# MONITORING AIR QUALITY FROM SPACE

The Case for the Geostationary Platform

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A geostationary multispectral sensor provides the high spatiotemporal resolution continental-scale observations of lower-tropospheric pollutants needed to monitor, forecast, and manage air quality on a daily basis.
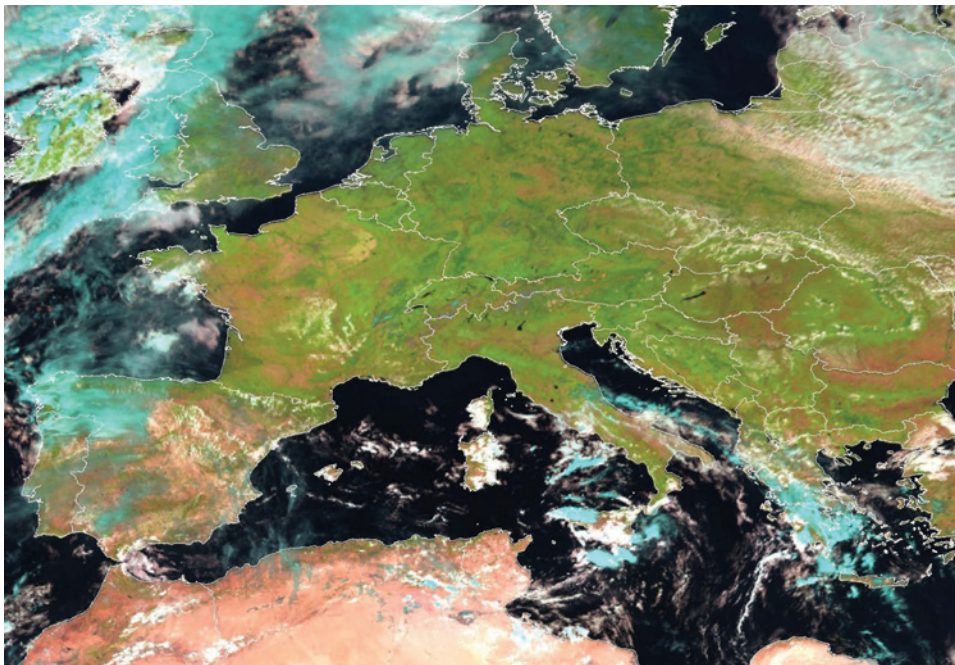
Europe as observed from a geostationary satellite (RGB composition of MSG-SEVIRI data, 22 Sep 2010): red and green show land and vegetation, respectively, while white and blue show thick and cold clouds, respectively. (Courtesy of F. Olesen, KIT)

A fundamental challenge for humankind at the start of the twenty-first century is to respond in the most efficient way to global changes, which put increasing pressure on ecosystems, the economy, and human society. This challenge has the following three key interlinked aspects: 1) global change in the Earth system, 2) ecosystem degradation and its impact on the sustainability of human society, and 3)

growing human demand on resources and associated societal vulnerability. Atmospheric composition is a key parameter, both contributing to processes associated with global change and reflecting the outcome of these processes.

AQ (see the appendix) 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 transport processes; it is highly variable in space and time (McNair et al. 1996). Key lower-tropospheric pollutants include O_3, aerosols (e.g., PM), and the O_3 precursors NO_x (= NO + NO_2) and VOCs (Brasseur et al. 2003). Tropospheric O_3 controls the oxidation of many tropospheric species through reactions involving the OH (Brasseur et al. 2003). Owing to its relatively longer lifetime (in comparison with other easily observed species), tropospheric CO observations provide information on sources of pollution and transport processes affecting AQ. $C_2H_2O_2$ is virtually unaffected by road traffic emissions and thus is a good indicator of photochemical smog (Volkamer et al. 2005).

Air quality impacts human society: high concentrations of O_3, PM, and NO_2 near the Earth's surface cause health problems, in particular, pulmonary and cardiovascular diseases (Brunekreef and Holgate 2002), and recognition is growing of the combined health effects of multiple pollutants (Dominici et al. 2010). Tropospheric CO is not regarded as a health concern outdoors; however, recent work shows a possible link between exposure to urban CO concentrations and cardiac problems in rats (Lucas et al. 2010; Meyer et al. 2010). Reduction of life expectancy in the EU as a consequence of $PM_{2.5}$ pollution has been estimated to be up to 36 months in heavily polluted regions (e.g., Benelux and the Po Valley; see Deutsche Umwelthilfe 2005). Studies in the United States provide evidence that a reduction of $PM_{2.5}$ can increase life expectancy (Pope et al. 2009). Reduction of exposure to ozone and PM pollution is associated with decreases in mortality and hospital admissions resulting from respiratory and cardiovascular diseases. Weather can alter AQ, for example, during summer heat waves and winter episodes.[1] Health costs attributable to AQ are significant.[2]

Conventional air pollutant emissions affect climate directly (via O_3 and aerosol production) and indirectly via their influence on the oxidizing capacity of the atmosphere and, in particular, the methane lifetime (Solomon et al. 2007). Increasing pollutant emissions (e.g., CO and NO_x) results in increased tropospheric O_3 (Crutzen 1974), which is associated with a net positive radiative forcing (Solomon et al.

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[1] It is estimated the European heat wave of summer 2003 caused a loss of 14,802 lives (mainly elderly) in France (www.grid .unep.ch/product/publication/download/ew_heat_wave.en.pdf). High temperatures increased tropospheric O_3 amounts, and anticyclonic conditions ensured their persistence (Vautard et al. 2005). Surface temperature inversions play a major role in AQ, especially during winter when these inversions are strongest. During wintertime cold, calm periods, with a shallow PBL (a few hundred meters above the Earth's surface), PM emissions from road traffic become trapped close to their sources and cannot disperse due to reduced turbulence and mixing with air aloft. Pollution can build up over several days with adverse health effects (www.londonair.org.uk/london).

[2] The cost to the French health system of asthma and cancer incidences directly attributable to AQ has been estimated to be 300–1300 million Euros for 2006 (AFSSET 2007). Estimates of annual health damage (mortality and morbidity) due to air pollution in 2020 for the EU25 countries are estimated to range between 188 billion Euros and 608 billion Euros (see www .cafe-cba.org/assets/baseline_analysis_2000_2020_05-05.pdf). Savings in the EU from complying with WHO guidelines on $PM_{2.5}$ would total about 31.5 billion Euros annually, including savings on health expenditure, absenteeism, and intangible costs such as well-being, life expectancy, and quality of life (see www.aphekom.org).

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2007). The primary oxidant in the atmosphere of many greenhouse gases, including methane, is OH (Solomon et al. 2007). Thus, changes in OH (e.g., resulting from changes in abundances of pollutants such as O_3, NO_x, and CO) will directly affect the atmospheric lifetime of these greenhouse gases and, hence, their impact on the climate system.

Climate change in turn may cause significant AQ degradation by changing pollutant dispersion rates, the chemical environment for O_3 and aerosol production, and emission strengths [e.g., biosphere, fires, and dust; see Solomon et al. (2007)]. Surface air composition is highly sensitive to PBL[3] ventilation, winds, temperature, humidity, and precipitation. Thus, modification of these variables resulting from climate change could affect the concentration and/or lifetime of tropospheric pollutants (e.g., O_3). The sign and magnitude of these effects are, however, highly uncertain and will vary regionally (Solomon et al. 2007).

Simulations show increases in twenty-first-century tropospheric O_3 associated with climate change and increased stratospheric O_3 flux into the troposphere (Hegglin and Shepherd 2009; Zeng et al. 2010). An evaluation of the high-emissions IPCC SRES A2 scenario showed global mean surface O_3 increases of about 5 ppbv by 2030 and 20 ppbv by 2100 (Prather et al. 2003). More recently, Dentener et al. (2006) confirmed a value of 4.3 ± 2.2 ppbv for 2030 using an ensemble of global models. These increases are expected to affect human health, ecosystems (Cooper et al. 2010), and climate. Only the introduction of stringent abatement technologies involving international cooperation will keep surface O_3 and its impact to acceptable levels (Rypdal et al. 2009).

Throughout the world, decision makers are taking action on emissions abatement to monitor, forecast, and manage AQ. In Europe, for instance, the importance of taking action on AQ and the need for abatement technologies led to the implementation of EU legislation concerning AQ thresholds (Directive 96/62/EC and daughter directives; see http://ec.europa .eu/environment/air/quality/standards.htm), development of a long-term EU strategy for AQ (the CAFE program), and operational services for monitoring and forecasting AQ [e.g., PREV'AIR project in France (Rouïl et al. 2009); GEMS and MACC projects in the context of the GMES European program (Hollingsworth et al. 2008)]. In North America, the EPA has set national ambient AQ standards (see www .epa.gov/air/criteria.html). These activities are based on the monitoring of surface concentrations of key pollutants and the scientific understanding of their impact. This requires an understanding of the impact of AQ on human society; that is, health (WHO 2000), ecosystems (WHO 2005), agricultural production and management (Aneja et al. 2008), design and construction of megacities (Molina and Molina 2004), and climate change (Solomon et al. 2007).

Despite implementation of policies in the EU and elsewhere to reduce emissions, AQ issues are likely to remain critical over the next few decades. Benefits should come from enforcing and extending worldwide AQ legislation (Dentener et al. 2006). For NO_x, CO, and VOCs, industrialized regions show reductions in emissions, while regions dominated by developing countries show significant growth in emissions (Solomon et al. 2007). Observations show trends in tropospheric O_3 during the last few decades that vary in sign and magnitude at many locations, but there are indications of significant upward trends at low latitudes (Solomon et al. 2007), as expected from global models (Akimoto 2003). Increasing emissions in China, India, and other developing countries, coupled with transcontinental transport of pollutants, will increase Northern Hemisphere background levels of tropospheric O_3 and $PM_{2.5}$ (Lawrence and Lelieveld 2010).

While emissions that affect pollutants in the troposphere are local, subsequent exchange between the PBL and lowermost free troposphere leads to consequences that are regional and global due to intercontinental transport and the chemical processing that takes place during transport. A pollutant can be transported over regional scales within one day and around the hemisphere within one week; the exchange between hemispheres takes approximately one year in the troposphere. Intercontinental transport thus has a significant impact on the budget of tropospheric pollutants. Simulations from Lin et al. (2010) highlight the important roles of rapid convective transport, orographic forcing, urban photochemistry, and PBL processes in controlling intercontinental transport; these processes may not be well resolved in large-scale AQ models. Difficulty in discriminating between regional and local pollutants fundamentally limits our current understanding of AQ and our ability to quantify AQ and establish what level of AQ is beneficial for human society.

To monitor, forecast, and manage AQ, observations are needed at a high spatiotemporal resolution that is appropriate for capturing variability in the

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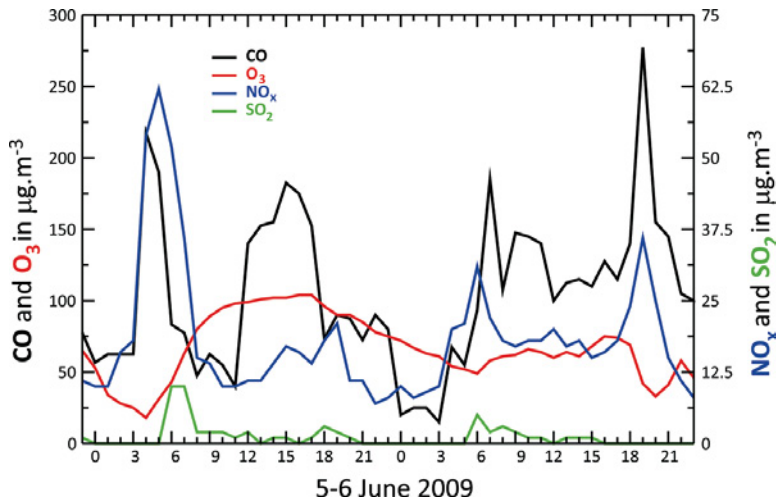[3] The PBL extends from the surface to ~1 km at midlatitudes.

Fɪɢ. 1. Temporal variability of O$_3$ (red), CO (black), NO$_x$ (blue), and SO$_2$ (green) measured over the period 5–6 Jun 2009 at Reims, France [x axis: hour; y axis: concentration (μg m^{-3})]. This shows high-frequency variability of these species at the ground, where human activity makes AQ an issue. Observations of trace gases and aerosols must be able to capture this temporal variability. Data obtained from BDQA and measurements made and validated by the local network of Reims Atmo-Champagne-Ardenne.

lowermost troposphere (0–3-km height) of either pollutants or their proxies (e.g., HCHO is a proxy for a large number of oxygenated VOCs), including emission sources and sinks, transformation, and transport from urban to intercontinental scales. Appropriate resolutions are 1) temporal frequencies less than 1 h (see CEOS 2011; Fig. 1), and 2) spatial scales less than ~10 km (see CEOS 2011; Figs. 2–3). Although local contributions to AQ are well sampled by surface networks (e.g., the EMEP network in Europe), there is a lack of height-resolved regional/continental-scale spaceborne observations of pollutants in the lowermost troposphere, in particular in the PBL (IGACO 2004).

A CASE FOR ADDITIONAL SATELLITE OBSERVATIONS TO MONITOR AIR QUALITY.

The large-scale coverage requirements to monitor AQ indicate the use of satellite platforms. These mostly operate either in geostationary orbit or low Earth orbit. GEO satellites located at 36,000 km on the equatorial plane orbit Earth with the same angular velocity as the Earth's rotation and, therefore, provide continuous viewing of a selected portion of the Earth (the same location at a constant footprint). LEO satellites in sun-synchronous orbits, the most common for atmospheric measurements, orbit Earth at 700–800 km with orbital periods of ~100 min. In both cases (GEO/LEO satellites), a constellation of satellites is required to provide adequate global coverage. This is achieved by current operational meteorological satellite constellations (Thépaut and Andersson 2010).

Satellite observations (LEO and GEO) and in situ observations (e.g., ground-based from surface networks) for AQ monitoring are complementary. In particular, satellite observations rely on ground-based observations for calibration and validation (USGEO 2010). In operational meteorology, data assimilation is used to combine the high accuracy of in situ observations with the high spatial coverage of satellite platforms (Andersson and Thépaut 2010). The relative merit of surface networks and satellite platforms (and their impact on the GOS versus cost), as well as the combination of in situ and satellite observations
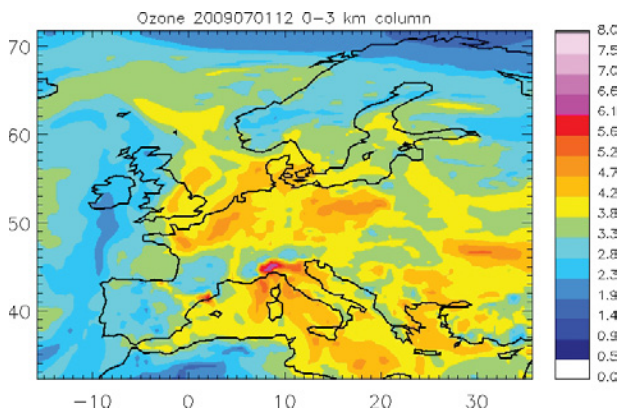

Fɪɢ. 2. Map of O$_3$ partial column (calculated over the height range 0–3 km; height above the model surface) over Europe (x axis: longitude; y axis: latitude) for 1200 UTC (daytime) 1 Jul 2009; units are 10^{17} molecules cm^{-2}. Red to purple colors denote the relatively high values of the O$_3$ partial column, indicative of high levels of pollution and a need to monitor AQ; Blue colors denote relatively low values of O$_3$ partial column. Note the relatively high values over the Po Valley in northern Italy and the Mediterranean and relatively low values over the Alps immediately to the north of the Po Valley. The influence of transport processes on tropospheric O$_3$ concentrations over southern Europe and the Mediterranean has been reviewed by Cristofanelli and Bonasoni (2009). Map is derived from a state-of-the-art CTM (MOCAGE; Bousserez et al. 2007). It shows high spatial variability over local scales in the lowermost troposphere, including the area near the ground (where human activity is of dominant influence).

for AQ monitoring, is being studied in the POGEQA project using the notion of OSSEs (Masutani et al. 2010a,b). Claeyman et al. (2011a,b) describe initial efforts toward this goal.

A recent WMO gap analysis of space missions with respect to GCOS requirements (WMO 2011) discusses future plans for various tropospheric species that are relevant for AQ. The main conclusion is that for O_3, CO, NO_2, SO_2, and HCHO long-term continuation of the observational record seems secured, in particular, from the LEO *Sentinel-5* and post-EPS platforms. Plans for future operational satellites, although not optimal, are increasingly taking account of the need to measure aerosol properties (aerosol optical depth, concentration, effective radius, and type).

The twenty-first century is expected to see societal challenges that affect AQ: population growth, climate change, increased resource demand, and continual development of coastal and urban areas. Monitoring, forecasting, and managing AQ in the twenty-first century requires information about the Earth system and how it changes over time. This requires implementation and maintenance of a robust

GOS (USGEO 2010). Additional satellite observations (GEO and LEO) are needed to complement, extend, and fill gaps in the current GOS for AQ, in particular, high spatiotemporal, height-resolved, continental-scale data on pollutants in the PBL and lowermost free troposphere. Additions to the GOS provide further observational data to constrain AQ forecast models with data assimilation/inverse modeling methods (Lahoz et al. 2010; Elbern et al. 2010). This constraint brings model improvement and increased understanding of processes affecting AQ. Users of these additional satellite data and their derived products include decision makers (e.g., the EC), local and national governments, pollution authorities, health authorities, industry, agriculture, and meteorological agencies. The main benefit is improved monitoring, forecasting, and management of AQ. The main beneficiary is human society.

THE CASE FOR THE GEOSTATIONARY PLATFORM OVER A LOW EARTH ORBIT PLATFORM. Low Earth orbit satellites observe partial or full columns of several species relevant to AQ
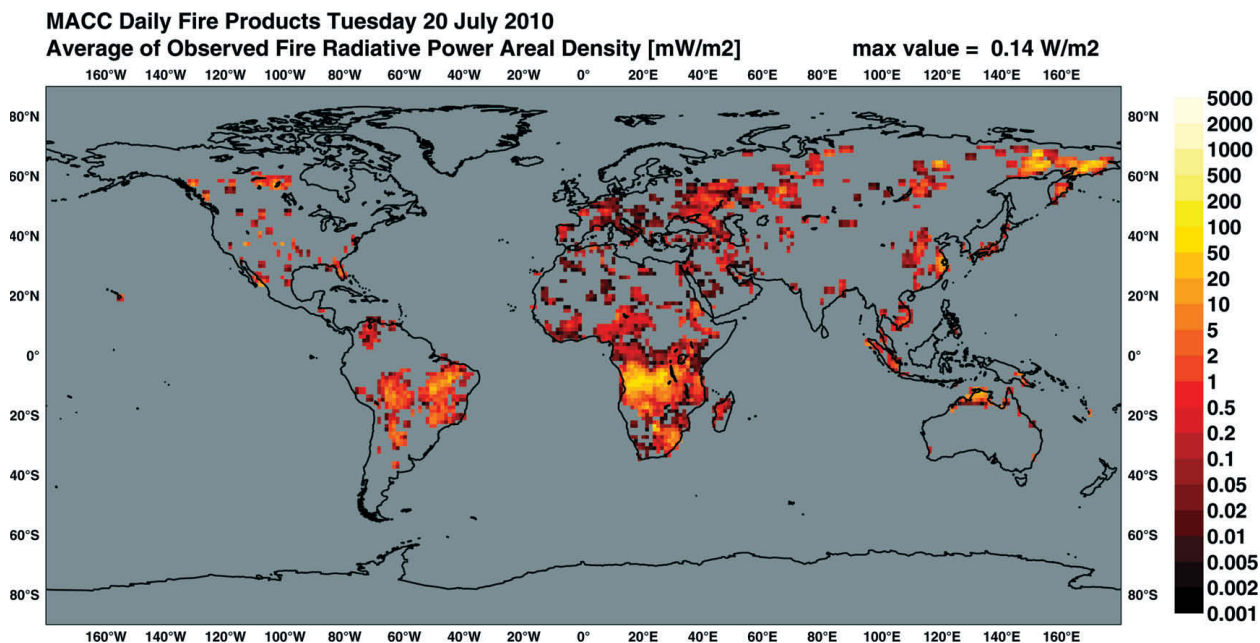

FIG. 3. Global map of average observed FRP areal density on 20 Jul 2010. It represents the thermal radiation measured from spaceborne sensors and detected as coming from actively burning vegetation and other open fires. It is expressed as the daily average of the FRP observations made in 125-km grid cells and expressed in units of mW m⁻². The rate of release of thermal radiation by a fire is understood to be related to the rate at which fuel is being consumed and smoke produced. Daily-averaged FRP areal intensity data are used in the global estimation of open vegetation fire trace gas and particulate emissions. The map shows the spatial variability of fires over local scales; fires are a source of CO, NO_x, and aerosols (Andreae and Merlet 2001; GEO-CAPE 2008). Carbon monoxide is a proxy for pollutant transport; NO_x is a precursor for O_3; O_3 and aerosols affect human health adversely, and their concentrations help define AQ. The map is a MACC Daily Fire Product (from www.gmes-atmosphere.eu/about/project_structure/input_data/d_fire/; see also Heil et al. 2010).
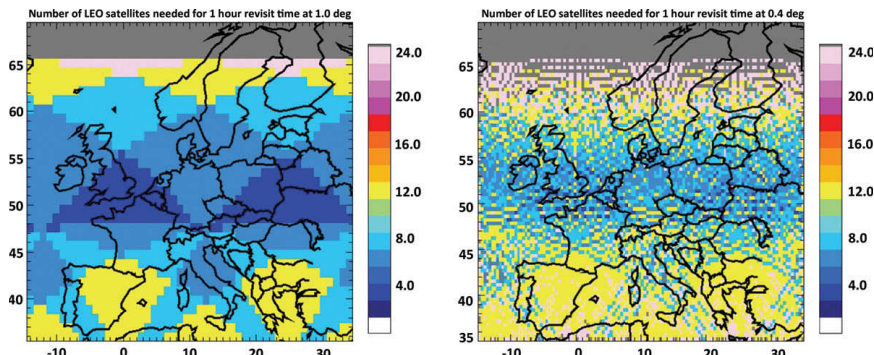
Fig. 4. The number of LEO satellites required for 1-h revisit time over Europe. (left) 1° × 1° resolution (~100 km) and (right) 0.4° × 0.4° resolution (~40 km). Gray indicates no measurements are possible. In both cases, the least number of LEO satellites required is three (dark blue regions), but this is only for very small regions over Europe. For 1-h revisit time and ~10-km (or less) resolution, the least number of LEO satellites required to cover Europe up to 60°N is more than 10; by contrast, only one GEO satellite is required.

(O_3, CO, NO_2, HCHO, and SO_2) and make important contributions to pollution sources, transport, and characterization of air pollution variability at global, continental, and regional scales (NRC 2008). The last decade has seen major advances in observations of tropospheric species from LEO satellites (Fishman et al. 2008).

Low Earth orbit satellites provide a long-term global view of atmospheric composition, but they have limitations with respect to sampling atmospheric constituents in the lower troposphere at the spatiotemporal resolution necessary to monitor AQ. Their main advantage concerning AQ is their global coverage (this is possible from a single LEO satellite), typically covering most of the Earth, including regions close to the poles (in contrast, GEO satellites are limited to about a quarter of Earth's surface, and do not normally make observations poleward of 60°N or 60°S). Thus, the main drawback for LEO satellites is the difficulty of achieving full temporal coverage, because for this purpose a constellation of more than 10 LEO satellites is required to give long-term hourly coverage at continental scales (Fig. 4).

A GEO platform has much better sampling of diurnal variability than a LEO platform (Fig. 4), and an improved likelihood of cloud-free observations (this, however, depends on pixel size) with continuous observations of a particular location during at least part of the day. This "stare" capability from a GEO provides significantly greater measurement integration times compared to those from a LEO satellite. This feature of the GEO satellite platform makes it very effective for the retrieval of the lowermost troposphere information for capturing the diurnal cycle in pollutants and emissions, and the import/export

of pollutants or proxies for pollutants. Realistically (given technical, scientific, and cost considerations), a GEO satellite is the only satellite platform that can provide this information at the spatiotemporal scales that are associated with variability of tropospheric pollutants (temporal frequencies less than 1 h; spatial scales less than ~10 km). A single GEO satellite provides AQ information with complete temporal coverage over a key continental area of the globe (e.g., Europe, East Asia, or North America), whereas many LEO satellites would be required to provide the same information (Fig. 4).

As of 2011, no observations of trace gases have been made from a GEO satellite. By contrast, multichannel imagers providing information on aerosols and fire-related parameters at high spatiotemporal resolution have been flying on NWP satellites in geostationary orbit for the past three decades (e.g., NOAA GOES series and the EUMETSAT Meteosat series). Both qualitative (smoke plume analysis and a dust mask) and quantitative (aerosol optical depth, main fire hot spots, and the size of unexpected fires and burned area) AQ products are currently available from GEO satellites.

To address shortcomings in the GOS, a number of initiatives in Europe are planning GEO satellites capable of monitoring chemical species. The GMES *Sentinel-4* UVN platform (ESA 2007) will measure tropospheric O_3, NO_2, HCHO, SO_2, and aerosol properties (column-averaged optical thickness and aerosol type). The MTG IRS platform (Munro 2011) will measure tropospheric O_3 and CO (although as a NWP sounder, it is not optimized for these species). *Sentinel-4* UVN and MTG IRS instruments are due for launch from 2017/18 onward. The POGEQA and MAGEAQ initiatives (Peuch et al. 2009, 2010) focus on tropospheric O_3 and CO. The general concept behind these initiatives is discussed in Claeyman et al. (2011a,b).

A number of projects outside Europe are developing GEO satellites for monitoring chemical species. These include the NASA GEO-CAPE mission, with a proposed 2020 launch (GEO-CAPE 2008), the Korea MP-GEOSAT mission, with a planned launch in 2017/18

(Lee et al. 2010), and the JAXA AQ-Climate mission, with a 2020 proposed launch [Akimoto et al. 2008; see www.stelab.nagoya-u.ac.jp/ste-www1/div1/taikiken /eisei/eisei2.pdf (in Japanese)]. These developments in Europe, the United States, and Asia focus on tropospheric aerosols and trace gases such as O_3. Synergies between European, the United States, and Asian GEO satellite platforms would be of great benefit for the quasi-global monitoring of AQ (CEOS 2011). Synergy between GEO and LEO satellite platforms and surface observations would provide further benefits.

ACCOMPLISHMENTS OF SATELLITE PLAT-FORMS AND TECHNICAL DIFFICULTIES ASSOCIATED WITH GEOSTATIONARY MEASUREMENTS. To extract tropospheric information from GEO and LEO platforms, it is necessary to separate stratospheric and tropospheric contributions to the signal received by the satellite. Commonly, this is achieved by taking advantage of the different penetration depths into the atmosphere of different spectral regions (UV, VIS, TIR, and NIR).

This approach has been used to measure tropospheric trace gases and aerosols from LEO platforms in the UV, VIS, and infrared (Fishman et al. 2008). For the UV/VIS these include 1) a tropospheric O_3 column from GOME with mean biases of up to 3 DU and standard deviations within 3–8 DU against ozonesondes (Liu et al. 2005); 2) O_3 profiles from OMI with tropospheric information of up to 1.5 DFS[4], peaking between 500 and 700 hPa and sensitivity down to ~800–900 hPa, and random errors of ~10% (Liu et al. 2010); 3) tropospheric columns of NO_2, SO_2, HCHO, and $C_2H_2O_2$ from GOME and/or SCIAMACHY (Chance 2005, 2006, and references therein); and

4) aerosol products from biomass burning: aerosol optical depth from MODIS and aerosol absorption optical depth and UV aerosol index from OMI (Torres et al. 2010). For the infrared these include 1) lower-troposphere (between the surface and 700 hPa) CO profile retrievals from MOPITT (Deeter et al. 2007); 2) near-surface (from the surface to 800 hPa) increased CO information (quantified by the DFS) from TIR + NIR MOPITT retrievals in comparison to TIR-only MOPITT retrievals (Worden et al. 2010); 3) the partial O_3 column (0–6 km) and tropospheric O_3 column (0–11 km) from IASI, with a bias of 5% or less against ozonesondes (Eremenko et al. 2008; Keim et al. 2009); and 4) a capability for height-resolved tropospheric O_3 information (DFS of 2.4) from TES and a demonstration of sensitivity to CO concentrations between 5 and 15 km from TES (Worden et al. 2004). As part of this effort, ESA missions have been instrumental in building a picture of pollution over various regions of the globe (Fig. 5).

The ability to retrieve trace gas concentrations in the PBL is important for the characterization of pollutant sources. In addition to source determination, a measure of PBL concentration in conjunction with free troposphere profile information allows local production to be separated from transported pollution. However, these retrievals are challenging for both LEO and GEO platforms. Spectral signatures from the UV to NIR are subject to interferences from clouds, aerosols, scattering, and surface reflectivity uncertainties. In the TIR, the general lack of temperature contrast between the atmosphere and surface limits PBL retrieval capability (Orphal et al. 2005). For O_3, because the tropospheric column accounts for less than 10% of the total column, it is challenging to

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[4] The DFS quantify the number of useful independent quantities in the measurement (Rodgers 2000).

SCIAMACHY tropospheric NO₂ - 2009

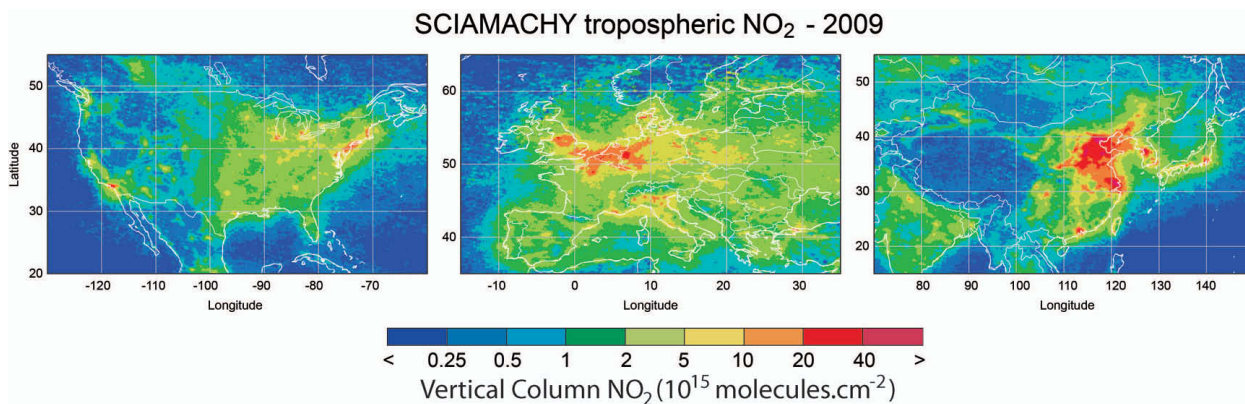Vertical Column NO_2 (10^{15} molecules·cm^{-2})

FIG. 5. NO_2 tropospheric densities (representative of the vertical column), averaged for 2009, from the SCIAMACHY instrument on board the ESA Envisat satellite. (left) United States, (middle) Europe, and (right) China. Units are 10^{15} molecules cm^{-2}. [Figure courtesy A. Richter (IUP-IFE, University of Bremen).]

separate PBL O_3 from stratospheric O_3, even for LEO satellites (Fishman et al. 2008).

Notwithstanding these challenges, studies show the potential of multispectral observations to extract PBL information, with O_3 and CO being the best candidate species at present. Retrieval studies for combining OMI and TES O_3 measurements (Landgraf and Hasekamp 2007; Worden et al. 2007) indicate that such combinations are highly promising. This approach requires measurements from at least two O_3 bands from among the ultraviolet Hartley–Huggins (200–360 nm), the visible Chappuis (375–650 nm), and the thermal infrared v_3 band (9.6 μm).

The combination of TIR + VIS (combinations such as UV + VIS, TIR + UV, and TIR + UV + VIS are also being considered) measurements for O_3 (in a LEO or GEO platform) is desirable because, for clear skies, the visible Chappuis bands view directly to the ground, overcoming the difficulties from UV O_3 measurements (which are limited in near-surface sensitivity by Rayleigh scattering) and infrared O_3 measurements (limited by low thermal contrast between the Earth's surface and the lower atmosphere; note that the VIS and UV do not provide information at night). However, the absorption in the Chappuis band is weak, and the potential aerosol contamination of species retrievals and variations in the surface reflectance as a function of wavelength may present challenges.

Measurement of PBL O_3 concentrations to desired precision levels is the major current technical difficulty for GEO platforms. The major missing components of tropospheric O_3 measurements are 1) the ability to make precise O_3 measurements from the nadir (downward looking) geometry using the visible Chappuis band, as has been used for SAGE-II and other measurements of O_3 in solar occultation geometry (e.g., McCormick et al. 1989); and 2) the capability to perform multispectral retrievals, which improves the sensitivity to different atmospheric altitudes (Fig. 6). Studies on the feasibility of the multispectral approach to make O_3 measurements in the PBL from a GEO platform are being performed for GEO-CAPE (Natraj et al. 2011), and will be undertaken for the POGEQA project (Claeyman et al. 2011b). OSSEs will be a key tool in these studies.

Regarding CO measurements in the PBL from a GEO platform, these observations will require a multispectral TIR + NIR retrieval (GEO-CAPE 2008). Regarding tropospheric aerosol measurements, multiangle observations over the course of a day from a GEO platform are expected to provide information on aerosol properties such as aerosol optical depth (Zhang et al. 2011). The proposed GEO-CAPE spectral coverage in the UV/VIS is expected to provide the capability to simultaneously measure aerosol optical depth, size distribution, and aerosol absorption (GEO-CAPE 2008). Availability of UV channels in the GEO-CAPE mission are expected to allow identification and characterization of organic aerosols that have a unique spectral signature in the UV but
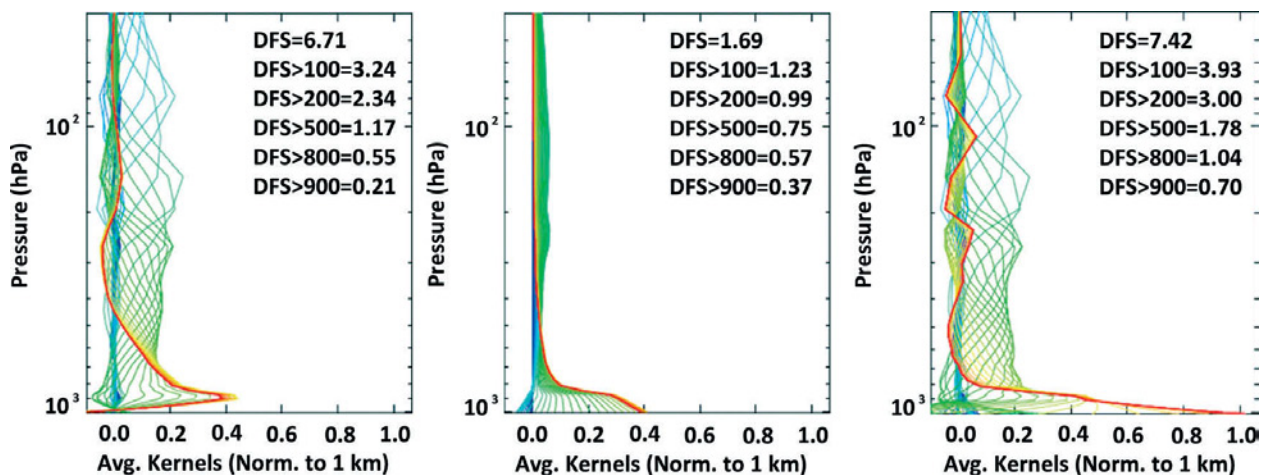

Fig. 6. Representative O_3 averaging kernels (normalized to 1 km; green and red) for 6-nm sampling. (Left) TIR, (middle) VIS, and (right) TIR + VIS. Averaging kernels relate the sensitivity of the retrieval to the true state (Rodgers 2000), and here identify the location in the vertical where measurements have information. This figure shows the TIR + VIS multispectral retrieval improves on individual TIR and VIS retrievals in the lowermost troposphere. Improvement is quantified by an increase in the DFS: 1) pressures greater than 800 hPa are 1.04 for TIR + VIS versus 0.55 for TIR and 0.57 for VIS; and 2) pressures greater than 900 hPa are 0.70 for TIR + VIS versus 0.21 for TIR and 0.37 for VIS. Multispectral retrievals are being studied by Natraj et al. (2011).

are not easy to differentiate from other aerosol types with visible-only observations.

Despite the advantages for monitoring the AQ of a GEO satellite compared to a LEO satellite, a GEO satellite will significantly lose signal and spatial resolution owing to its longer distance from the Earth (compared to a LEO satellite). Thus, a GEO platform will be challenged by data accuracy and spatial resolution. This requires the use of larger telescopes by a GEO satellite. However, the continued observation of a given area by a single pixel by a GEO satellite allows the integration of signals to recover a satisfactory signal-to-noise ratio while still achieving a high temporal resolution (less than 1 h) and providing an improved likelihood of cloud-free observations (this, however, depends on pixel size).

Regardless of the eventual instrumentation in GEO platforms to provide the required spatiotemporal information of tropospheric trace gases and aerosols, a substantial challenge is the development of modeling and data assimilation tools to use this information. Work on developing these tools has already started (Lahoz et al. 2010; Elbern et al. 2010), and their application to the study of tropospheric species that define AQ will play a crucial role in the development of a robust capability to monitor, forecast, and manage AQ.

SUMMARY. The importance of taking action on AQ and the need for abatement technologies has led to a strong societal response based on monitoring surface concentrations of key pollutants and scientific understanding of their impact. This requires the ability to observe the lowermost troposphere at regional and continental scales at high spatiotemporal resolution. A geostationary platform is the only realistic space-based solution (given technical, scientific, and cost considerations) providing this information from space, but important technical difficulties concerning instrument design must be overcome. This paper outlines how the potential of a geostationary platform for AQ monitoring can be achieved. A key part of this effort will be the use of satellite and in situ data to constrain AQ forecast models with data assimilation/inverse modeling methods. This will bring model improvement and increased understanding of processes affecting AQ. Geostationary platforms will improve our ability to monitor, forecast, and manage AQ, benefitting human society. Current plans for the future GOS lack the constellation of dedicated GEO missions needed for monitoring AQ over Europe, North America, and Asia; this shortcoming should be remedied.

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APPENDIX A: ACRONYMS USED IN THIS ARTICLE.

|	
AQ	Air quality
BDQA	Base d Données sur la Qualité de l'Air
$C_2H_2O_2$	Glyoxal
CAFE	Clean Air for Europe
CEOS	Committee on Earth Observation Satellites
CO	Carbon monoxide
CTM	Chemistry transport model
DFS	Degrees of freedom for signal
DU	Dobson unit
EC	European Commission
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
EPS	EUMETSAT Polar System
ESA	European Space Agency
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EU25	25 members in the European Union
FRP	Fire radiative power
GCOS	Global Climate Observing System
GEMS	Global Earth System Monitoring Using Space and In Situ Data
GEO	Geostationary
GEO-CAPE	Geostationary Coastal and Air Pollution Events
GMES	Global Monitoring for Environment and Security
GOES	Geostationary Operational Environmental Satellite

GOME	Global Ozone Monitoring Experiment
GOS	Global Observing System
HCHO	Formaldehyde
IASI	Infrared Atmospheric Sounding Interferometer
IGACO	Integrated Global Atmospheric Chemistry Observations
IPCC	Intergovernmental Panel on Climate Change
JAXA	Japan Aerospace Space Exploration Agency
LEO	Low Earth Orbit
MACC	Monitoring Atmospheric Composition and Climate
MAGEAQ	Monitoring the Atmosphere from Geostationary Orbit for European Air Quality
MOCAGE	Modélisation de Chimie Atmosphérique à Grande Echelle (Model of Atmospheric Chemistry at Large Scales)
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Troposphere
MP-GEOSAT	Multipurpose Geostationary Satellite
MTG-IRS	Meteosat Third-Generation Infrared Sounder
NASA	National Aeronautics and Space Administration
NIR	Near infrared
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxide
NOAA	National Oceanic and Atmospheric Administration
O_3	Ozone
OH	Hydroxyl radical
OMI	Ozone Monitoring Instrument
OSSE	Observing System Simulation Experiment
PM	Particulate matter
$PM_{2.5}$	Particulate matter integrated up to a diameter of 2.5 μm
POGEQA	Plateforme d'Observation Geostationnaire pour la Mesure de la Qualité de l'Air (Observation of air quality from a geostationary platform)
ppbv	Parts per billion by volume
SAGE	Stratospheric Aerosol and Gas Experiment
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SRES	Special Report on Emissions Scenarios
TES	Tropospheric Emission Spectrometer
TIR	Thermal infrared
UVN	Ultraviolet–visible–near infrared
VIS	Visible
VOC	Volatile organic compound
WHO	World Health Organization
WMO	World Meteorological Organization
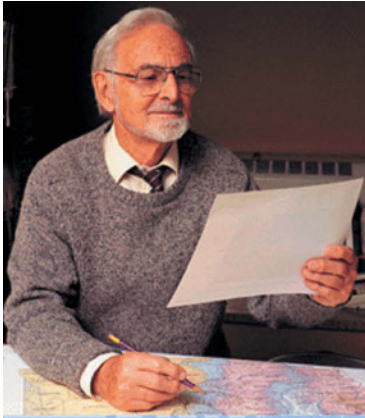
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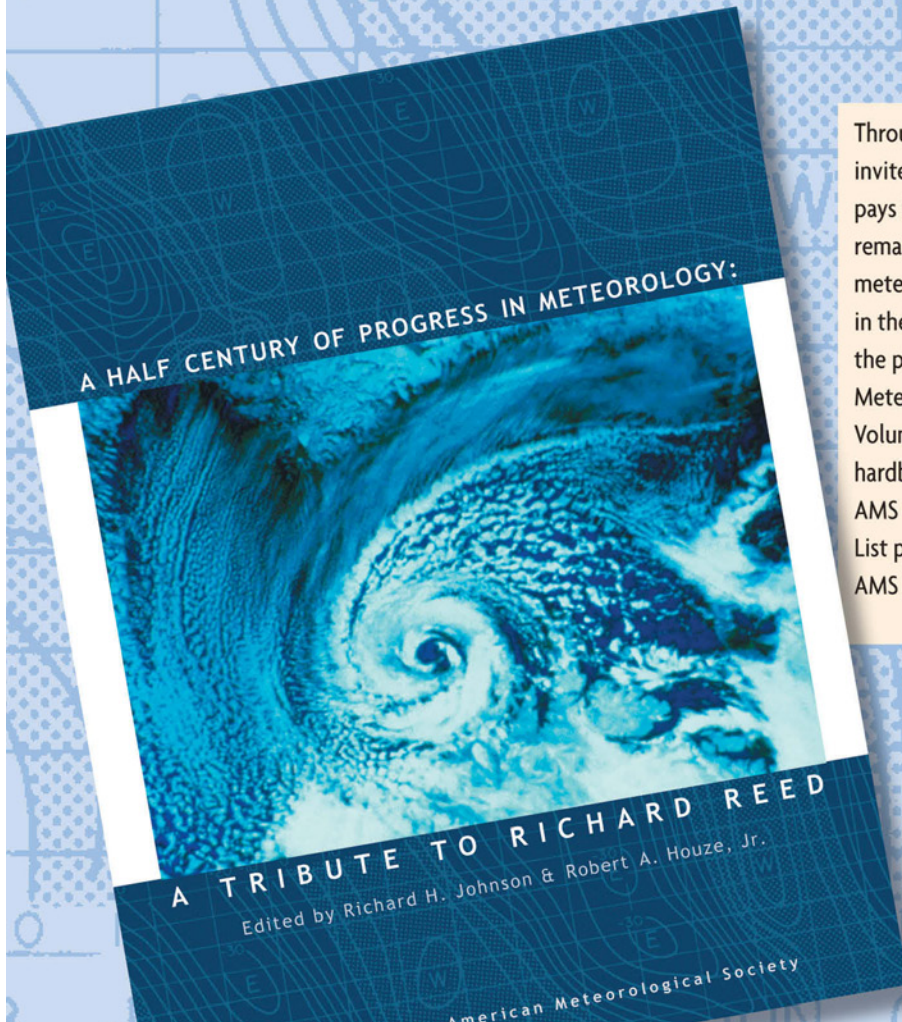
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