A Geostationary Satellite Constellation for Observing Global Air Quality: An International Path Forward

Prepared by the CEOS Atmospheric Composition Constellation
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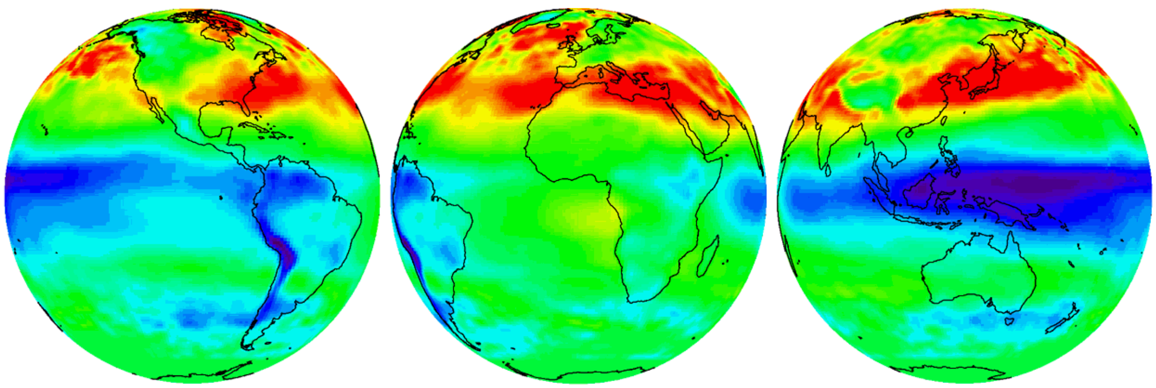

Cover image: Average tropospheric column ozone in May-July 2008 derived from measurements made by the OMI and MLS instruments on the Aura satellite. Purple-blue colors correspond to 10-20 Dobson Units and green-red to 35-50 Dobson Units. Image courtesy J. Ziemke, NASA GSFC, and the OMI and MLS instrument and algorithm teams.

Executive Summary

Several countries and space agencies are currently planning to launch geostationary satellites in the 2017-2022 time frame to obtain atmospheric composition measurements for characterizing anthropogenic and natural distributions of tropospheric ozone, aerosols, and their precursors, which are important factors in understanding air quality and climate change. Ozone, the ozone precursors NO_2 and CO, and aerosols are pollutants that adversely affect human and plant health and the environment. Ozone and aerosols are also the primary short-lived climate forcers, meaning that future air quality and climate are closely linked. Emissions of these pollutants are strongly influenced by human activities. Their distributions in the atmosphere depend on complex physical and chemical transformations that are controlled by sunlight and weather, including the rapidly varying planetary boundary layer and continental- and intercontinental-scale transport of pollution. Understanding and monitoring these processes requires continuous measurements with high temporal and spatial resolution possible only from geostationary Earth orbit.

While a single geostationary satellite can view only a portion of the globe, it is possible for a minimum of three geostationary satellites, positioned to view Europe/Middle East/Africa, Asia/Australasia, and the Americas, to collectively provide near-global coverage. Harmonizing the planned geostationary missions to be contemporaneous and have common observing capabilities and data distribution protocols would synergistically enable critically needed understanding of the interactions between regional and global atmospheric composition and of the implications for air quality and climate. Such activities would directly address societal benefit areas of the Global Earth Observation System of Systems (GEOSS), including Health, Energy, Climate, Disasters, and Ecosystems, and are responsive to the requirements of each mission to provide advanced user services and societal benefits.

An integrated observing system for atmospheric composition is key to abatement strategies for air quality as laid down in various international protocols and conventions. The Integrated Global Atmospheric Chemistry Observations (IGACO) strategy, now endorsed by GEO, provides a framework to harmonize the common interests of the major space-based and in-situ systems for global observation of the Earth for scientists, policymakers, and the public. This framework is now being implemented through the World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) programme. The importance of integrated observations, and the particular role of a constellation of geostationary platforms, was recognized in 2009 at the Fifteenth meeting of the WMO Commission on Atmospheric Sciences (CAS). Research leading to a closer integration of air quality, weather and climate systems at regional and global scales was identified as an issue of immediate concern throughout the world. Coordinated chemical observations are needed to improve capabilities to manage air quality and related services and to better conduct assessments of ozone depletion, global warming, changing climate, health impacts of pollutants and damage to ecosystems. Such observations thus constitute an important part of the development and implementation of international conventions to limit emissions of atmospheric pollutants and reduce risk to society.

The missions being planned now will regularly observe the industrialized Northern Hemisphere. Having these missions in orbit during a common period of at least one year would allow a prototype demonstration of an integrated global observing system by capturing at least one complete annual cycle of hemispheric emissions and resultant initiation of intercontinental pollutant transport. Best efforts to cooperate on defining common requirements, capabilities, data products and validation activities will allow improved designs and data utilization of all sensors and allow cost savings by minimizing duplication of effort. Through such harmonization and cooperation, it is possible to improve the scientific return and societal benefit of each of the individual missions while also initiating a crucial component of the global observing system that will be impossible for any one country to implement alone. While recognizing that unique requirements exist for individual missions, this vision defines achievable common objectives to improve current missions while building a foundation for a future operational atmospheric composition constellation within an integrated global observing system.

Recommendations

1. Continue (or initiate, as appropriate) mutual participation of scientists in the working groups of each mission. Because of the commonality in measurement objectives of each of the geostationary missions, mutual participation in the respective mission science advisory groups provides an effective means for information sharing and building collaborations to ensure that emerging capabilities are widely applied as soon as possible. When feasible, encourage common instrument specifications (e.g. wavelength range and spectral resolution) to enable easier combination of future data sets as provided by different geostationary missions.
2. Facilitate scientific collaboration on retrieval algorithms, retrieval approaches, and Observing System Simulation Experiment (OSSE) studies. Scientific activities associated with each mission are working to improve capabilities for retrieving species relevant to air quality including the maturation of multi-spectral techniques. These activities are already benefiting from international collaboration of scientists and their continuation should be a priority. Efforts are also directed toward extending OSSE techniques developed for meteorology to atmospheric chemical and aerosol composition. Because the OSSE work requires significant computing resources, cooperation to define, conduct, and analyze common scenarios would be of mutual benefit. Best efforts should be undertaken immediately to align and extend the ongoing regional studies and to systematically incorporate them into global studies.
3. Develop techniques for quantifying societal benefits of satellite air quality observations. Each mission has the mandate to provide services, or benefits, to the public in return for the investments in national resources being made in them. The quantification of such benefits is a specialized emerging discipline that traditionally involves social and financial scientists. Sharing methods would stimulate mutual progress.
4. Collaboratively work to enhance the quality of data products from all missions and to implement easy accessibility of data, thereby extending a global focus to these observations. Activities that should be initiated in the near term include agreement on data content, establishing protocols for mutual open and timely data distribution, and development of goals for pre-launch calibration against common standards. Longer-term joint activities include comparing measurements, evaluating retrieval algorithms, and developing collaborative post-launch calibration and validation approaches for measurements from airborne, ground-based and satellite platforms.
5. Cooperate on the development and improvement of air quality models and data assimilation techniques to combine in-situ and satellite measurements in consistent ways to better prepare for the use of these satellite observations by air quality forecasters, managers and other end users.
6. Undertake best efforts to overlap these missions by at least one year and produce common constellation data products to provide simultaneous continuous observations of the Northern Hemisphere through a full annual cycle. These missions share their fundamental common objectives yet individually are restricted to regional relevance. If this constellation framework succeeds, a global perspective will be provided that will be otherwise impossible to achieve. Significant progress will be realized toward quantifying the regional contributions to hemispheric air quality, which has tremendous relevance to development of air quality attainment policies.
7. Whilst endorsing and welcoming the instruments being currently developed to make measurements over Europe, the USA, and East Asia, pursue strategies to acquire geostationary measurements with similar temporal sampling and spatial resolution over, respectively, Europe, the Middle East and Africa; North and South America; and Asia and Australasia. This direction is responsive to GEO, CEOS, and IGOS IGACO recommendations. It could be achieved in part by including north-south scanning in the current instrument designs. Common instrumentation on multiple platforms should be considered as appropriate, particularly for later missions, to reduce costs and possibly enable broader coverage. Common instrumentation would also greatly facilitate collaboration on retrievals and data products.

1 Introduction

1.1 Current CEOS Air Quality Recommendations

In support of Group on Earth Observations (GEO) objectives and as a space component of the Global Earth Observation System of Systems (GEOSS), the Committee on Earth Observation Satellites (CEOS) has developed the concept of virtual space-based Constellations. The goal of a Constellation is to demonstrate that added value can result through partnerships among the space agencies and their supported institutions to coordinate existing and future international space assets. The Atmospheric Composition Constellation (ACC) focuses on observations needed to improve monitoring, assessment and predictive capabilities for changes in the ozone layer, air quality and climate forcing associated with changes in the environment. The ACC Constellation directly addresses the GEOSS Societal Benefit Areas (SBA) of Health, Energy, Climate, Disasters, and Ecosystems.

In June 2009 CEOS convened an ACC Workshop on Air Quality [CEOS, 2009]. Meeting participants included scientists and data users from Europe, Asia and the US. Presentations and subsequent discussion concluded that satellite observations can make an impact on air quality assessments and forecasts, particularly if data assimilation techniques are employed. Although the meeting was not specifically focused on geostationary observations, the near term opportunity to coordinate geostationary missions planned over Asia, Europe and the US was the primary workshop recommendation:

> "Coordinate a real future Air Quality Constellation based on geostationary satellites planned by Korea (GEMS), ESA (Sentinel-4), NASA (GEO-CAPE), and Japan (Geostationary Atmospheric Observation Satellite). The missions should be planned to take advantage of their synergistic capabilities. Cost efficiencies might be achieved if there are common instrument requirements. Coordinated algorithm development, data content and format, and cal/val should be planned. All are expected to be launched in the period 2018-2026 and should be used as the backbone of a true Air Quality Constellation."

It was also noted that low Earth orbit (LEO) missions have critical roles in providing global coverage and profile data essential for understanding the upper troposphere/lower stratosphere chemical and dynamical processes that contribute to air quality in the troposphere. Such LEO missions are also critical for assessing future changes and potential recovery of stratospheric ozone. Upcoming low Earth orbit European and US missions, including NPP/NPOESS, the METOP series, Sentinel 5 Precursor and Sentinel 5, as well as potentially PREMIER, ACE and GACM, should be coordinated to minimize data gaps and provide complimentary data to the geostationary missions. International collaboration on retrievals, validation, and applications was strongly advocated by the workshop attendees. It was recommended that CEOS and bilateral discussion to coordinate these activities be initiated soon.

1.2 Background

Air quality is defined by the atmospheric composition of gases and particulates near the Earth's surface. This composition depends on local contributions (emissions of pollutants), chemistry, and long-range transport processes; it is highly variable in space and time (McNair et al., 1996). The degradation of air quality associated with high levels of tropospheric ozone (O_3), aerosols, and other pollutants has impacts on human health and welfare, agricultural productivity and natural ecosystems. Tropospheric aerosols and ozone are also the primary short-lived forcers of climate yet estimates of their radiative impacts remain subject to high uncertainty [IPCC, 2007]. Understanding air quality requires accurate knowledge of emissions, photochemistry, and meteorology. The three pollutants of most interest for health impacts are ozone, aerosol, and nitrogen dioxide (NO_2) [Brunekreef and Holgate, 2002; Stieb et al., 2008] and recognition is growing of the combined health effects of multiple air pollutants [Dominici et al., 2010]. Ozone is produced by the oxidation of carbon monoxide (CO) and hydrocarbons in the presence of reactive nitrogen oxides (NO_x). Aerosols enter the atmosphere both directly and through formation from gaseous precursors. Pollutant emissions worldwide originate from many different local sources that can vary substantially throughout the day, including combustion, biogenic activity, and wind-driven mobilization. Regional and global consequences of these local emissions stem from atmospheric transport and the chemical and physical processing that takes place during transport.

Excess ozone and particle concentrations are environmental problems that have been addressed on the national and international level. Emissions ceilings or concentration limits imposed by different environmental directives and national laws have led to significant improvements in several aspects of air quality, or at least helped to reduce the impact of increasing energy use through the implementation of more efficient technologies and exhaust filters. Success stories include the reduction of SO_2 and sulphate surface concentrations in Europe [Mylona, 1996; Boucher and Pham, 2002] and North America [US EPA, 2009a] and decreases in NO_x, CO, and benzene concentrations in urban areas due to catalyst-equipped vehicles, refined engines and fuels, and power plant emission controls [Gwilliam et al., 2004]. Yet the impacts of today's societies with large numbers of people striving for a high "standard of living" have reached continental and global-scale dimensions. While still an issue for industrialised countries, urban pollution has also become a very serious issue for developing countries with fast rising energy consumption and quickly growing motorized traffic. In tropical regions, deforestation and the burning of crop residues and other biomass exacerbates air pollution (as demonstrated clearly for example during the Indonesian forest fires in 1997/1998). Growing ship traffic with high emissions of SO_2 and NO_x perturb the chemical environment of the marine boundary layer with possible far reaching consequences for tropospheric ozone and the self-cleansing capacity of the atmosphere [e.g. Corbett and Fischbeck, 1997]. Air pollutant concentrations in some of the world's largest and fastest growing megacities are now regularly exceeding the peak levels observed in North America and Europe during the 1950s to 1980s.

Air quality monitoring is based mainly on in-situ measurements. Because of the multitude of constituents involved and their inherently high temporal and spatial variability, modeling and prediction of air quality remain challenging (see Section 3). Satellite observations offer unique promise for their improvement by providing constraints on key atmospheric constituents (Figure 1) with wide geographic coverage. In recent years, instruments on low Earth orbit satellites have begun providing daily (or in some cases twice-daily) observations of O_3 and aerosol optical thickness and also of important precursors and pollutants including CO, NO_2, SO_2, and HCHO (Table 1). Because of episodic interference from clouds and regular gaps in horizontal coverage associated with orbit geometry, these data are typically aggregated on a monthly averaged basis. As an illustration, Figure 2 shows tropospheric column O_3 for July 2008 produced from the OMI and MLS instruments on the Aura satellite [Ziemke et al., 2006].

Continuous observations at a temporal frequency of many times per day, as are possible from geostationary Earth orbit, will enable revolutionary monitoring of these pollutants and capabilities for improving their prediction, including verification of emissions and understanding of the rapid and complex processes that transport and transform them. Several nations and their space agencies are currently developing geostationary air quality missions for these reasons (Table 2). Each mission is responsive to requirements for delivering societal benefits as defined by their sponsoring organizations, as described in Section 2. However, an individual geostationary satellite can provide observations of only a portion of the globe. A minimum of three geostationary satellites, positioned to view Europe, East Asia, and North America, can in principle collectively provide continuous observations with near-global coverage of populated regions.

Research has shown that transport of tropospheric pollutants occurs on intercontinental scales such that emissions of pollutants and their precursors on one continent can contribute to degraded air quality over other continents [Task Force on Hemispheric Transport of Air Pollution, 2007; NRC, 2009]. Pollutants can be transported over country boundaries within a day and between continents within a week. There is growing evidence for a continued increase in the background levels of ozone in the troposphere associated with the long range transport of pollution from other regions of the globe [Parrish et al., 2009; Cooper et al., 2010]. This increase in background can contribute significantly to overall local pollutant amounts, posing challenges to air quality regulatory policy in that local or even regional abatement strategies may be insufficient for achieving local compliance. Figure 3 shows typical pathways for intercontinental pollution transport in the Northern Hemisphere. Comparison with Figure 2 shows that in the Northern Hemisphere summer the highest O_3 concentrations tend to reflect not only industrialized regions but also large areas downwind of them. Estimates of intercontinental transport of pollutants vary widely between models, and few constraints are available from observations [Fiore et al., 2009].

To significantly improve quantification of the impact of long range transport on local air quality requires better constraints on the rapid processes by which pollutants are exchanged between the surface and the free troposphere, both where the emissions occur (source regions) and where the air quality impacts are experienced (receptor regions). Each of the planned geostationary missions is expected to provide observations over its own regional domain capable of resolving the hourly scale processes that control the venting of emissions from the surface into the free troposphere, including convection and frontal lifting, and the entrainment of pollutants from the free troposphere into the local boundary layer. By combining observations from geostationary platforms viewing Europe, East Asia, and North America, most major anthropogenic pollutant source regions in the developed Northern Hemisphere (Figure 4) will be observed at hourly frequency. Daily LEO observations provide a critical component of this observing system by viewing the intermediate stages of intercontinental pollutant transport in the free troposphere, where the dominant time scales are typically longer (days to weeks) and are primarily determined by horizontal wind speeds and the time scale of the loss processes of the source being transported.

This first generation of geostationary tropospheric composition observations over the pollution belt of the industrialized Northern Hemisphere will provide a prototype demonstration of a future global operational system. As a consequence of minimizing the not insignificant cost and operating requirements, the currently planned geostationary air quality missions will result in lack of coverage for large parts of the world, including Africa, parts of Asia, Australia, and South America. The transport and transformation of pollution from and to these regions is recognized to be of great significance, often resulting from short term events such as biomass burning and dust storms. The provision of near-global hourly coverage is technically feasible now and will become more tractable as technology matures and the cost of access to geostationary orbit decreases. Possible steps might include scanning the currently planned instruments North-South rather than East-West, flying additional copies of the instruments, or allowing the instruments to be somewhat larger.

An integrated observing system for atmospheric composition, combining in-situ and satellite measurements, is key to improving existing abatement strategies for air quality as laid down in various national and international protocols and conventions. The Integrated Global Atmospheric Chemistry Observations (IGACO) strategy (IGACO, 2004), now endorsed and taken on by GEO, provides a framework to harmonize the common interests of the major space-based and in-situ systems for global observation of the Earth for scientists, policymakers, and the general public. This framework is being implemented through the World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) programme. The importance of integrated observations, and the particular role of a constellation of geostationary platforms, was recognized at the Fifteenth meeting of the WMO Commission on Atmospheric Sciences (CAS). Research leading to a closer integration of air quality, weather and climate systems at regional and global scales was identified as an issue of immediate concern throughout the world affecting societies from perspectives of air quality, food security, and water availability and quality (CAS, 2009). Coordinated chemical observations are needed to improve the capabilities to manage air quality and related services and to better conduct assessments of ozone depletion, global warming, changing climate, health impacts of pollutants and damage to ecosystems. Such observations thus constitute an important part of the development and implementation of international conventions to limit emissions of atmospheric pollutants and reduce risk to society.

1.3 Current State of Practice for Air Quality Products from a Geostationary Constellation

A prototype for the potential capabilities of an air quality constellation exists in the observations made from the current generation of operational geostationary environmental satellites. Observations of trace gases have not yet been made from geostationary orbit. Multi-channel imagers that provide information on aerosols and fires at high spatial and temporal resolution have been flying on operational weather satellites in geostationary orbit for the past three decades (e.g, NOAA GOES series and EUMETSAT Meteosat series).

Both qualitative (smoke plume analysis and dust mask) and quantitative (aerosol optical depth, smoke plume concentration, fire hot spot, instantaneous fire size, burned area, and biomass burning emissions) air quality products are currently available from geostationary satellites. As an example, Figure 5 shows the desert dust indicator from SEVIRI/MSG being used to help determine attribution for a PM_{10} exceedance in northern Italy. As highlighted in Table 3, several of these products are now available from multiple satellites to provide quasi-global data. Most of these products are available at a spatial resolution of 4 km and a temporal resolution of 15 to 30 minutes. Geographic coverage varies depending on the longitudinal position of the satellite. The meteorological community has recommended that a constellation of six geostationary satellites assures near global coverage, including oceans (WMO, 2009), however a minimum of three can in principle cover all populated continents.

GOES aerosol and fire products are widely used to monitor and predict air quality. The models that provide U.S. national air quality forecast guidance now use GOES fire hot spots as inputs and GOES aerosol products to verify the forecasts. Another operational aerosol model that uses GOES fire products is the Navy Aerosol Analysis and Prediction System (Reid et al., 2009). For monitoring applications involving the implementation of exceptional events rule, EPA has begun ingesting the products into its Remote Sensing Information Gateway (RSIG) (Paulsen et al., 2009). For hazards applications, the rapid refresh rate of geostationary satellite imagery has facilitated the analysis of smoke and volcanic ash plumes and their regional transport. Data on aerosol and fire from SEVIRI on Meteosat are planned to be used in GMES atmosphere prototype services in 2010/2011.

Despite reasonable accuracies and wide applications, these existing geostationary satellite products have some limitations. Navigational errors associated with satellite jitter, absence of onboard calibration for visible channel, broad spectral response functions, and fixed viewing geometry contribute to a range of errors. Some of these issues (satellite jitter, onboard calibration, etc.) will be alleviated for the next generation sensor, the Advanced Baseline Imager (ABI), to be flown on GOES-R (Laszlo et al., 2008) and the Korean MP-GEOSAT mission. The fixed viewing geometry is problematic for extreme viewing angles (near the edge of the scan) and contributes to errors that are a function of the position of Sun and satellite. However, quality control procedures currently in place are capable of screening for bad data.

2 Status of planned missions

2.1 Europe - Sentinel 4

Sentinel 4, together with Sentinel 5 in Low Earth Orbit, is part of the European Global Monitoring for Environment and Security (GMES) initiative, an end user-focused program of services for environment and security. GMES is the European contribution to GEOSS and ESA is responsible for the space component of GMES. Primary requirements for Sentinel 4 are hourly space measurements of chemical species needed for regional European air pollution application and services, as for example detailed in the report of the GMES Atmospheric Core Services Implemenetation Group [GACS, 2009]. The Sentinel 4 data shall support applications and services on regional to local air quality forecasts; improved air-quality-related alerts and forecasts by health services supporting vulnerable communities; integrated air quality indices; improved air-quality-related alerts and forecasts for extreme events involving the combined effects of heat stress, high UV-B exposure and poor air quality; analysis of national, regional and local air pollution abatement policies and measures through inverse modeling; as well as improvement of emission inventories and reconciling bottom-up and top-down emission inventories.

The Sentinel 4 mission consists of a UV-VIS-NIR spectrometer (UVN) to be added to the sounding platforms of Meteosat Third Generation (MTG-S), the utilization of data from Eumetsat's IR sounder (IRS) on the same platform, and the utilization of data from Eumetsat's imager (FCI) on the imaging platforms MTG-I. MTG is the next generation of Europe's operational meteorological geostationary observing system. Eumetsat and ESA performed several scientific studies to define and optimize the Sentinel 4 mission requirements.

The Sentinel 4 UVN instrument (Bovensman et al., 2002; Burrows et al., 2004; Bovensman et al., 2004) is designed to make hourly measurements of the up welling radiation at the top of the atmosphere covering the wavelength range from 305 nm to 500 nm and 750 nm to 775 nm at moderate to high spectral resolution (UV-VIS: 0.5 nm, NIR: 0.12 nm) with a spatial resolution of 8 km x 8 km over Europe. From the measured radiation, the total and tropospheric columns of several atmospheric constituents of great significance for European air pollution and air quality applications will be derived: the gases ozone O_3, nitrogen dioxide, NO_2, sulphur dioxide, SO_2, and formaldehyde HCHO, as well as height resolved aerosol information. In addition, there is the potential to deliver glyoxal (CHOCHO). The IRS instrument on MTG is designed to measure the upwelling thermal radiation in the spectral ranges from 700 cm-1 to 1210 cm-1 and 1600 cm-1 to 2175 cm-1. These measurements provide information on O_3, H_2O, and CO. The IRS instrument will provide total column CO and tropospheric column O_3, with limited sensitivity in the PBL, but studies have shown that the instruments should provide useful data for large pollution events (high O_3

levels or high CO due to fires) [Clerbaux et al., 2008]. It is envisaged that cloud information from the imager FCI will be used in the Sentinel 4 system.

Funding within the ESA GMES program to build, integrate and fly two Sentinel 4 UVN instruments on two consecutive MTG sounding platforms from 2017/18 onwards for approximately 15 years was agreed at the ESA Ministerial Council meeting in November 2008. The Sentinel 4 UVN industry Phase B1 started in early 2010. Sentinel 4 UVN will be complemented by Sentinel 5 and its precursor, the LEO component of Europe's satellite based atmospheric composition monitoring system required to meet GACS requirements [GACS, 2009]. A combined Sentinel 4 and 5 Mission Advisory Group was implemented recently by ESA.

2.2 Japan – GMAP-ASIA

JAXA's Geostationary mission for Meteorology and Air Pollution-Asia (GMAP-Asia) was defined through a Mission Definition Review (MDR) held in December 2009. The mission scopes are Air Quality, Meteorology, and Climate Change. The mission purposes are to monitor trans-boundary atmospheric pollution of Ozone and aerosols (including their precursors) in Asia, measure vertical profiles of temperature and water vapor to contribute to weather forecasts and meteorological process studies, and demonstrate hyperspectral sounder technology for air quality and meteorological observation from geostationary orbit. Preliminary feasibility studies of instruments and retrieval of physical parameters, funded by JAXA in 2009, were conducted. They recommended measurements of O_3 and NO_2 (with HCHO and SO_2 as research products) using a UV/Visible spectrometer, and measurements of temperature, humidity, O_3, and CO (with HNO_3 as a research product) using a thermal infrared imaging FTS from geostationary orbit. However, technical difficulties of a geostationary imaging FTS and further needs from several Ministries and Agencies were recognized through the MDR. In 2010 JAXA will make further studies especially about imaging FTS and consolidate mission requirements. The design and development phase is currently anticipated in the third mid-term plan (2013-2017), and the launch is no earlier than 2017.

2.3 Korea – MEST MP-GEOSAT

As specified in the National Space Program, the Multi-Purpose GEOstationary SATellite (MP-GEOSAT) has been planned in Korea as a follow-on mission to the geostationary Communication, Ocean color and Meteorology Satellite (COMS) launched in June 2010. The Ministry of Science and Technology (MEST) is the coordinating ministry for the development of the MP-GEOSAT, supported also by the Ministry of Land, Transport and Maritime Affairs (MLTM), Ministry of Environment (ME), and Korea Meteorological Administration (KMA). Under the auspices of MEST, Korea Aerospace Research Institute (KARI) is the system integration organization of the MP-GEOSAT mission with the launch planned in 2017-2018.

ME will be responsible for developing the payload for atmospheric composition measurements in the Asia-Pacific region. Both the subsystem and system level feasibility studies have been finished. Feasibility study of an air quality monitoring mission completed in 2008 recommended measurements of SO_2, NO_2, O_3 and aerosol using a scanning UV/Visible spectrometer from GEO. As options, measurements of CO, CO_2 and CH_4 were also recommended using IR instruments from GEO, if technology is available. Feasibility studies for meteorological and ocean color monitoring missions were finished in 2007 and 2008, respectively. As a result of these studies, the next geostationary mission, MP-GEOSAT under the supervision of MEST, was selected for atmospheric environmental monitoring together with meteorological and ocean color monitoring. Twin satellites are being planned by KARI: 2A with a meteorological payload and 2B with air quality and ocean color payloads. For the air quality mission, ME formally established the Global Environmental Satellite Program Office in June 2009, in the National Institute of Environmental Research (NIER) of ME. First phase funding has been initiated to study the requirements of science and instrument, algorithm development strategy, and evaluation of social benefit, through the Global Environment Satellite Research Center (GESC) established at Yonsei University, in March 2009.

The user requirements for the GEMS mission have been driven mainly by ME and established by its science team. Trans-boundary pollution and its quantification of contribution to the local air quality has been a keen issue among countries in East Asia. With the technological capabilities available to address such issues and strong demand from the user community in Korea, the user requirements are being finalized by GESC with the active participation of an international Science Advisory Group.

In 2009, the four coordinating ministries submitted a proposal for budget to the Committee of Preliminary Investigation of Financial Budget. In December 2010, the Committee passed the proposal for the MP-GEOSAT Mission with launch scheduled in the 2017-2018 time frame, under the condition for additional technical review of payloads for 2B satellites before the preliminary design review. There still exists opportunity for international collaboration, including the possibility for foreign organizations to provide instruments while KARI provides spacecraft and launch services.

2.4 United States – NASA Geo-CAPE

The NASA Geostationary Coastal and Air Pollution Events (Geo-CAPE) mission was recommended for launch in the second tier of missions by the 2007 National Research Council Earth Science Decadal Survey (DS). The mission's purpose is to quantify human and natural sources of aerosols and ozone precursors, track air pollution transport, and understand the short-term dynamics of coastal ecosystems. Hourly observations throughout each day from Geo-CAPE's geostationary perspective will allow for adequate temporal monitoring of population exposure and the ability to relate pollutant concentrations to their sources or transport, thereby providing data to improve air quality forecasts and management decisions.

NASA is implementing the DS missions in sequence as budget permits. Geo-CAPE is currently anticipated for launch in the 2020-2022 period. Science and mission working groups are being funded to define the observing requirements, develop mission concepts, and identify potential partnerships. Current activities are developing “baseline” and “threshold” requirements for the air quality component of the mission. Both sets of requirements specify regular and systematic hourly observations of North America. The threshold requirements presently specify measurements of O_3, NO_2, CO, HCHO, and SO_2 at approximately 8 km nadir horizontal resolution and aerosol optical depth (AOD) at 2 km resolution. Such measurements may be made using a combination of two instruments that have mature space heritage: a near infrared (NIR) radiometer (MOPITT instrument heritage) to detect CO and an Ultraviolet-Visible (UV-Vis) spectrometer (GOME/SCIAMACHY/OMI instrument heritage) to detect the other species. The baseline requirements extend the suite of products to be retrieved, adding CH_4, NH_3, and absorbing aerosol products, and refine the nadir spatial resolution to 4 km for gas and 1 km for aerosol. Such capabilities are expected to require that measurements be made in thermal IR wavelengths in addition to UV-Vis-NIR.

The DS recommended that capability to differentiate upper and lower tropospheric concentrations of CO and potentially O_3 would be desirable if technologically feasible. Due to the inherent challenge of achieving vertical resolution from nadir viewing, the Geo-CAPE Science Working Group (SWG) is actively evaluating multi-spectral retrieval techniques for providing improved sensitivity to the lower troposphere to assist with refining instrumentation requirements [Natraj et al., 2011]. NASA is also funding instrument development activities to increase technology readiness levels, improve capabilities, and reduce sizes of candidate instrumentation. The formulation team is actively exploring concepts to reduce mission costs, including launch options such as commercial hosting of instruments of opportunity, to potentially enable earlier launch dates. Another possible option is to include one or more of the Geo-CAPE instruments on one or more of the satellites in the GOES-R series, beginning with GOES-S that is expected to become operational in 2020.

Geo-CAPE will complement the operational air quality products from the GOES-R/S Advanced Baseline Imager (ABI): AOD, smoke detection, dust detection, total column O_3, fire hot spot characterization, and biomass burning emissions. Geo-CAPE aerosol measurements in UV wavelengths will enable better discrimination of aerosol type, in particular the identification of absorbing versus non-absorbing aerosols. The CO and NO_2 detection capability of Geo-CAPE along with the fire characterization capability of ABI will together provide improved constraints on emissions from biomass burning.

2.5 Low Earth Orbit Missions

Gaining an understanding of the components of global composition change can only be realized with a system that includes satellites in both geostationary and low Earth orbits. Complementary LEO satellites provide improved coverage at high latitudes and improved information on the vertical distribution of pollutants in the atmosphere. Observations from a single LEO satellite would overlap those from each GEO satellite once per day, providing a means for combining the GEO observations and a necessary perspective for interpreting the global impact of the smaller scale processes. Such an atmospheric composition constellation would provide the backbone of a true Earth observing system [IGACO, 2004].

When these geostationary air quality missions are launched, currently planned operational polar-orbiting satellites are expected to be providing relevant atmospheric composition species measurements during separate morning and afternoon orbits. The Eumetsat Metop series, with GOME-2 and IASI instruments, will continue to provide observations of O_3, NO_2, CO, HCHO, SO_2, and aerosol in the morning orbit. The NOAA/NASA JPSS series, with OMPS, CRiS, and VIIRS instruments, will provide observations of O_3, SO_2, and aerosol in the afternoon orbit beginning with the NPP mission in 2011. CRiS may also provide CO observations pending expression of user requirements and availability of funding. The ESA Sentinel-5 Precursor mission with the TropOMI instrument will additionally provide NO_2 and HCHO in the afternoon orbit beginning in 2015 and will also provide enhanced capability for air quality observations due to its spatial and spectral characteristics. The ESA Sentinel-5 (~2020) and NASA ACE and GACM (post-2020) missions will provide the next generation of atmospheric composition measurements relevant for air quality. The ESA Sentinel-3 mission will contribute to enhanced aerosol information (e.g. retrieved aerosol effective radius) based on its measurements by the Sea Land Surface Temperature Radiometer (SLSTR) and Ocean Land Colour Instrument (OLCI) instruments.

2.6 Constellation products

Flight of these missions, along with expected operational meteorological missions including the GOES-R and MTG series, will allow common air quality products to be produced around the globe. The combination of the Flexible Combined Imager on Meteosat Third Generation and Advanced Baseline Imager on GOES-R and MP-GEOSAT will allow continued production of the products listed in Table 3 over both Northern and Southern Hemispheres. Based on the current specifications (Table 2), the data from the UV-visible sensors from Sentinel-4, GMAP-ASIA, GEMS, and Geo-CAPE will also allow a set of common products to be produced over the industrialized Northern Hemisphere. Common air quality trace gas products will be tropospheric column O_3, NO_2, HCHO, and SO_2 nominally at 8 km spatial resolution and 1 hour temporal frequency. Detection of aerosols in the UV will allow absorbing aerosols to be distinguished from total aerosol optical depth, significantly complementing the information available from the meteorological imagers. This will provide some information on aerosol speciation and will be particularly relevant to the air quality/climate interface associated with aerosol radiative forcing.

There are also some differences among the specifications of the planned missions. A number of additional constellation products could be produced given specific developments over each region. There is not yet a requirement for CO detection for either of the missions over Asia, though it is a consideration in both missions. Addition of CO to at least one of the Asian platforms would potentially allow production of a common CO product. A lowermost troposphere O_3 product, exploiting multispectral retrievals combining UV, IR, and perhaps visible wavelengths [Natraj et al., 2011], is another candidate product. This product is planned for Geo-CAPE, is possible over Asia if GMAP-ASIA implements its TIR FTS concept, and is possible over Europe with the combination of data from Sentinel-4 and IRS. However in the case of both the CO and lowermost troposphere O_3 products, additional instrumentation is likely required over Europe (e.g., Section 2.7.1), as IRS is not optimized to provide sensitivity for trace gases. Depending on which implementation options are selected for Geo-CAPE and GMAP-ASIA, a common thermodynamic profiling capability may be available. IRS will provide this over Europe and it would also be available over Asia and the US if the respective TIR concepts are selected.

2.7 Other Prospective Regional Missions

2.7.1 European Mission Concepts

In complement to current plans for Sentinel-4 and MTG-IRS, a community of scientists and users is promoting a new geostationary mission concept to better meet requirements for forecasting European air quality in the lowermost troposphere [Orphal et al., 2005; Claeyman et al., 2011a, 2011b; Lahoz et al., 2011]. Envisaged instrument targets include achieving 5 to 15 km horizontal resolution and less than 1 hour revisit time. The objectives are to derive an instrument with adequate technology readiness level and cost, while optimizing two aspects: the number of independent pieces of information in the tropospheric distributions of O_3 and CO, and averaging kernels peaking as low as possible in the lowermost troposphere. The concept is based upon a multi-spectral VIS+TIR (O_3) and TIR+SWIR (CO) concept endorsed by European industry. This approach builds on missions proposed to ESA for EE-7 and EE-8, but so far no mission has been selected for implementation.

2.7.2 Canada – PCW

The Polar Communication and Weather (PCW) Satellites Project is a Canadian initiative to provide communication and continuous atmospheric measurements over the North circumpolar area. PCW aims to provide new Earth observation capabilities in the Arctic to improve numerical weather predictions, environmental monitoring and climate monitoring. PCW is led by the Canadian Space Agency and Environment Canada (EC) is the main partner for the meteorological component. EC will have the mandate to distribute nationally and internationally the imagery and derived products. Many other Canadian federal departments are involved. The Users and Science Team includes members from major international agencies and meteorological institutes.

The PCW system is defined by a constellation of two satellites in a highly elliptical orbit (HEO), with apogees at 63.4 degrees, perigee near 600 km, and orbital period of 12-h. The configuration in a single plane results in four apogees, 90 degrees apart, with fixed positions. The committed meteorological instrument is a 20-channel imager covering the spectral range 0.45-14.5 µm, with 0.5-1 km resolution for visible channels and 2 km resolution for infrared channels. Additional instruments are considered, subject to budget and time constraints, such as a hyper-spectral sounder and a UV-VIS-NIR instrument for atmospheric chemistry. Earth coverage will be complete from 55-90 N, with imagery being refreshed every 15 min. Thus PCW will provide geostationary-like imagery over the circumpolar area. It is important to note that full Earth disks will be observed, not only the northern latitudes. The coverage in terms of hours per day will be very good (> 18 hours/day) down to 30 N.

The list of products from the 20-channel imager includes cloud variables, total ozone, volcanic ash, SO_2, and fires/smoke. The launch of the two satellites is planned for 2016 with operational status in 2017. The PCW system is proposed with a view that it can operate for a minimum of 20 years, with ageing satellites being replaced when needed. The list of AQ variables provided by PCW may be extended based on the availability of additional instruments, potentially including instruments provided by NOAA through mutual agreement. This project is at development level and at this point there is no firm commitment from the CSA for implementation although there is strong interest. Synergy with operational meteorological geostationary satellites is clear, and emphasized by imaging requirements which are very similar to those defined for the next generation of GEO satellites (MTG and GOES-R).

A major objective of the Geostationary Atmospheric Composition Constellation is to advance understanding of the interactions between regional and global atmospheric composition. The orbit of PCW would complement the constellation by providing diurnally varying observations that overlap with each geostationary satellite over 30N - 60N, adding opportunities for intercalibration at multiple times per day.

3 Science and Societal Benefits of Geostationary Observations

3.1 Services and societal benefit from integration of satellite data into decision making

The 2004 IGOS IGACO report called for a strategy for ensuring accurate comprehensive observations of key atmospheric trace gases and aerosols by integrating surface, in-situ, and satellite observations in capable models and making the integrated observations available to users. In recent years, an integrated observing strategy with an emphasis on use of the data has been reflected in the different but related motivations for better observations of air quality by space-faring nations. ESA’s Sentinel 4 Mission has been developed within the Global Monitoring for Environment and Security (GMES) framework. Korean mission requirements include an emphasis on quantifying societal benefits from integrating satellite data into decision making. The Japanese mission concept supports key national priorities within the international Global Earth Observation System of Systems Societal Benefit Areas. In the United States, NASA’s motivations include both fundamental Earth system science and the societal benefits of delivering sound science to users. In each case, a consistent feature of planned new observing systems has been the provision of improved temporal resolution from space (~hourly) with similar or better spatial resolution compared to existing low-Earth orbit observations.

ESA’s PROMOTE (PROtocol MOniToring for the GMES Service Element; http://www.gse-promote.org/) air quality services demonstrated an integrated air quality platform for European regional and local air quality forecasts and assessments. First demonstration services used atmospheric measurements provided by existing European polar orbiting satellites like ERS-2, Envisat, and METOP. The services included the provision of Air Quality Records to end users, the development of an Integrated Air Quality Platform for Europe, Regional/Local Air Quality Forecasts, and satellite-based dust, particulate matter and pollen concentration observation and forecast Services. Fifteen end-users (European Environmental Monitoring Agencies) evaluated these services. The general view of most users was that the modeling and forecasting services were very useful and provided additional value to existing information sources. The PROMOTE project is seen as essential in the fruitful but yet developing collaboration between users and service providers. Several users highlighted the importance of the services for short-term air pollution reduction strategies and evaluation of the results of abatement measures. Experience gained in PROMOTE has shown the following benefits of using satellite measurements for AQ monitoring in Europe:

Air pollution (especially ground ozone and fine particles) has huge socio economic costs in terms of both morbidity and mortality. 288.000 premature deaths and some 83000 hospital admissions cost the European society 159 billion Euro each year. Strict regulations are already being implemented to reduce air pollution. The PROMOTE air quality monitoring services provided for better means to monitor air pollution and in particular to optimise likely impact on measures to be implemented to reduce air pollution.

AQ forecast services benefit in particular citizens already suffering from respiratory diseases or heart problems. Restricted activity days (loss of productivity) and chronic bronchitis cost the European society on the order of 84 billion Euro per year. Experiences with "Your Air" services in the UK suggest that the number of incidents can be reduced if vulnerable people can be warned beforehand that excess values of critical air pollutants are to occur, thereby preventing people from being fully exposed by altering their behaviour.

The satellite data used in combination with in-situ measurements enhanced the accuracy of the AQ forecasts. New methods use a model ensemble approach for AQ forecasting on a European scale and easy data access to the public via the internet (http://www.gse-promote.org/) have been successfully established.

These services are now being extended within the EC GMES projects PASODOBLE and MACC. User involvement on several levels resulted in the definition of the GMES Atmosphere Services (GAS) and its Core Service (GACS) meeting user requirements by using data in an integrated way (in-situ, satellite, modelling/assimilation) [GACS, 2009]. The need for high spatial and temporal resolution satellite data for regional to local air quality applications was identified during the process of service definition. Currently first core services are under implementation within the project MACC at ECMWF, a pilot project for GACS.

In the US, NASA’s Air Quality Applications program promotes innovative uses of NASA Earth science products to enhance air quality planning, forecasting, assessments of regulatory activities, and emissions inventories. The US National Oceanic and Atmospheric Administration (NOAA) has responsibility to provide numerical guidance for national air quality forecasts, which are the responsibility of the US Environmental Protection Agency (EPA). EPA also provides national air quality policy, regulation, and enforcement. These agencies have become increasingly sophisticated in their abilities to use satellite observations to assess compliance to regulatory action, to forecast air quality for health services, and to develop regionally effective air quality strategies. Partnerships among the three agencies address forecast model development and evaluation (Joint Center for Satellite Data Assimilation), joint research projects that investigate the detailed relationships between remotely sensed and in-situ measurements of pollutants (for example, Al-Saadi et al. [2005], Pierce et al. [2009]), and techniques to bridge disciplines of atmospheric composition and public health, urban planning, and economics.

The National Finance Act of Korea requires that a benefit-cost analysis be conducted to justify the significant investment required by space development programs. An important part of this benefit-cost analysis is to identify and quantify social benefits of each instrument utilizing various methodological approaches provided by economic science. Unlike conventional environmental policies where environmental qualities such as air and water are directly affected, geostationary observations will provide air quality-related data products and applications with more accuracy and higher frequency. Once air quality monitoring and forecasting data are released to the public, they can serve as relevant environmental information to positively affect economic agents’ activities, which can include individuals, companies, local governments, and the nation as a whole. Therefore, measuring the economic value of added air quality information becomes an integral component of social benefits from the project.

In correspondence to the nine Societal Benefit Areas of GEOSS in space applications, Japan emphasizes Disasters, Climate and Water. Therefore, the long-term Earth observation plan of JAXA consists mainly of contribution to these three areas. JAXA develops and operates space systems for disaster monitoring (ALOS and its follow-ons ALOS-2 and 3), climate changes and water cycle variation (Global Climate Observing Missions GCOM-W and GCOM-C, Cloud Profiling Radar on the EarthCARE satellite, Dual-frequency Precipitation Radar on the GPM satellite), and global warming and carbon cycle changes (GOSAT) that are dedicated to the corresponding SBAs. Recently JAXA has developed a concept on Space Initiatives for Health, such as information systems for Air Quality and Aerosol Mapping and Vector Habitat/Transmission Route Characterization and Mapping. ALOS, TRMM, Aqua/AMSR-E, and follow-on missions (ALOS-2&3, GCOM-W&C, and GPM) are used for land cover mapping and environmental monitoring (e.g., rainfall, sea surface temperature, aerosol) which will be significant for health effects and climate change monitoring. The geostationary atmospheric and meteorological satellite is in phase A study, preparing for air quality and aerosol monitoring.

Making these measurements with accuracy sufficient for air quality and climate needs is technically feasible; the challenges are finding the necessary funds to build the system and develop the logistical infrastructure. The limitations of funding result in the currently planned geostationary missions having no coverage for large parts of the world societal need is large and where anthropogenic activity is of great significance, including Africa, Western Asia, and South America. The recognition of the need for accurate evidence of health hazards and short lived and long lived greenhouse constituents has never been higher. Coverage from the system being currently planned could be extended to include the missing regions with the provision of additional funding.

3.2 Air quality science

Air quality regulations are in general based on epidemiological and toxicological studies that indicate threshold values below which no additional risks to population or vegetation are determinable. Current insights [WHO, 2003b; US EPA, 2009b] indicate increasingly lower thresholds for many pollutants and it is to be expected that legislation will follow this trend. The air pollution regulations of the USA, Japan, and the EU are rather similar and it may be expected that developing countries will to a large extent follow these legislations. Table 4 is a partial listing of current legislation and conventions related to air pollution and Table 5 lists the concentration standards used in the EU, Japan and USA. With the lowering of exposure thresholds, geographically larger extents of populations will be subject to the adverse health effects of poor air quality.

Ozone (O_3) has been associated with health effects, in particular pulmonary and cardiovascular diseases, and crop and ecosystem damage even under moderate concentration levels. O_3 is not emitted directly but is produced in the troposphere by the photochemical oxidation of CO and hydrocarbons in the presence of reactive nitrogen oxides [Haagen-Smit, 1964] and in the stratosphere by natural photolysis of oxygen. Its budget in the troposphere is controlled by the balance between photochemical production and loss, transport from the stratosphere, and deposition at the surface.

Nitrogen dioxide (NO_2) is associated with adverse respiratory effects, is the most important precursor for production of O_3 in the troposphere, and is important to aerosol formation. Because of rapid photochemical cycling among the reactive oxides of nitrogen, it is usual to consider their total combined amounts, or NO_x, in emissions frameworks (Figure 6). The burning of fossil fuels is the largest NO_x source. Mobile sources, i.e. vehicles with combustion engines, are the largest emitters of NO_x. There is large uncertainty in mobile source emission estimates and their spatial and temporal variability further complicate their representation in air quality models. Other large tropospheric NO_x sources, including biomass burning, soil emissions, and lightning, are also highly variable. Biomass burning is always episodic and is subject to both natural and anthropogenic factors. Soil NO_x emissions pulse following precipitation and in rural regions these emissions may be larger than anthropogenic sources. Overall, NO_2 undergoes large variation throughout the day (Figure 7) because of variations in emissions (e.g., morning and afternoon rush hours) and the diurnal photochemical cycling with other nitrogen species. Largest variations are not necessarily spatially correlated with largest NO_2 concentrations, yet both characteristics are important to air quality.

Aerosols, in particular particles of 2.5 micrometer diameter or less ($PM_{2.5}$), have profound impacts on human health and life expectancy [e.g., Neuberger et al., 2004; Pope et al., 2009; http://www,aphekom.org] and also play an important role in the climate system because they interact with solar radiation through scattering and absorption. Particles enter the atmosphere either directly via physical processes (combustion and burning, dust, sea salt, biological debris, pollen, bacteria), or are formed in the atmosphere via gas to particle conversion (e.g. sulphate, nitrate, ammonium, secondary organic aerosol). While the importance of aerosols and their interaction with air quality and climate change has been realized, there are still important knowledge gaps concerning the processes of gas-particle reactions, cloud chemistry, precipitation formation, and radiative interactions [e.g. IPCC, 2007].

Carbon monoxide (CO) is one of the most common and widely distributed air pollutants. CO is not a direct health concern, although recent work shows a possible link between urban concentrations of CO and cardiac function in rats [Meyer et al., 2010; Andre et al., 2010]. CO is a by-product of incomplete combustion and also generated in the process of atmospheric VOC oxidation. CO has strong contributions from biomass burning in particular and plays an important role in regulating the budget of OH radicals. Its moderate lifetime and insolubility make it an excellent tracer for the detection of long-range and convective transport.

Volatile organic compounds (VOC) are responsible, together with NO_x, for the photochemical formation of O_3 and other photo-oxidant pollutants including secondary aerosol. VOC are emitted from car traffic, industrial processing and solvent use, and there is a strong contribution from the biosphere. They are removed from the atmosphere by reaction with the hydroxyl radical and subsequent oxidation to CO_2 and H_2O. The main importance of VOC is in the lower troposphere over, and downwind of, populated areas, and in regions with high natural emissions (e.g., isoprene and terpenes). Several VOC compounds have been identified to cause health damage. Formaldehyde (HCHO) and glyoxl (CHOCHO), intermediate products of VOC oxidation giving information about methane and non-methane hydrocabons, are detectable from satellites and their measurement provides a good indication of the overall amount of VOCs present.

Sulphur dioxide (SO_2) is a key species in particle formation and in acid rain. At the present time SO_2 concentrations have declined by an order of magnitude or more in European and North American cities due to abatement measures and replacement of coal by cleaner fuels. However, there are still occasional peaks in concentrations, possibly the result of distant emissions from coal burning sources. These are important because in a cleaner atmosphere, with lower particulate loads, the health effects may be driven more by short term exceedances than by long term averages.

Despite some decades of research, there are still considerable knowledge gaps with respect to the sources, mechanisms, and impacts of air pollution. To a significant extent, this is due to incomplete or inadequate observational data. Ground based measurements alone cannot provide a representative description of the atmospheric composition as they are often influenced by local pollution sources and orographic effects, and there are some issues concerning the homogeneity of data quality and standardisation of methods between national or regional authorities. The situation has generally improved over recent years because of the successful employment of observations from research satellite instruments such as TOMS, GOME, MOPITT, SCIAMACHY, and OMI (Table 1) and because of routine and campaign measurements from aircraft. However, these systems generally do not offer a long-term perspective, and there is currently no clear mandate for the long-term monitoring of tropospheric composition from space and aircraft. There is an urgent need for better integration of the existing ground-based, airborne, and satellite systems, for example by further developing numerical models and data assimilation [EU, 2004; IGACO, 2004].

Capabilities of satellite remote sensing for air quality observations have progressed dramatically over the last decade (Table 1; Figure 1) [Fishman et al., 2008; Martin, 2008; Hoff and Christopher, 2009]. Satellite remote sensing is being applied to infer ground-level $PM_{2.5}$ concentrations from retrieved aerosol optical depth at regional [Engel-Cox et al., 2004; Liu et al., 2004; Al-Saadi et al., 2005] and global [van Donkelaar et al., 2010] scales. Lamsal et al. [2008] extended this approach to estimate surface NO_2 concentrations from satellite observations of NO_2 columns. There are encouraging prospects for improving satellite-based estimates of lower tropospheric O_3 [Worden et al., 2007; Liu et al., 2010]. Satellite observations complement ground based networks by providing data over the large parts of the globe where there are no surface monitors and are now essential tools for evaluating air quality models and improving emissions inventories.

To date these advances have largely been made with the approximately daily observations available from polar orbiting satellites in low Earth orbit. Due to the presence of clouds, and orbital and instrument viewing characteristics, a particular spot on the globe may be viewed only every few days. These data have been invaluable for monitoring trends that can be discerned from monthly averages (Figure 4). Yet continuous observations throughout the diurnal cycle from geostationary orbit will fundamentally improve capabilities for monitoring air quality and important controlling processes that vary hourly and daily. Such observations will allow spatio-temporal emission patterns, such as those associated with vehicle emissions, to be deconvolved from meteorological parameters such as wind speed and boundary-layer growth and collapse. Impacts of episodic events important at various times of day, such as biomass burning and convective redistribution, can be determined. Hourly observations will enable improved health exposure assessment, complementing the sparse spatial sampling of regulatory networks especially in rural or developing regions [Paciorek and Liu, 2009]. A geostationary constellation offers the near-global spatial and temporal coverage needed to address world-wide public health.

The improved temporal and spatial constraints that geostationary observations will place on regional scale emissions and atmospheric processing are critical for quantifying the episodic export of pollutants to the free troposphere. The cumulative export and subsequent long-range transport of pollutants from all regions establishes background air quality levels throughout the hemisphere. With joint coverage of the entire industrialized world at comparable resolutions and accuracies, a geostationary constellation will collectively enable better quantification of the impact of long-range transport on regional and global air quality. Such knowledge will be particularly important in crafting air quality compliance strategies in regions where the regional background is influenced by rapidly industrializing parts of the globe.

3.3 Climate science interrelated with air quality

There is increasing awareness of the strong interdependence of air quality and climate change. In particular, tropospheric ozone and aerosols are important to the atmospheric radiation balance in addition to being the key species regulated for air quality. These species, together referred to as short-lived climate forcers (SLCF) because of their relatively short lifetimes (less than one month) in the atmosphere, can be regulated to achieve both air-quality and climate-change mitigation objectives. Because of the commonality in sources of long-lived greenhouse gases (CO_2) and aerosol and ozone precursors, the concept of climate/air-quality co-benefits is receiving increasing policy emphasis [Pleijel, 2009; Nemet et al., 2010].

The most recent IPCC Assessment [IPCC, 2007] summarizes estimated anthropogenic radiative forcing (RF) estimates for tropospheric ozone and aerosols (1750-2005, direct and indirect combined) as +0.35 and -1.2 Wm-2, respectively. The uncertainties in these estimates, approximately a factor of 2, are large compared with other forcing agents. Tropospheric ozone has the third highest impact as a greenhouse gas in terms of direct RF but is distinguished from other greenhouse gases by having significant spatial and temporal heterogeneity, due to large global variations of ozone precursors and the relatively short lifetime in the troposphere. Ozone is also coupled with other greenhouse gases such as methane and carbon dioxide through chemical and indirect effects. Ozone chemical loss is dependent on water vapor. Ozone destruction in turn decreases the lifetime of methane, the second most important greenhouse gas. These interactions lead to chemistry-climate feedbacks with water vapor and methane [Stevenson, et al., 2006]. Ozone has additional climate impacts through the carbon and hydrological cycles by reducing global primary productivity and therefore the CO_2 uptake by biota. Sitch et al. [2007] estimated that suppression of CO_2 uptake due to ozone damage could lead to an indirect RF of 0.62 to 1.09 W/m2.

Studies since the 2007 IPCC Assessment have found that changes in SLCF are expected to have a significant impact on global temperatures, especially over the northern hemisphere [Levy et al., 2008a]. By 2050, short-lived air pollutants could be responsible for up to 20% of simulated global mean annually averaged warming and up to 40 percent of the total projected summertime warming in the central United States [Levy et al., 2008b]. However, the contribution of short-lived species to simulated change in global-mean surface temperature has a strong regional dependence [Shindell and Faluvegi, 2008]. The feedback of climate change onto AQ is another important facet. Physical climate change (changes in temperature, winds, and the hydrological cycle) will directly and fundamentally impact AQ [Jacob et al., 2009]. Biomass burning is a large and variable source of aerosol and O_3 precursors, and climate-related changes associated with drought and species migration [Soja et al., 2006] will change locations and intensities of fires, thereby changing emission amounts and injection altitudes. All of these factors have led to an increasing interest in policies that mitigate both poor air quality and global warming [West et al., 2006; West et al., 2007; Van Vuuren, 2006; Wallack and Ramanathan, 2009; Ramanathan and Xu, 2010], with the concomitant need for accurate measurements and models.

Field campaigns have been initiated to examine these potential co-benefits. For example, the recent NOAA CalNex field study focused on addressing science questions that are at the nexus of air quality and climate change within California (http://esrl.noaa.gov/csd/calnex/scienceplan.pdf). Emissions associated with the combustion of fossil fuels account for the vast majority of California's CO_2, NO_x, black carbon, and SO_2 emissions. From an AQ/Climate co-benefit perspective, reductions in fossil fuel consumption can lead to improved air quality due to reductions in ozone precursors and less climate warming due to lower CO_2 emissions and lower tropospheric ozone. Similarly, reductions in emission of black-carbon aerosols, which are highly absorbing, can lead to improved air quality and less climate warming due to less absorption of solar radiation. On the other hand, while reductions in SO_2 emissions have led to significant improvements in air quality due to reduced sulfate aerosol loading, they have also lead to decreased atmospheric cooling due to aerosol scattering which offsets green house gas warming. Quantitative information on non- CO_2 green house gas emissions such as methane, ozone and aerosol precusors such as NO_x and SO_2, and primary aerosol emissions is necessary to understand their relative impacts on the atmosphere, both in terms of air quality and climate change.

Geostationary observations offer a potentially unique resource for climate research through the information that they can provide on (1) diurnally varying concentrations and fluxes of climate forcing agents including the essential climate variables ozone, aerosol and long-lived greenhouse gases, (2) 24-hour integrated radiative forcing by ozone and aerosol on the continental scale, and (3) continental outflow of ozone and aerosol to drive global radiative forcing. Radiative forcings from aerosol and ozone have large diurnal variations due to changes in their column amounts, changes in sun geometry, coupling with cloud cover, and surface properties. LEO satellites in sun-synchronous orbit can induce significant aliasing, while a geostationary platform can resolve this diurnal cycle. By integrating the top-of-atmosphere outgoing radiation over 24 hours, a geostationary satellite can provide a direct and unbiased measure of the radiative forcings from these two agents on a continental scale. Measuring this continental-scale forcing is important not only because it contributes to the overall global radiative forcing from the source continent but also because it can elicit a regional climate response. Export of aerosol, ozone, and their precursors from the source continents further adds a global component to the radiative forcings from PM and ozone, even though exported fractions are small, because lifetimes in the free troposphere are long. Continuous observation of continental venting from a geostationary platform is needed to quantify this export and thus complete the characterization of radiative forcing associated with pollutant emissions. Geostationary observations thus offer a unique perspective for better understanding the interactions between air quality and climate forcing.

3.4 Other measurements and modeling capabilities in an integrated system

Surface networks provide the reference standard measurements for regulating air quality. Networks have been put in place to satisfy a range of requirements. Local sites are used for quantifying the exposure of people to regulated pollutants and for monitoring emissions. Regional or background monitoring sites are important for determining source-receptor relationships, transboundary air pollution, and exposure of crops. Surface networks also provide needed ancillary measurements for relating satellite measurements of column integrated trace gas and aerosol abundances to boundary layer concentrations.

The U.S Environmental Protection Agency's (EPA) National Environmental Monitoring Initiative supports a number of networks including the State and Local Air Monitoring Stations (SLAMS), National Air Monitoring Stations (NAMS), Clean Air Status and Trends Network (CASTNET), and Photochemical Assessment Monitoring Stations (PAMS). Combined, these networks provide measurements at over 3000 sites; even so, the coverage is considered too sparse to fully assess population and ecosystem exposure [Demerjian, 2000]. Most routine air quality monitoring stations in the US are owned and operated by nearly 300 state and local governmental and Tribal agencies. These SLAMS sites are the principal source of ambient measurements of the six criteria air pollutants (ozone, nitrogen dioxide, carbon monoxide, sulfur dioxide, lead, PM_{10} and $PM_{2.5}$), each of which has one or more National Ambient Air Quality Standard specifying a specific concentration level and averaging period (http://www.epa.gov/ttn/naaqs/). Most of these networks also include stations operated by federal agencies, typically in rural/remote sites.

In Europe, AQ monitoring is coordinated at a hierarchy of levels ranging from local and regional authorities to country and ultimately European level. Coordination to European level is achieved through EMEP and the European Environment Agency (EEA). Within GMES, EEA has a mandate to coordinate surface air quality observations from the different member states of the Union. Observations of O_3, NO_2, CO, SO_2, PM_{10}, and $PM_{2.5}$ are gathered for a total of a few thousand sites in the database Airbase. However, as is also the case in the US, a large fraction of the sites are under the influence of local sources (urban, industrial or traffic emissions) and have low spatial representativeness. In the project GEMS and its successor MACC, near-real-time concentration measurements have been demonstrated for approximately 1200 sites in 14 European countries, allowing for pre-operational assimilation and verification activities.

There are national air quality monitoring networks in each country in East Asia, however their data are in general not open to the public. For example, in China there are a number of monitoring sites at provincial and national levels but the data are not yet distributed to the public. While long-lived greenhouse gas data at WMO/GAW sites are reported to the world data center, air quality related measurements such as surface O_3 data are not yet reported. Air quality monitoring networks in East Asia include the Acid Deposition Monitoring Network in East Asia (EANET), established in 1998 with 13 participating countries. There are currently 55 monitoring sites for wet deposition and 44 sites for air concentration monitoring. While EANET initially emphasized rainwater monitoring, a filter pack method is now generally used to measure NO_2, SO_2, HNO_3 and aerosol ion components. Real-time air concentration measurements of O_3, NO_x, SO_2, and PM_{10} are made at selected sites. All the data are submitted to and compiled by the Asia Center for Air Pollution Research (ACAP) and open to public (http://www.eanet.cc/product/index.html#datarep). The spatial coverage of EANET is too sparse considering the vast area of East Asia. For example, in China there are only four monitoring cluster centers, at Xi'an, Xiamen, Chongqing, and Zhuhai.

In Japan, there are over a thousand air quality monitoring sites nationwide. These data are open to public in near real-time (http://soramame.taiki.go.jp/). Monthly averaged annual data are also open to public through the National Institute for Environmental Studies (NIES) (http://www.nies.go.jp/igreen/index.html).

The air quality monitoring network in Korea is operated by NIER of ME. As of the end of December 2007, there were 410 nationwide observation sites and an additional 227 urban atmosphere monitoring sites. There is also one global atmosphere observation site in the Jeju area that regularly monitors global warming and ozone-depleting substances. The data collected by the nationwide air quality monitoring network is processed by the National Atmosphere Pollution Information Management System (NAMIS, collaboratively operated by the Ministry of Environment and the Environment Management Corporation) and is utilized as a resource for the regulation of the atmosphere in order to understand air quality, analyze the effectiveness of environmental regulations, and preserve the health of citizens. Among the data collected by NAMIS, 5 criteria air pollutants (SO_2, CO, NO_x, PM_{10} and O_3) are distributed to the public in real time.

Aircraft have been used for many years to probe the free troposphere and lower stratosphere on a research basis. Routine aircraft measurements are an efficient means of obtaining information on the upper troposphere/lower stratosphere (UT/LS) and vertical profiles in the troposphere at high resolution and with uniform quality. The first use of commercial aircraft for regular atmospheric observations was the NASA Global Atmospheric Sampling Programme (GASP) in the 1970s. GASP was terminated in 1979 but the idea was reactivated in the 1990s. In the European programme MOZAIC (Measurements of OZone, water vapour , carbon monoxide and nitrogen oxides by in-service AIrbus airCraft), automatic instruments for O_3 and H_2O (plus CO and NO/NO_y in 2001) were installed on several commercial aircraft in 1994 and have provided regular data for the UT/LS with more than 2000 flights and 4000 tropospheric profiles per year. Other projects with commercial aircraft include grab sampling packages, flown biweekly since 1993 between Australia and Japan, to provide CO_2, CH_4 and CO data at cruise altitude. The Swiss NOXAR project provided the first regular NO_x data with 500 flights between 1995 and 1996. In CARIBIC, an air freight container with in situ instruments for O_3, CO, and aerosol measurements and grab samples for VOCs, CFCs, N_2O and isotopic analysis was deployed during 83 flights between 1997 and 2002. Most ongoing projects are funded under short term research contracts and are in continuous danger of being terminated. The MOZAIC measurements will be carried into a high level monitoring programme with an expansion in global coverage and measurement capabilities through the follow-on program IAGOS (In-service Aircraft for a Global Observing System).

Numerical models of atmospheric dynamics and composition provide the only way to integrate measurements from different platforms and with varying spatial and temporal extent into a continuous and self-consistent analysis of the state of the atmosphere. A critical challenge is to bring together the myriad in-situ and remote observational capabilities in such a way that the collective data are used efficiently and confidently to enable monitoring, prediction, retrospective analysis, and the development of sound science-driven policy. The IGACO report [2004] emphasized the need for a strong modeling and data assimilation effort that brings together all the measurements and provides the necessary theoretical framework for advancing the science to a higher level.

There are two basic modeling approaches for synthesizing measurements from an integrated observation system. The traditional approach uses a chemical transport model (CTM), which is driven by independent meteorological analyses and forecasts that constrain the prevailing meteorological conditions under which emissions are chemically processed within diurnal cycles of photon flux. Alternatively, the emissions and chemical processing can be performed online within the meteorological modeling system. This allows explicit coupling between meteorology, chemistry, and aerosols, including improved representation of turbulent and convective mixing processes, radiative feedbacks, and aerosol/cloud interactions. In either case, the chemical model is based on the laws of physics, an emissions module, and a chemical module, which may include tens or hundreds of species and hundreds or even thousands of chemical reactions. The simpler gas phase chemical reactions are treated explicitly, but aerosols, liquid processes in cloud droplets, and often the reactions of some larger chemical species are treated through parameterization.

Present global CTMs are reasonably successful in characterizing the present day large-scale distribution of atmospheric trace gases [Stevenson et al, 2006; Shindell et al., 2006; Fiore et al., 2009] and aerosols [Textor et al, 2005; Kinne et al., 2005] although there are weaknesses in the parameterisations, the emission scenarios, and the chemical and aerosol mechanisms used. The mathematically most robust way to incorporate measurements of the atmospheric chemical composition and their uncertainties into a model is data assimilation. Different data assimilation methods have been developed, which often require considerable computational efforts (e.g. Optimal interpolation, 3D-variational or 4D-variational assimilation, Kalman filter). While data assimilation has been used for some time now in numerical weather prediction, its application to chemical models is still in the pioneering phase. The European Global and Regional Earth-System Monitoring Using Satellite and In situ Data (GEMS) project [Hollingsworth et al., 2008] is the first attempt to develop an operational global to regional assimilation/forecasting system to support air quality prediction and climate change applications. GEMS is an extension of the Integrated Forecasting System (IFS) used operationally at the European Center for Medium Range Weather Forecasts (ECMWF). The ECMWF four-dimensional variational data assimilation (4DVAR) system has been extended to allow assimilation of satellite measurements of atmospheric trace gases and aerosols. Ground-based observations are used for assimilation and validation of the GEMS analyses.

Accurate prediction of regional and local air quality is complicated by the combined influences of spatio-temporal variations in background concentrations, photochemical production, local emissions, and meso-scale circulation patterns [Pierce et al., 2009]. Evaluation of ozone forecasts from the NOAA National Weather Service North American Meso-scale (NAM) Community Multi-scale Air Quality (CMAQ) Modeling System (NAM-CMAQ) [Otte et al., 2005] and Weather Research and Forecasting model with chemistry (WRF-chem) [Grell et al., 2005] during the Second Texas Air Quality Study (TexAQS II) [Wilczak et al., 2009] showed that both models failed to capture the observed frequency of both low and high ozone events in Houston, TX. Forecast models require near-real-time chemical data acquisition and meteorology, typically within three to six hours. For rapidly varying species, sampling must be frequent enough to capture these variations. For example, species that exhibit significant diurnal variation require measurements at sub-daily and, ideally, hourly intervals. Building an operational system for chemical weather forecasting imposes challenging requirements on the quality and consistency of the input data, the quality and reliability of the data generation and distribution, as well as the long-term continuity prospect of the entire system.

The inclusion of accurate time-dependent emission scenarios remains a key weakness of many of these models, particularly with regard to biomass burning [Al-Saadi et al., 2008] and mobile source [Sawyer et al., 2000] emissions. The hourly observations of trace gases and aerosols from geostationary platforms will greatly advance our understanding of regional scale transport processes and provide valuable constraints on modeled emissions, either through emission adjustments using inverse modeling approaches or adjustment of trace gas and aerosol mixing ratios using data assimilation.

4 Collaboration opportunities

The simultaneous development of these individual missions over Earth's industrialized regions presents a clear opportunity for International collaboration to improve the preparation for these missions and their collective capabilities within a global system. While recognizing that unique requirements exist for individual missions, this vision defines objectives of mutual benefit that build a foundation for a future integrated observing system for atmospheric composition. Best efforts to cooperate on defining common requirements, capabilities, retrieval algorithms, data quality, data access, and assimilation systems can enable improved designs and data products of all sensors and allow cost savings by minimizing duplication of effort. Work to harmonize retrievals and to use similar design tools such as OSSEs will also enable future instruments to be jointly defined with consideration given to continuity and consistency of observations, possibly extending to assessment of opportunities for cost synergy of building multiple copies of the same instruments to put on different platforms around the globe.

4.1 Mutual participation in mission working groups

Because of the commonality in measurement objectives of each of the geostationary missions, mutual participation in the respective mission science advisory groups would provide an effective means of ensuring that emerging capabilities continue to be widely applied as soon as possible. Mission requirements for measurement precision, frequency of observation, and spatial resolution are defined to address specific objectives for end-user applications and science questions. These requirements are established through scientific analysis of satellite data, airborne data, and model simulations. Regular interaction of the scientific and application leadership of these missions will help advance preparations for widespread use of the data once the missions are operating. This interaction will also enable synergistic definition of common instrument requirements for those missions in which final requirements are still under refinement.

4.2 Scientific collaboration on retrieval algorithms and approaches

There is widespread interest in capabilities to obtain more information on the vertical distribution of trace gases and aerosols from nadir viewing satellite instruments. A particular emphasis is improved sensitivity to the lower troposphere. Each of these missions is considering multi- or hyper-spectral instrument concepts and panchromatic retrieval algorithms. The use of a broader set of wavelengths improves sensitivity to vertical distribution and characterization of cloud and aerosol properties. Individual working groups are now assembling analysis codes and geophysical data that allow for forward model (radiative transfer) calculations to perform linearized retrievals with consistent constraints to quantify the potential sensitivity of trace gas and aerosol retrievals to different wavelength combinations. Analysis of ozone sensitivity (averaging kernels, estimated errors) is underway, including comparisons of UV, visible, crossover, and infrared bands and combinations of these bands. Polarization of the UV measurements is also being studied. A particular focus is quantifying the changes to sensitivity in the troposphere, particularly the lower troposphere, when combinations of bands are included (building on previously published papers, e.g., Worden et al., 2007; Landgraf and Hasekamp, 2007). Other molecules, including HCHO, SO_2, CO, and CH_4, are now being analyzed in the same framework. These fundamental analyses are applicable to all of the geostationary missions, and focused scientific collaboration would foster exchange of the findings and enable more fundamental calculations to be defined and conducted. Aspects of fundamental algorithm improvements that could be considered for both existing as well as future GEO and LEO missions include a-priori, fitting windows, air mass factors (including clouds and aerosol), surface reflectivity, and maintaining and improving spectroscopic databases.

4.3 Collaborative Observing System Simulation Experiment Studies

A constellation of geostationary satellites that measure environmentally significant trace gases and aerosols will revolutionize our capacity to predict and understand air quality at both regional and global scales. Systematic examination of the key measurement requirements of each satellite and their combination will allow optimization to ensure that specific air quality objectives can be achieved [Fishman et al., 2008; Martin et al., 2008]. The information has to be evaluated in the context of other existing air quality observing systems, in particular surface observations, to assess how the new measurements would complement existing or other proposed measurements. As in meteorology, chemical observing system simulation experiment (OSSE) studies have emerged as vital tools to help define quantitative measurement requirements for satellite missions and to evaluate the expected performance of proposed observing strategies. OSSE frameworks usually consist of measurement simulation, data assimilation and modeling elements [Edwards et al., 2009; Masutani et al., 2010; Claeyman et al., 2011 a,b]. A model is used to produce "nature" runs that are then sampled with the expected instrumental characteristics and noise. These synthetic observations are assimilated in other models and their ability to constrain hindcasts or forecasts is evaluated against the reference "nature" run. The outcome of an OSSE is critically dependent on its experimental design, the specific question(s) to be addressed, and the level of sophistication used to simulate each of the elements. Since the different GEO platforms of the international constellation each face the task of quantitatively evaluating the performance of similar measurements, and considerable resources are required to perform such studies, there exists an opportunity for the science teams to collaborate on OSSE studies. It would be particularly useful to consider several models and assimilating systems in performing nature runs and assimilation experiments. Such collaboration would facilitate the exchange of ideas and standardization of experimental approaches, leading to greater confidence in the use of OSSE results as a basis for instrument and observing strategy trade-off studies and cost-benefit analyses.

4.4 Improved quantification of Societal Benefits

Identifying and/or measuring social benefits are common requirements for these missions. However, the application of standard benefit analysis techniques to satellite data is still in its infancy, particularly for atmospheric composition observations. Better benefit-to-cost analyses critically depend on definition of standard methods for quantifying measurement uncertainties of satellite tropospheric composition observations. Collaboration through an OSSE framework as described above would be one way to inform such standard definitions. Previous studies have conducted benefit analyses for observations from geostationary meteorological satellites. Tropospheric composition data have policy implications (e.g., air quality assessment, emissions source attribution) that introduce additional aspects to benefit analysis. An international focus on this topic has the potential to revolutionize value assessments of satellite observations. A goal for the foreseeable future would be practitioner-friendly standardized approaches describing both theoretical and empirical aspects of measurement of social benefits of geostationary satellite projects. International cooperation among scholars in diverse academic disciplines in addition to the involvement of active researchers in various institutions will be needed to facilitate this process.

4.5 Data quality, content, access and utilization

There is tremendous mutual benefit to enhancing data quality of all missions in the constellation and in ensuring timely mutual data access to their data. Exploiting these regional data to the fullest extent requires a high degree of commonality in the data products and in their characterization through consistent calibration and validation. Such activities align well with existing CEOS activities including the Working Group on Information Systems and Services (WGISS) and the Working Group on Calibration and Validation (WGCV). Best efforts should be made to harmonize data product content (e.g., the inclusion of averaging kernel information in the data files) and develop data format, archive and distribution protocols. All parties should also support a data sharing policy based on open exchange of data at minimum time delay. Given the mutual value of using these data within the global observing system, it is critical to conduct pre-launch calibration to common standards, also extending to the instruments on the LEO platforms to the extent possible. Collaborative activities should include developing pre-launch calibration goals, understanding post-launch calibration and validation approaches including measurements from airborne, ground-based and other satellite platforms, and beginning to plan for joint calibration activities. Finally, collaboration on advancing capabilities for better exploitation of such satellite observations will improve readiness for use of these data. These activities include ongoing development of chemical data assimilation systems and of fundamental research clarifying the relationships between satellite observations and surface air quality measurements.

4.6 Improvement of air quality models and data assimilation techniques

Advanced meteorological/chemical modeling systems are required to combine measurements from different platforms, with varying spatial and temporal characteristics, into continuous and self-consistent representations of the state of the atmosphere required for forecasting and assessment. While data assimilation has been used for some time now in numerical weather prediction, its application to chemical models is still in the pioneering phase, although developments are increasing in maturity [Lahoz et al., 2007; Elbern et al., 2010]. Concerted and sustained collaborative effort to accelerate such model development will help the air quality user community prepare for the routine use of these satellite observations. A particular emphasis should be simultaneous multi-constituent chemical/aerosol data assimilation encompassing the range of scales from in-situ point measurements to remote satellite observations from LEO and geostationary platforms.

5 Justification for at least a one year overlap

Satellites can provide urgently needed quantitative data for estimating the contribution of distant and local emission sources on ambient pollution levels. Observations of tropospheric composition many times per day from geostationary orbit will provide an entirely new perspective for regional and local air quality forecasts and assessments. Geostationary air quality missions are scheduled for launch from countries with major concerns for regional and local air quality and that have made major investments to understand and provide operational data for air quality applications. These countries include the European Union, Japan, Korea, and the United States. While these missions are planned to serve each country's operational and scientific needs, the missions flying as a constellation will provide a watershed demonstration of the capability of Earth's space faring nations to work together for the benefit of our planet. A unique opportunity arises to fly these missions nearly simultaneously.

These missions will collectively provide coverage over the major industrialized Northern Hemisphere continental regions. A specific collaboration goal should be to for all of the missions to overlap in their on-orbit lifetimes by at least one year in order to capture at least one full annual cycle of emissions and intercontinental transport within the mid-latitude pollution belt of the Northern Hemisphere. A constellation approach will *enhance* several technical and operational activities, including more effective and efficient calibration/validation activities through use of common calibration and validation assets, improved algorithms through mission team exchanges, and data sharing and enhanced interoperability of mission data products. More critically, such a constellation will *enable* global relevance of the observations and associated science and policy.

Trans-border and intercontinental transport of pollution continues to emerge as an important policy issue. The Convention on Long-range Transboundary Air Pollution is an example of a cooperative venture that brings together countries, regions and continents to implement effective action for cleaner air. The 2009 NRC report "Global Sources of Local Pollution" identified frequent satellite observations of pollutants as a key component of improving capabilities for characterizing long range pollutant impacts and predicting future trends. User requirements for such observations have been developed by various international organizations and compiled within the WMO Space-based Component of the Global Observing System (GOS-2010) (available at http://www.wmo.int/pages/prog/sat/Refdocuments.html). As an example, considering aerosol, O_3 and NO_2 in the lower troposphere, satellite observing requirements for air quality include a repeat cycle of 0.5 hrs objective/ 2 hrs breakthrough/ 4 hrs threshold and a spatial resolution of 5 km objective/ 20 km breakthrough/ 50 km threshold. These geostationary missions will each achieve repeat cycles and spatial resolutions at the breakthrough level and approaching the objective level. Operating together in a constellation, they will collectively meet these air quality user requirements for the industrialized Northern Hemisphere. Currently planned LEO missions provide global coverage but will not achieve even the threshold repeat cycle.

Quantifying emissions of pollutants is central to air quality policy. Satellite observations provide unique constraints, particularly when used within inverse modeling frameworks. Standardized methodologies are increasingly being applied in development of first-time and updated emissions inventories around the planet (for example, http://www.epa.gov/ttn/chief/conference/ei18/index.html). There is tremendous policy relevance of having simultaneous continuous observations, of uniform quality and consistency, of pollutants emitted from the entire industrialized world. Through the observations and associated science and applications enabled by the coordination described herein, it will be possible to effectively address the over-arching policy relevant science questions posed by the Hemispheric Transport of Air Pollution report (2007), particularly including the following:

> For each region in the Northern Hemisphere, can we define source/receptor (S/R) relationships and the influence of intercontinental transport on the exceedance of established standards or policy objectives for the pollutants of interest? How confident are we of our ability to predict these S/R relationships? What is our best estimate of the quantitative uncertainty in our estimates of current source contributions or our predictions of the impacts of future emissions changes?
>
> For each country in the Northern Hemisphere, how will changes in emissions in each of the other countries in the Hemisphere change pollutant concentrations or deposition levels and the exceedance of established standards or policy objectives for the pollutants of interest?
>
> What efforts need to be undertaken to develop an integrated system of observational data sources and predictive models that address the questions above and leverage the best attributes of all components?

Satellite data for atmospheric composition have a particular relevance in Asia because of its continuing rapid economic growth. Asian air pollution on regional and mega-city scales is of major health and ecological concern not only within this region but also throughout the hemisphere. No Asian countries have yet joined the United Nations Convention on Long Range Transboundary Air Pollution, and the transboundary air pollution issue is a sensitive topic in Asian international politics. Simultaneously overlapping observations of air pollutants by geostationary satellites each focusing on Asian, European and North American emissions will document the flow of air pollutants over the annual cycle with global consistency. Such knowledge will greatly facilitate international discussion on transboundary air pollution and provide new observational insight that can lead to the development of future policy.

A minimum one-year overlap of these missions will allow a successful demonstration that the requirements for the space component of a global air quality observing system can be efficiently met with a constellation approach. Demonstration will also rely on sustained cooperation to improve the predictive and assessment models that will make use of such data. Once initiated and demonstrated, it should be straightforward to continue and extend the system to enable detection of longer term changes associated with compliance strategies and a changing climate.

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Tables

Table 1. Overview of recent and present polar orbiting satellite instruments which provide tropospheric composition information.

Instrument	Platform	Species	Time of operation
Interfereometric Monitor for Greenhouse Gases (IMG)	ADEOS	O_3, CO, CH_4	1996-1997
POLarisation and Directionality of the Earth's Reflectances (POLDER)	ADEOS	aerosol	1996-1997
Global Ozone Monitoring Experiment (GOME)	ERS-2	NO_2, O_3, HCHO, SO_2, BrO, H_2O	1996-2003
Sea-viewing Wide Field-of-view Sensor (SeaWifs)	SeaStar	aerosol	1997 -
Measurements Of Pollution In The Troposphere (MOPITT)	TERRA	CO	2000-2003
MODerate resolution Imaging Spectroradiometer (MODIS)	TERRA, AQUA	aerosol	2000- (TERRA) 2002 – (AQUA)
Atmospheric Infrared Sounder (AIRS)	AQUA	CO, CH_4, SO_2	2002-
SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY)	Envisat	NO_2, O_3, HCHO, SO_2, BrO, H_2O, CO, CH_4, CO_2	2002-
Ozone Monitoring Instrument (OMI)	AURA	NO_2, O_3, HCHO, SO_2, BrO	2004 -
Tropospheric Emission Spectrometer (TES)	AURA		2004 -
Global Ozone Monitoring Experiment-2 (GOME-2)	METOP-2	NO_2, O_3, HCHO, SO_2, BrO, H_2O	2005 -
Infrared Atmospheric Sounding Interferometer (IASI)	METOP-2	O_3, CH_4, CO, CO_2, (NO_2, SO_2, HCHO, PAN)	2005 -
POLarisation and Directionality of the Earth's Reflectances-2 (POLDER-2)	ADEOS-2	aerosol	2003 -

A comprehensive overview of current and planned satellite missions for upper atmosphere monitoring is provided at http://daac.gsfc.nasa.gov/upperatm/CODI/ozone_satellite.html

Table 2. Characteristics of the geostationary air quality missions planned for launch in the 2017-2020 timeframe.

	ESA Sentinel 4	**NASA Geo-CAPE**	**KARI MP-GEOSAT GEMS**	**JAXA GMAP-ASIA**
Launch	2018	~2020	2018	~2017
Domain	Europe and surrounding	Contiguous US and surrounding	Asia-Pacific	Japan and East China (4000 km×4000 km)
Resolution	8km x 8km (40N), revisit 1hr	8km x 8km (40N), revisit 1hr	5km x 15km, revisit 1hr	10km x 10km (310-600 nm), revisit 1hr
Payload	UV-Vis-NIR 305-500, 750-775 nm	UV-Vis-IR (tbd) 300-500 nm, SWIR 2.3 & 4.6 micron, Vis &/or TIR	UV-Vis (tbd) 300-500 nm	UV-Vis 280-600nm, TIR
Species	O_3, NO_2, SO_2, HCHO, AAI, AOD, height-resolved aerosol	O_3, NO_2, CO, AOD, HCHO. SO_2 (height resolved CO & O_3)	O_3, NO_2, SO_2, HCHO, AOD	O_3, NO_2 (SO_2, HCHO, AOD desired)
Notes	On meteo sounding platform MTG-S and in formation with meteo imager platform MTG-I. Use MTG-S TIR (expect sensitivity to large O_3 and CO events); synergy with meteo. imager w.r.t. aerosol/PM	Includes ocean color mission. In orbit with GOES-R series meteo imagers. Baseline mission to include TIR and additional species: CH_4, NH_3, CHOCHO, AAOD, AI, AOCH	Includes meteo and ocean color missions with meteo imager in formation. Optional accommodation for small IR instrument (CO, CO_2, CH_4)	Includes meteo mission. Hyperspectral TIR FTS: O_3, CO, HNO_3

Table 3. Current geostationary operational air quality products for which coverage of most of the Northern Hemisphere is provided by a constellation approach.

Product	Satellite	Location	Coverage	Error	Spatial Resolution	Product Provider
Aerosol Optical Depth[a]	GOES-E	65°W	15°N – 66°N 151°W – 52°W	0.04*	4 km	NOAA
	GOES-W	135°W	14°N – 75°N 180°W – 50°W	0.06*		
	MSG SEVIRI	0°	65°S – 65°N 65°E – 65°W	0.07*	3 km	EUMETSAT
	COMS MI	128.2°E	65°S – 65°N 60°E – 160°E	TBD	9 km	KMA[f]
	COMS GOCI	128.2°E	25˚N - 48˚N 115˚E-145˚E.	TBD	500 m	KORDI[g]
Fire Hot Spots/Fire size[b]	GOES-E	65°W	65°S – 65°N 140°W – 10°W	2%/50%	4 km	NOAA
	GOES-W	135°W	65°S – 65°N 160°W – 70°W	2%/50%		
	MSG SEVIRI	0°	65°S – 65°N 65°E – 65°W	N/A**	3 km	
	MTSAT-1R	140°E	40°S – 30°N 80°E – 200°E	N/A**	2 km	
Burned Area[c]	GOES-E	65°W	15°N – 66°N 151°W – 52°W	15%	4 km	NOAA
	GOES-W	135°W	14°N – 75°N 180°W – 50°W			
	MSG SEVIRI	0°	65°S – 65°N 65°E – 65°W	N/A**	3 km	
	MTSAT-1R	140°E	40°S – 30°N 80°E – 200°E	N/A**	2 km	
Biomass Burning Emissions[d]	GOES-E	65°W	15°N – 66°N 151°W – 52°W	30%	4 km	NOAA
	GOES-W	135°W	14°N – 75°N 180°W – 50°W			
	MSG SEVIRI	0°	65°S – 65°N 65°E – 65°W	N/A**	3 km	
	MTSAT-1R	140°E	40°S – 30°N 80°E – 200°E	N/A**	2 km	
Volcanic ash plume analysis[e]	GOES-E	65°W	15°N – 66°N 151°W – 52°W	N/A	N/A	NOAA
	GOES-W	135°W	14°N – 75°N 180°W – 50°W			
	MSG SEVIRI	0°	65°S – 65°N 65°E – 65°W	N/A	3 km	NOAA pre-operational[h]

[a] Accuracy estimates are determined using approaches described in Prados et al. (2007) but the accuracy numbers reported here are based on improved algorithm and new validation work based on multiple years of AERONET data.
[b] Fire product accuracy reported by Schroder et al., 2008.
[c] Burned area product accuracy reported by Zhang and Kondragunta, 2008
[d] Biomass burning emissions product accuracy reported by Zhang et al., 2008
[e] http://www.ssd.noaa.gov/VAAC/. Accuracy information for volcanic ash plume analysis is not available.
[f] Pre-operational, currently under IOT, algorithm described in Kim et al.(2008)
[g] Pre-operational, currently under IOT, algorithm described in Lee et al.(2010)
[h] Pre-operational (http://cimss.ssec.wisc.edu/goes_r/proving-ground/geocat_ash/loops/iceland.html), algorithm described in Pavlonis et al. (2006)
*AOD is a unit-less quantity.
** Error estimates are not available for SEVIRI and MTSAT-1R fire products but are expected to be similar to GOES.

Table 4. Legislation and International Conventions related to air quality.

Region	Description	Thematic Area	Further information
	Legislation		
EU	Summary of Existing Legislation in the EU	Air Quality	http://ec.europa.eu/environment/air/quality/legislation/existing_leg.htm
EU	Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe	Assessment of Ambient Air Quality in Europe	http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0050:EN:NOT
EU	CAFE programme Air Quality, Deposition	Transboundary Air Pollution	http://europa.eu/legislation_summaries/environment/air_pollution/l28026_en.htm
USA	Clean Air Act	Air Quality	http://www.epa.gov/air/caa/peg/
Asia	Overview of regulations in Asia	Air pollution, Climate Change	http://www.cleanairnet.org/caiasia/
Korea	Clean Air Conservation Act	Air Quality, Emissions	http://www.moleg.go.kr/FileDownload.mo?flSeq=26473
Korea	Indoor Air Quality Control in Public Use Facilities	Air Quality	http://eng.me.go.kr/content.do?method=moveContent&menuCode=pol_hnc_liv_ind_contents
	International Conventions		
Many	UNECE CLRTAP (CLRTAP, Geneva Nov. 1979;	Transboundary Air Pollution	http://www.unece.org/env/lrtap/lrtap_h1.htm http://rod.eionet.eu.int/show.jsv?id=578&mode=S
Many	Vienna Convention and Montreal Protocol	Stratospheric Ozone	http://www.unep.org/ozone/pdfs/montreal-protocol2000.pdf
Many	UNFCCC and Kyoto Protocol	Climate Change	http://unfccc.int/resource/convkp.html
Many	Convention for the protection of the marine environment of the north-east Atlantic	Pollution by off-shore activies.	http://www.ospar.org/
Many	Convention concerning the Protection of the World Cultural and Natural Heritage	Not yet direct links to air pollution.	http://www.unesco.org/

Table 5. Selected current EU, US, Japan, and Korea air quality concentration standards.

Species	Limit	Remark
Particulate Matter		
EU PM_{10}	24-hour limit value 50µg/m^3	Not to be exceeded more than 7 times/year. In effect 01.01.2010
EU PM_{10}	Annual 20µg/m3	Median of daily averages.
US PM_{10}	24-hour standard 150 µg/m3	Not to be exceeded more than once per year over 3 years
US $PM_{2.5}$	24-hour standard 35µg/m3	3-year average of 98% percentile
US $PM_{2.5}$	Annual standard 15 µg/m3	3-year annual average.
JAPAN Total Particulate Matter	24 hour limit 100 µg/m3 Hourly limit 200 µg/m3	Notification on May 8, 1973.
JAPAN $PM_{2.5}$	Annual standard 15 µg/m3 24 hour standard 35 µg/m3	Notification on September 9, 2009.
Korea PM_{10}	Annual average 70µg/m3 24-hour average 150µg/m3	ß-Ray Absorption Method
Ozone		
US O_3	8-hour standard 75-ppb	Effective May 27, 2008. Under review.
EC O_3	8 hourly limit 120 µg/m3	Health protection. Thresholds for information and alert are 180 and 240 µg/m3
EC O_3	AOT40= 6000 µg h/m3	Vegetation Protection. Accumulated ozone above 40 ppbv from May to July.
EC O_3	AOT40=20000 µg h/m3	Forest Protection. Accumulated from April to September.
Japan OXIDANTS	Hourly 60 ppbv.	Not to be exceeded. Notification on May 8, 1973. Maybe not latest information.
Korea O_3	8-hour average 0.06 ppm Hourly average 01.ppm	U.V. Photometric Method
WHO O_3	8 hourly 35 ppbv	Expected WHO standard, covering human health and ecosystem exposure.
SO_2		
EC SO_2	1 hour average 350µg/m3	Not to be exceeded more than 24 times/year
EC SO_2	24 hour average 125µg/m3	Not to be exceeded more than 3 times/year. Per 01.01.2005.
EC SO_2	Winter average 20 µg/m3	1 October-31 March.
Japan SO_2	Hourly 40 ppbv Daily 100 ppbv.	Notification on May 16, 1973.
Korea SO_2	Annual average 0.02 ppm 24-hour average 0.05 ppm 1 hour average 0.15 ppm	Pulse U.V. Fluorescence Method
NO_2		
EC NO_2	1 hour average 200 µg/m3	Gradually implemented, to be met 01.01.2010.
EC NO_2	Annual 40µg/m3	Gradually implemented, to be met 01.01.2010
EC NO_2	Annual 30µg/m3	For vegetation.
Japan NO_2	Daily average 40 - 60 ppbv.	Notification on July 11, 1978.
Korea NO_2	Annual average 0.05 ppm 24-hour average 0.08 ppm 1-hour average 0.15 ppm	Chemiluminescent Method

Figures

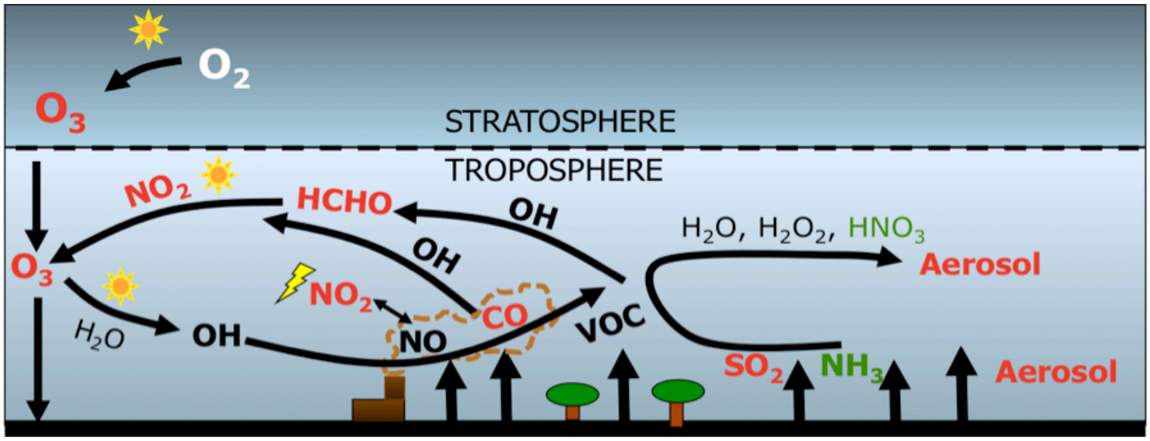

Figure 1. Schematic diagram of simplified tropospheric photochemistry. Species in red would likely be measured from a geostationary platform and species in green may possibly be measured. CO, NO, VOC, SO_2, NH_3 and aerosol are emitted in the planetary boundary layer from both anthropogenic and biogenic sources. NO_2 is rapidly converted in the troposphere from emitted NO and the two nitrogen oxides (NO_x) establish an equilibrium ratio between each other depending on a number of atmospheric variables such as the intensity of sunlight and the amount of O_3. HCHO is an intermediate product of VOC oxidation, and its measurement is a good indicator of the amount of VOC present. The amount of O_3 produced is directly proportional to how much NO_2 is present when sunlight is available (denoted by the "sun" symbol). Ozone can also be transported to the troposphere from the stratosphere where it is produced naturally by the photolysis of molecular oxygen. Lightning is also a natural source of NO_x in the free troposphere. In addition to direct emission/mobilization from the surface, aerosol particles are created in the atmosphere via gas to particle conversion.

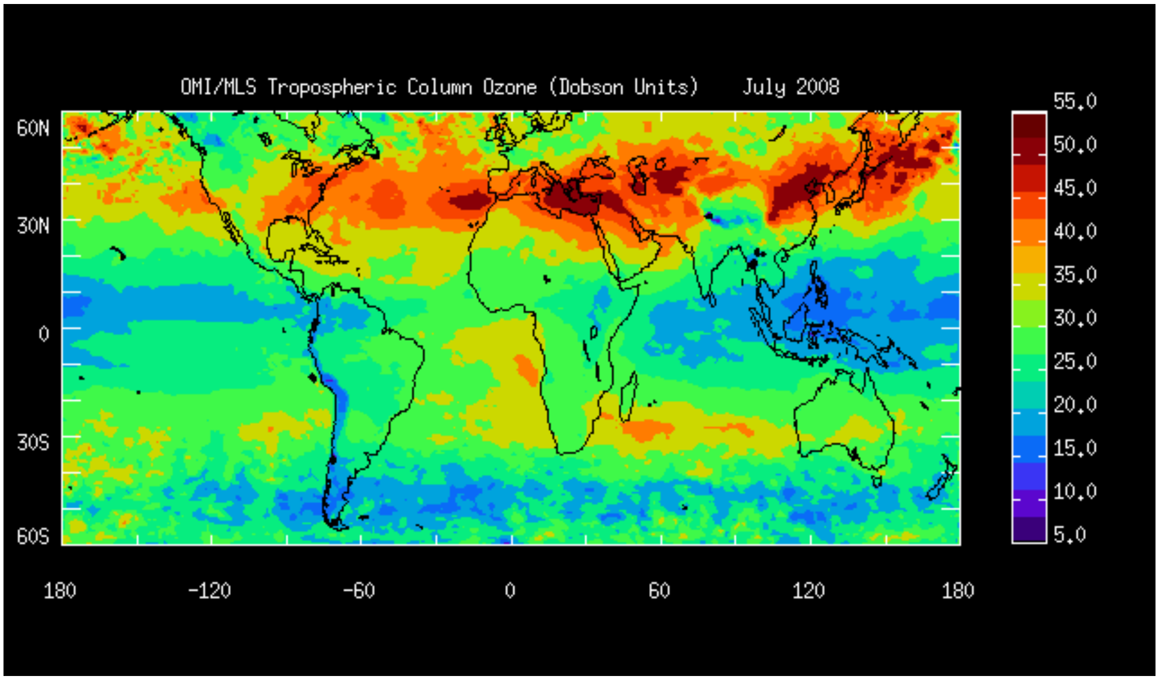

Figure 2. Monthly averaged tropospheric column ozone in July 2008 derived from measurements made by the OMI and MLS instruments on the Aura satellite. In the Northern Hemisphere during summer, large ozone values observed in industrialized regions also extend into remote regions such as the Atlantic and Pacific oceans.

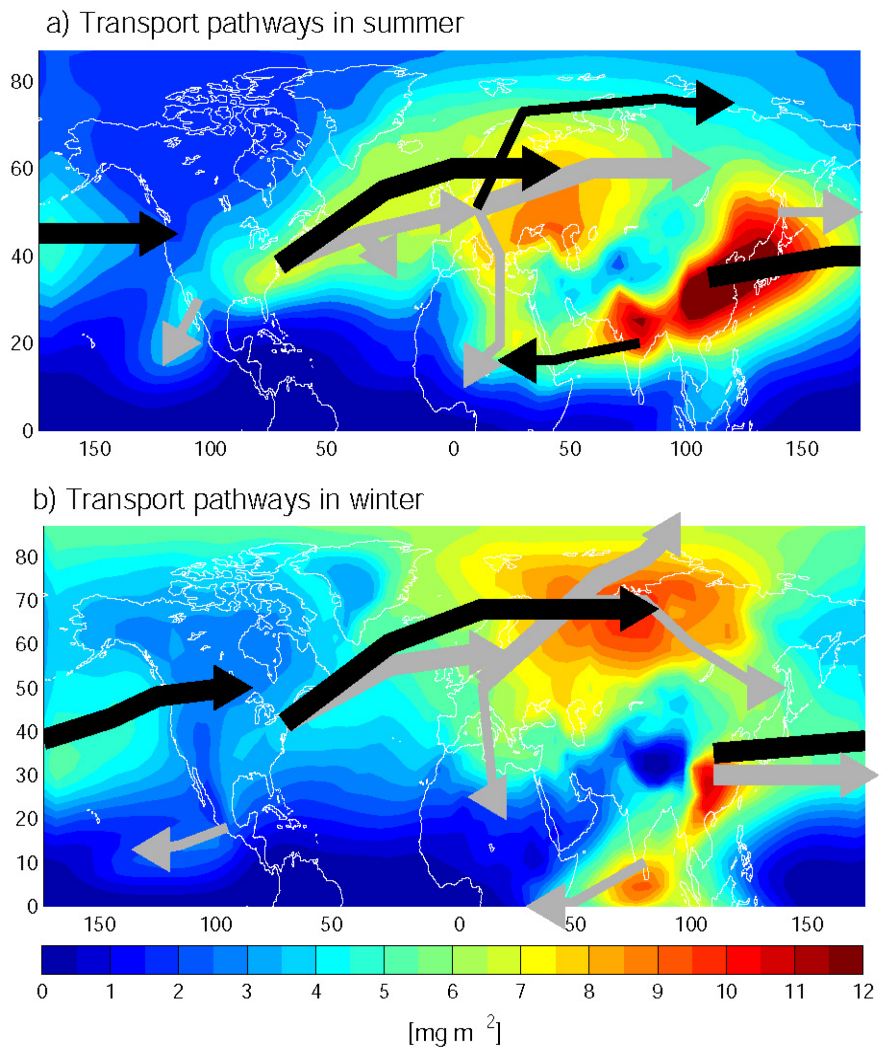

Figure 3. Pathways of intercontinental pollution transport in the Northern Hemisphere. Shading indicates the location of the total column of a passive anthropogenic CO tracer released over the Northern Hemisphere continents after 8-10 days of transport, and averaged over 15 years. Shown are transport pathways in summer (June, July, August) (upper panel), and winter (December, January, February) (lower panel). Gray arrows show transport in the lower troposphere (< 3 km) and black arrows show transport in the mid- and upper troposphere (> 3 km). Image reproduced from Chapter 1, Figure 2, page 6, of Stohl, A. and S. Eckhardt (2004) {Stohl, 2004 #1906}, with kind permission of Springer Science and Business Media.

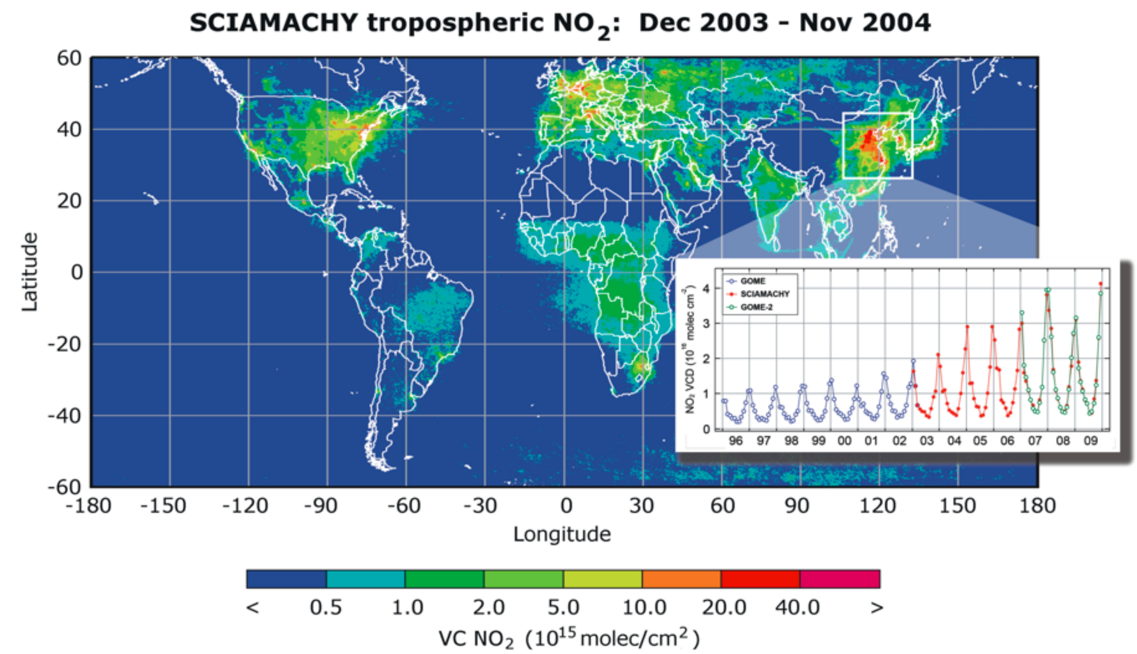

Figure 4. Global survey of tropospheric NO_2 concentrations for December 2003 to December 2004 as measured with SCIAMACHY on ENVISAT. Clearly visible are the industrialised regions in the northern and southern hemisphere as well as regions of biomass burning in the southern hemisphere. The inset illustrates how NO_2 concentrations have risen in China from 1996-2009. The trend analysis uses data from GOME (1996-2002) and SCIAMACHY (2003-2009). (figure courtesy: A. Richter, IUP-IFE, University of Bremen).

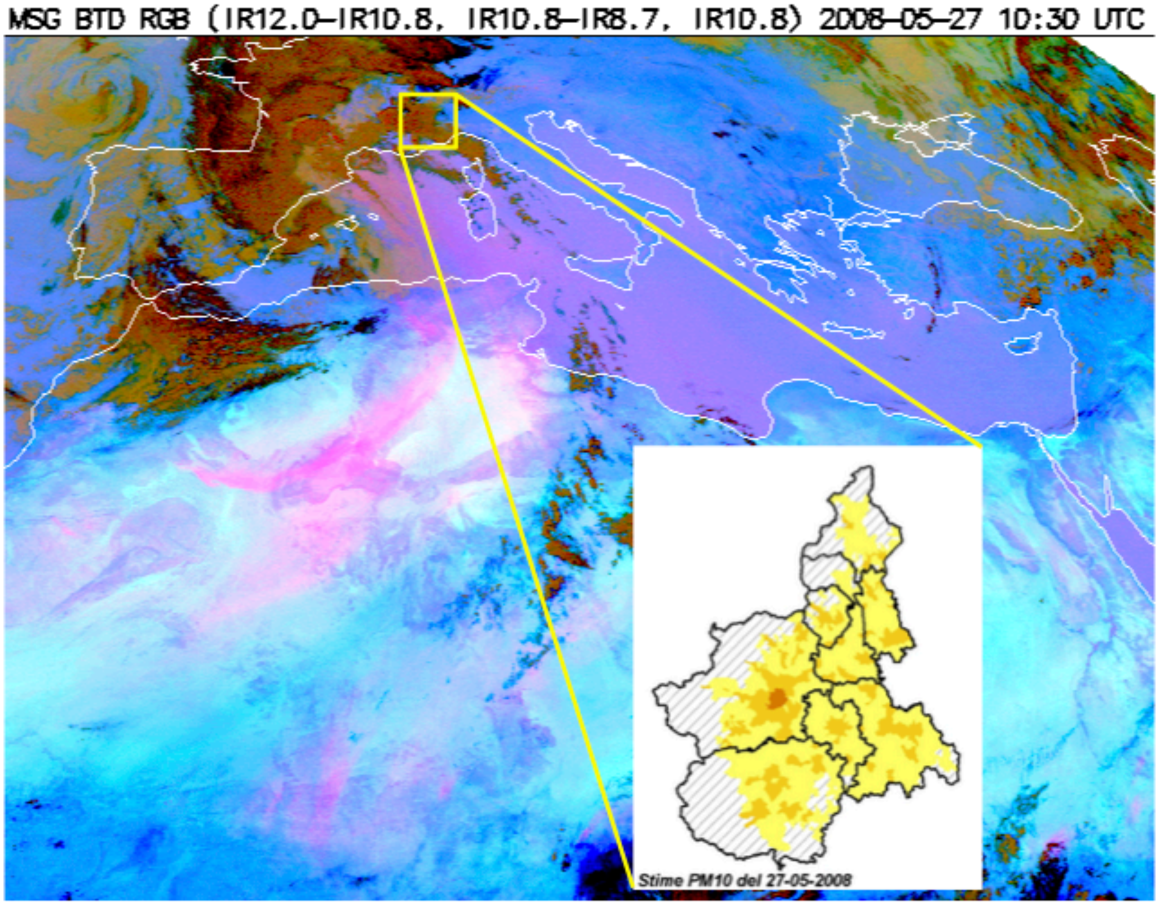

Figure 5. Desert dust indicator from SEVIRI/MSG: RGB composite with brightness temperature differences related to IR channels (IR12.0-IR10.8, IR10.8-IR8.7, IR10.8). Pink colour indicates desert dust as being transported by the storm over the Mediterranean Sea towards Europe. Brown colour indicates clouds. This event caused an air quality exceedence of PM10 threshold values in Northern Italy (measured with ground-based instruments by the Italian Environmental Agency) on 27 May 2008. (figure courtesy: Roberto Cremonini, Regional Environment Agency, Piemonte, Italy)

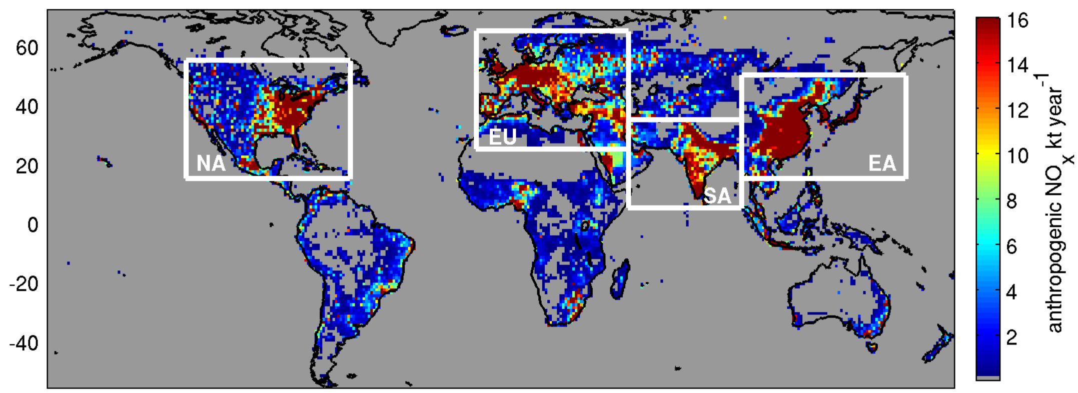

Figure 6. Distribution of global anthropogenic NO_x emissions during the year 2005 from the latest HTAP inventory [van Aardenne, 2010]. Data are in units of kilo-tons NO_x per 1x1 degree grid cell per year. White boxes encompass the four main TF HTAP source-receptor regions, North America (NA), Europe (EU), South Asia (SA) and East Asia (EA).

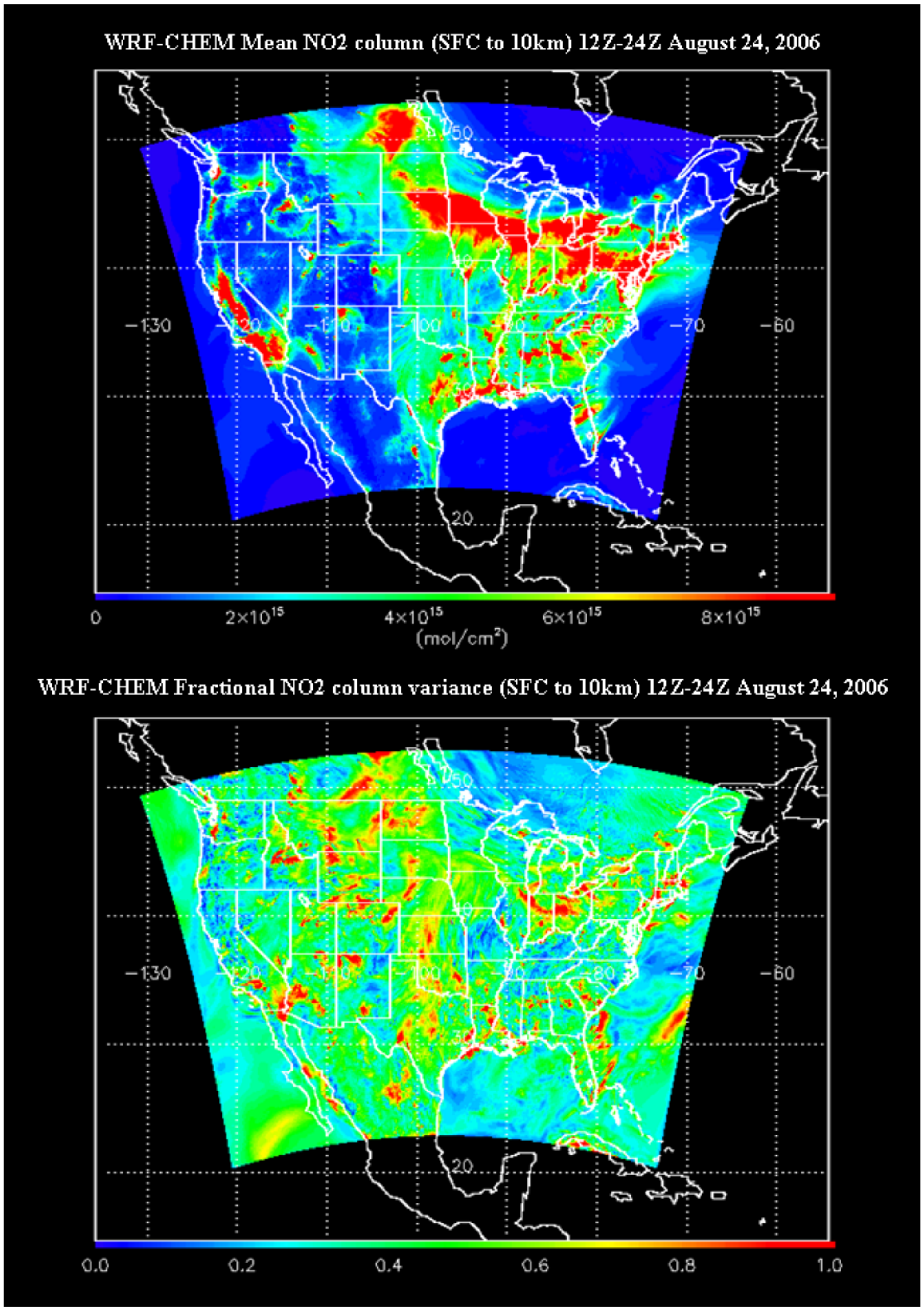

Figure 7. The single-day mean daytime tropospheric column (surface -10 km) NO_2 (upper panel) and the diurnal variation of the tropospheric column expressed as a fraction of the mean column (lower panel) calculated for Aug 24, 2006. A value of 1.0 means that the standard deviation is 100% of the mean.

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