/ftx/eng/stfc/stt018e/qr18pdf/STTqr1805.pdf.

75. China Ministry of Environmental Protection Ambient Air Quality Standard, Report on the State of the Environment http://english.mep.gov.cn/standards_reports/standards/Air_Environment/quality_standard1/200710/t20071024_111819.htm.

76. Taiwan Welcome to Environmental Protection Data In Taiwan, http://edb.epa.gov.tw/engenvdb2/.

77. Hong Kong Air Quality Monitoring Network. http://www.epd.gov.hk/epd/english/environmentinhk/air/air_quality/backgdf_2.html.

78. Macao Report on the State of the Environment. http://www.ambiente.gov.mo/tc/05/2006/en/0202.html.

79.South Kores Real-time Ambient Air Quality Dissemination System. http://www.airkorea.or.kr/airkorea/eng/realtime/main.jsp?action=pm10.

80. India Air Pollution Monitoring. http://www.rrcap.unep.org/male/baseline/Baseline/India/INCH2.htm.

81. Thai Air Quality Monitoring Network.
http://infofile.pcd.go.th/air/DIESEL2_Air%20Quality%20Monitoring%20Network.pdf?CFID=1005110&CFTOKEN=86536661.

82. Philippines Department of Environment and Natural Resources - Clean Air Drive Intensified.
http://www.denr.gov.ph/article/view/188/.

83. Singapore Air Quality Monitoring.
http://www.cse.polyu.edu.hk/%7Eactivi/BAQ2002/BAQ2002_files/Proceedings/Subworkshop2/sw2a-6Koh_paper.pdf.

86. The User and the GEOSS Architecture XXI: Air Quality and Human Health.
http://earthobservations.org/documents/committees/uic/200809_8thUIC/03-Health-Amy-Budge-Beijing-workshop-report.pdf.

87. Pollution in Brunei Darusaalam
http://www.env.gov.bn/link/domestic/pollution%20in%20brunei%20darussalam.htm. Accessed, September 2009.

88. Air Quality Forecasts for China. http://www.esa.int/esaEO/SEMBLOWIPIF_index_2.html.

89. Building up Air Pollution Prediction Model in Ho Chi Minh City using GIS and Neutral Network Technology. http://wgrass.media.osaka-cu.ac.jp/gisideas06/viewpaper.php?id=119.

90. Afganistan: Country Synthesis Report on Urban Air Quality Management.
http://www.cleanairnet.org/caiasia/1412/csr/afghanistan.pdf.

91. Iraq: Atmosphere Monitoring Iraq.
http://www.oosa.unvienna.org/pdf/sap/2007/graz/presentations/07_07.pdf.

92. Bangladesh Air Pollution Monitoring:
http://www.rrcap.unep.org/male/baseline/Baseline/Bang/BANGCH2.htm. Accessed, September 2009.

93. Clean Air Initiative for Asian Cities (CAI-Asia), 2009,
http://www.cleanairnet.org/caiasia/1412/articles-72696_AR2008.pdf.

94. Mol, W., van Hooydonk, P. & de Leeuw, F. European exchange of monitoring information and state of the air quality in 2007. ETC/ACC Technical paper 2007/1. (2007).

95. NARSTO, 2005, Emission Inventory Assessment Team, Improving Emission Inventories for Effective Air Quality Management across North America, a NARSTO Assessment,
ftp://narsto.esd.ornl.gov/pub/EI_Assessment/Improving_Emission_Index.pdf

96. NARSTO, 2009, Conclusions and Recommendations: Multipollutant Assessment, 2009 Executive Assembly April 15, 2009 Washington, D.C.
http://www.narsto.org/files/files/Conclusions_&_Recommendations.pdf

97. HEI, 2007, PAPA-SAN Public Health and Air Pollution in Asia, Science Access on the Net (1980-2007) http://www.healtheffects.org/Asia/Table1_AllStudies.pdf

98. World Bank (WB), 1999, Sustainable Rural and Urban Development, Ranking the cities above

100,000 population by estimated PM10 levels (quintiles), based on AQ in 1999. http://go.worldbank.org/IM6FRGJGL0

99. World Bank (WB), 1999a, Research at the World Bank, Urban population weighted average PM10 concentrations (micro grams per cubic meter) in residential areas of cities larger than 100,000), http://go.worldbank.org/3RDFO7T6M0

100. National Research Council (NRC), 2002, Estimating Public Health Benefits of Proposed Air Pollution Regulations, National Academy Press.

102. Chow, Judith C, John G Watson, Howard J Feldman, Janice E Nolen, Barry Wallerstein, George M Hidy, Paul J Lioy, et al., 2007, Will the circle be unbroken: a history of the U.S. National Ambient Air Quality Standards, Journal of the Air & Waste Management Association, 57, 1151-1163.

103. Molina, M. J, and L. T Molina, 2004, Megacities and Atmospheric Pollution,. Journal of the Air & Waste Management Association, 54, 1096-2247.

104. NARSTO, 2004. Particulate Matter Assessment for Policy Makers: A NARSTO Assessment. P. McMurry, M. Shepherd, and J. Vickery, eds. Cambridge University Press, Cambridge, England. ISBN 0 52 184287 5.

105. United Nations (UN), 2007, Economic Commission for Europe, Geneva, Hemispheric Transport of Air Pollution, Air Pollution Studies, No. 16, 2007, ISBN 978-92-1-116984-3.

106. IGACO, 2004, The Integrated Global Atmospheric Chemistry Observation, For Monitoring of the Environment from Space and from Earth, The Changing Atmosphere, An integrated Global Atmospheric Chemistry Observation Theme for IGOS Partnership. ESA SP-1282, September 2004Report GAW No. 159 (WMO TD No. 1235), September.

107. Cohen, A. J, H. R Anderson, B. Ostro, K. D Pandey, M. Krzyzanowski, N. Künzli, K. Gutschmidt, et al., 2009, Urban air pollution. WMO publication Comparative quantification of health risks, http://www.who.int/publications/cra/chapters/volume2/1353-1434.pdf

108. United Nations Environmental Program (UNEP), 2009, Inter-Governmental Network on Air Pollution in LAC, Frameworks For Regional Co-operation on Air Pollution: A Review of International Experience, March. http://www.pnuma.org/contaminacion_atmosferica/doc/doctrabajo/framework02march2009.doc

109. Air Pollution Information Network for Africa (APINA), 2009, Country Fact Sheets, http://apinanet.org/facts/

110. World Health Organization (WHO), 2002, World Health Report, http://www.who.int/whr/2002/en/whr02_en.pdf

111. Cohen Aaron J. C, H. Ross Anderson, Bart Ostra, Kiran Dev Pandey,Michal Krzyzanowski, Nino Künzli, Kersten Gutschmidt, Arden Pope, Isabelle Romieu, Jonathan M. Samet, Kirk Smith, 2005, The Global Burden Of Disease Due to Outdoor Air Pollution, Journal of Toxicology and Environmental Health, Part A, 68,1–7.

Ribeiro, H., and M. R.A Cardoso. 2003. Air pollution and children's health in Sao Paulo (1986–1998). Social Science & Medicine 57, no. 11: 2013–2022.

121. AirBase database. *AirBase - the European Air quality dataBase*. Available at: http://air-climate.eionet.europa.eu/databases/airbase/ [Accessed December 22, 2009].

120. Bachmann, J., 2007. Will the circle be unbroken: A history of the U.S. National ambient Air Quality Standards. *Journal of the Air & Waste Management Association*, 57(6), 652-697.

122. Hidy, G. et al., 2009. Introduction to the A&WMA 2009 Critical Review -- Remote Sensing of Particulate Pollution from Space: Have We Reached the Promised Land? *Journal of the Air & Waste Management Association*, 59(6), 644, 642.

123. Hoff, R.M. & Christopher, S.A., 2009. Remote Sensing of Particulate Pollution from Space: Have We Reached the Promised Land? *Journal of the Air & Waste Management Association (1995)*, 59(6), 645.

Appendix C: Input to the Cross-SBA Analysis

At the conclusion of the individual SBA priority-setting analysis, the Health SBA-Air Quality Analyst provided input on the overall critical Earth observation parameters for the Air Quality sub-area for inclusion in the Cross-SBA meta-analysis.[5] Upon receiving input from the SBA Analysts, the Cross-SBA Analyst reviewed the priorities in order to harmonize the terminology employed across SBAs. The Cross-SBA Analyst aggregated observation parameters that are the same or very similar but have different names (e.g., precipitation intensity and precipitation duration). In some cases, the Cross-SBA Analyst also disaggregated observation parameters from observation categories that were identified as priorities by individual SBAs. As a result, the number of observation priorities identified by individual SBAs may vary from the number of observations that were included in the Cross-SBA analysis. To the extent possible, the Cross-SBA Analyst focused on retaining the observation parameter terminology employed by the majority of the SBAs.

Three separate sub-reports (Air Quality, Infectious Diseases, and Aeroallergens) were prepared by separate Analysts for the Health SBA. The results of these sub-reports were merged and treated as a single SBA report for the purposes of the Cross-SBA analysis. The Health SBA-Air Quality Analyst determined the overall critical Earth observation priorities for the Air Quality sub-area by using a method involving multiple independent measures, as described in Sections 2.3.3 and Chapter 5. Based on the results of the prioritization analysis, the 15 observations listed below have the highest rankings and thus are considered to be the observation priorities for the Health SBA-Air Quality sub-area. The Health SBA-Air Quality Analyst divided the 15 observations into the three tiers representing “High,” “Medium,” and “Low” priority observations for numerical weighing in Cross-SBA Methods 2 and 3. The below-listed 15 observations were included as part of the single integrated list of Health SBA priorities for Methods 1-3 of the Cross-SBA Analysis. For Method 4, the Cross-SBA Analyst included all of the “High,” “Medium,” and “Low” priority observations as the “15 Most Critical” observations.

High
Surface $PM_{2.5}$
Surface SO_2
Surface NO_2
Surface O_3
Surface PM_{10}

Medium
Column $PM_{2.5}$
Column SO_2
Column NO_2

[5] For full description of methods and results, refer to: Group on Earth Observations. Task US-09-01a. Critical Earth Observation Priorities. Final Report. October 2010. Available on GEO Task US-09-01a website: http://sbageotask.larc.nasa.gov/.

Column O_3
Column PM_{10}

Low
Population
Surface Temperature
Surface Humidity
Surface $PM_{2.5}$ Composition
Surface VOCs

The list of 49 observations, provided below, is the union of the three Health SBA sub-reports' priority lists. This list was used for Method 1 (unweighted tally of observations) and Methods 2 and 3 (weighted tally of observations) in the Cross-SBA analysis. For Methods 2 and 3, the rankings of "High," "Medium," and "Low" were determined based on the highest ranking assigned to an observation parameter across the 3 Health SBA Analysts.

Ambient Nitrogen Dioxide Concentration
Ambient Ozone Concentration
Ambient Particulate Matter (fine) Composition
Ambient Particulate Matter Composition (coarse)
Ambient Particulate Matter Concentration (coarse)
Ambient Particulate Matter Concentration (fine)
Ambient Sulfur Dioxide Concentration
Ambient Volatile Organic Compounds
Biodiversity
Column Nitrogen Dioxide Concentration
Column Ozone Concentration
Column Particulate Matter Concentration (coarse)
Column Particulate Matter Concentration (fine)
Column Sulfur Dioxide Concentration
Deforestation
Density of animal hosts
Elevation
Field Cover (Continuous)
Forest Cover
Glacier/Ice Sheet Extent
Global Horizontal Irradiation (GHI)
Gross Primary Productivity
Health Care Access
Land Cover
Land Use
Leaf Area Index
NDVI
Ocean Topography
Pathogen Population Dynamic
Phenology
Photosynthetically Active Radiation (PAR)
Population
Precipitation
Sea Level
Sea Surface Temperature (SST)
Soil Moisture
Soil Type
Source of Drinking Water
Surface Air Temperature
Surface Humidity
Surface Wind Direction
Surface Wind Speed
Urbanization
Vector Population
Vegetation Cover
Vegetation Type
Water Algal blooms
Water Bodies (location)
Water Quality & Composition, pH and salinity, Dissolved Oxygen Content

For Method 4, the "15 Most Critical" observation list for the Health SBA was prepared collectively by the Health Analysts and Cross-SBA Analyst based on the commonality across the 3 sub-reports' "Most Critical" observation lists. The "15 Most Critical" observations for the Health SBA are listed below. The Health SBA-Air Quality sub-report contributed the 15 priority observations (listed previously) to this list.

1. Population Density
2. Precipitation
3. Air temperature
4. Humidity
5. Land Use/Land Cover
6. Vegetation
7. Water Bodies
8. Sea Surface Temperature
9. Wind
10. Sea Surface Height
11. Topography
12. Vector population
13. Atmospheric Particulates
14. Biodiversity
15. Atmospheric trace gases