# A Geostationary Air Quality Monitoring Platform for Africa

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## Abstract
African populations and economies are growing rapidly, but there are few surface observations to monitor the effects on air quality. Trend analysis of the 19-year record of space-based observations from remote sensors onboard low Earth orbit (LEO) satellites shows that anthropogenic pollution is on the rise. Conversely, biomass burning, the largest contributor to surface ozone, is declining. UV-visible instruments on LEO satellites with daily resolution have provided invaluable constraints on sources, evolution, and transport of air pollution in Africa. Sensors in geostationary orbit (GEO) with hourly resolution and a smaller ground pixel than current and past fleets of LEO satellites would further our understanding of air quality in Africa and address the dearth of surface monitoring sites on the continent. Africa has successfully launched Earth observation platforms to retrieve satellite imagery and should expand its remote sensing capabilities by joining the northern hemisphere constellation of GEO Earth observation satellites.

## Keywords
Africa, air quality, low Earth orbit, geostationary, satellite, remote sensing

## Introduction
Africa is experiencing rapid population growth, in particular West, East, and Central African countries, where fertility rates exceed 6 births per woman (Guengant and May, 2013). Economic projections for Africa are less certain. African countries are currently experiencing large positive economic growth. Nigeria could be the 13th largest world economy by 2050, but sustained economic growth there and in other African countries is contingent on strengthened political institutions, economic diversification, and increased access to reliable and affordable energy (PwC, 2013). Should Africa follow the development trajectory of Southeast Asia and India, degradation of air quality is guaranteed.

Indoor and ambient air pollution rank amongst the highest global burden of disease risks (Lim et al., 2012), largely from exposure to fine particulate matter with an aerodynamic diameter less than 2.5 µm, or $PM_{2.5}$ (Pope and Dockery, 2006). Surface ozone ($O_3$) affects human health to a lesser extent, but is phytotoxic to crops, threatening food security and agricultural revenue (Avnery et al., 2011). In Africa surface observations of atmospheric composition are sparse, environmental legislation is limited to a few countries, and only South Africa has well-defined standards and a widespread monitoring network (Kgabi, 2012). Still, successful environmental policy in South Africa is hindered by non-compliance (Groundwork, 2014), data gaps, and variable data quality (Hersey et al., 2015).

Sensors onboard satellites provide observations of pollutants and precursors in parts of the world that lack the resources, political will, or human capital to measure ambient air pollution. Even in North America and Europe satellite measurements are used to infer surface concentrations where monitoring is sparse (Lamsal et al., 2008; van Donkelaar et al., 2012). Here we provide a brief review of satellite observations of atmospheric composition used to better understand air quality in Africa. We consider measurements from UV-visible instruments onboard European Space Agency (ESA) and National Aeronautics Space Agency (NASA) low Earth orbit (LEO) satellites. We further discuss the value of a geostationary (GEO) air quality Earth observation platform over Africa.

## Low Earth Orbit Earth Observing Platforms

### General Features
The space-based global air quality monitoring network of LEO, sun-synchronous satellites began with the ESA Global Ozone Monitoring Experiment (GOME) in 1995. GOME was fully operational until 2003, had a spatial resolution of 40 km × 320 km (latitude × longitude), and required 3 days to achieve global coverage (ESA, 1995). Higher spatial resolution and daily global coverage is achieved with current sensors such as the Ozone Monitoring Instrument (OMI) that is 13 km × 24 km at nadir (Levelt et al., 2006). The next-generation ESA TROPOspheric Monitoring Instrument (TROPOMI), scheduled for launch in

2016, has 7 km × 7 km ground pixels at nadir (Veefkind et al., 2012).

Observations obtained with sensors on satellites are species concentrations within a column of air, retrieved using solar backscattered radiation in the UV-visible spectral range. Observed tropospheric gases include $O_3$, nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), formaldehyde (HCHO), and glyoxal (CHOCHO). Total column aerosol extinction optical depth (AOD) is derived with top of the atmosphere reflectance measurements obtained under cloud-free conditions (Torres et al., 2007). Other satellite products include absorbing AOD (AAOD), UVB daily erythemal dose, cloud fraction, and cloud top pressure.

# Application to Africa

## Top-down Emission Estimates

Figure 1 shows annual and seasonal mean concentrations of HCHO and CHOCHO (total column), $NO_2$ (tropospheric column), and $SO_2$ (planetary boundary layer (PBL) center of mass) for 2006-2007 from OMI at 13h30 local time, the OMI Equator crossing time (Appendix). Enhancements of $NO_2$, $SO_2$, and HCHO and CHOCHO provide constraints on emissions of $NO_x$ (=NO + $NO_2$), $SO_2$, and reactive non-methane volatile organic compounds (NMVOCs), respectively, for improved air quality modeling. At increasingly fine resolution transport degrades (smears) the local relationship between the observed quantity (e.g. total column HCHO) and inferred emissions (e.g. isoprene from vegetation) (Turner et al., 2012), but smearing can be addressed with advanced inversion techniques, such as an adjoint (Kopacz et al., 2010).

Tropical vegetation in Africa is coincident with large seasonal enhancements in HCHO, a high-yield oxidation product of the biogenic VOC isoprene, a precursor of $O_3$ and particulate matter (Stavrakou et al., 2009a). Isoprene emissions in Africa have been inferred using OMI HCHO after careful screening for biomass burning and anthropogenic influence (Marais et al., 2012). Satellite-derived isoprene emissions are consistent with limited flux measurements, while the state-of-the-science biogenic emission inventory, MEGAN, can be an order of magnitude too high in the tropics (Marais et al., 2014a).

A HCHO hotspot over Nigeria, in particular in December-February (Figure 1) is from oxidation of reactive anthropogenic NMVOCs

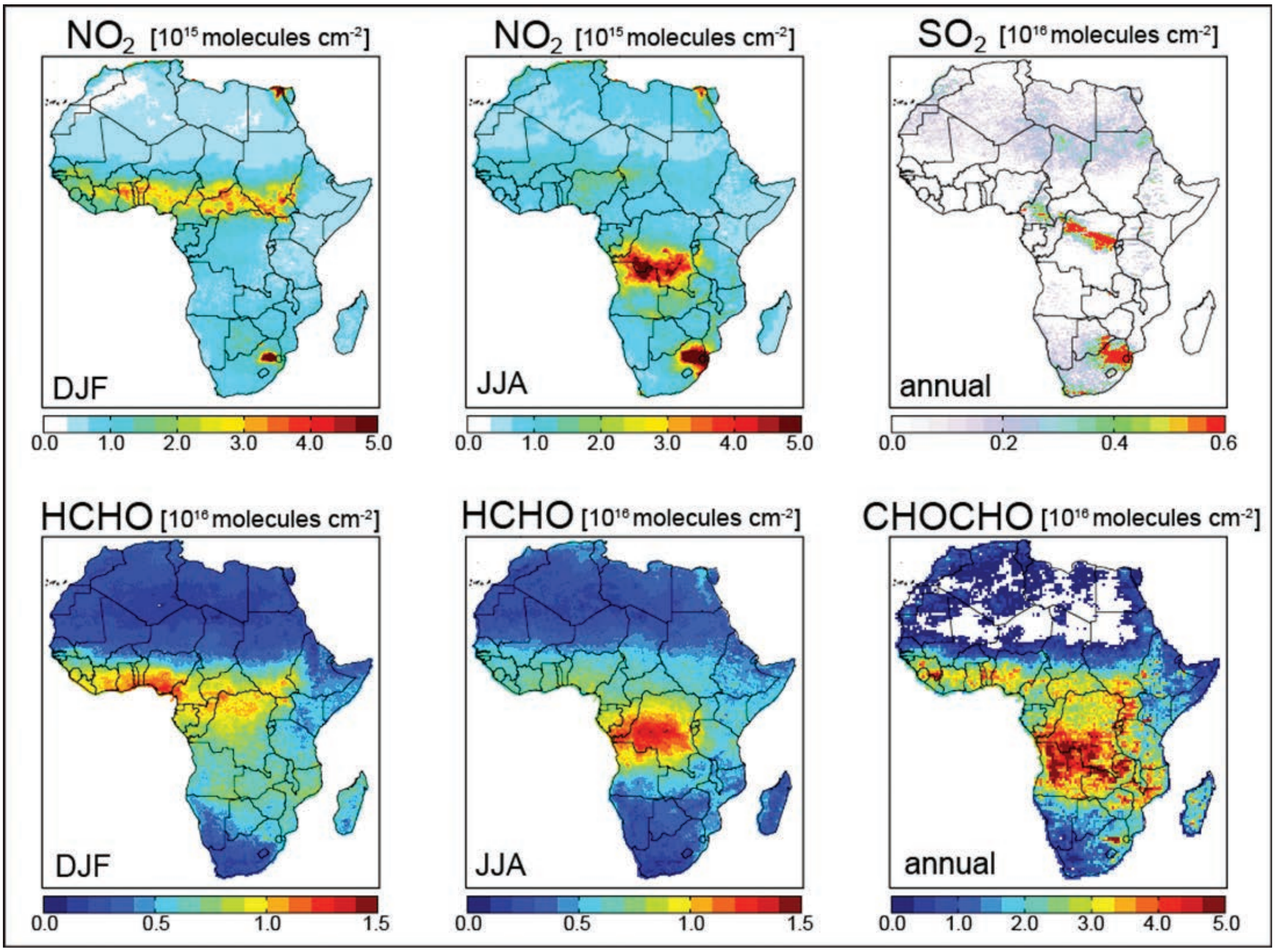


***Figure 1**: Mean concentrations of tropospheric nitrogen dioxide ($NO_2$), PBL-weighted sulfur dioxide ($SO_2$), and total column formaldehyde (HCHO) and glyoxal (CHOCHO) from OMI for 2006-2007.*

produced by inefficient sources of combustion and natural gas flaring and leakage. Marais et al. (2014b) found, with OMI HCHO, the chemical transport model (CTM) GEOS-Chem, and limited aircraft observations, that Nigerian 2006 anthropogenic NMVOC emissions were higher per capita than in China for the same year.

Satellite-derived $NO_x$ emissions along the Highveld in South Africa, obtained with OMI tropospheric $NO_2$, show incorrect grid allocation of power plant and other industrial sources in the widely used EDGAR emission inventory. EDGAR likely overestimates mobile sources of $NO_x$ in the Johannesburg-Pretoria metropolitan area (Stavrakou et al., 2014), but LEO satellites miss $NO_x$ produced by vehicles during morning and evening rush hours (Lourens et al., 2014). The spatial extent of $NO_x$ from soil bacteria along the Sahel, a global soil $NO_x$ hotspot, was first seen with GOME $NO_2$ (Jaeglé et al., 2004). A recent study used OMI $NO_2$ and the GEOS-Chem CTM to estimate the magnitude of this $NO_x$ source (Vinken et al., 2014).

Satellite observations of $SO_2$ are noisy, so that inference of emissions in Africa using standard retrieval techniques is limited to sizable point sources that include active volcanoes along the East African Rift Valley (Theys et al., 2013) and power plants in the Highveld region (Fioletov et al., 2013).

Dry season biomass burning makes the largest contribution to surface $O_3$ in Africa (Aghedo et al., 2007). The magnitude of the contribution, obtained by Aghedo et al. (2007) as the difference between a simulation with and without biomass burning, is sensitive to model emissions. Satellite-derived emissions of NMVOCs and $NO_x$ highlight large regional biases in bottom-up pyrogenic inventories (Jaeglé et al., 2005; Stavrakou et al., 2009b). Models also represent African savanna fires, the dominant seasonal $NO_x$ source in much of Africa, with fixed $NO_x$ emission factors ($NO_x$ produced as a function of biomass burned). Satellite $NO_2$ data show substantial temporal variability (Mebust and Cohen, 2013).

## Air Quality and Emission Trends

Global surface concentrations of $PM_{2.5}$ have been derived with satellite AOD and the modeled relationship between the two (van Donkelaar et al., 2006). $PM_{2.5}$ is high in North and West Africa, predominantly from Saharan dust. The anthropogenic contribution in Africa is low, but rapid development will add to air quality concerns.

Observations from multiple sensors have been stitched together to generate a 19-year satellite record (1996-2014) of atmospheric composition. Positive, significant trends in HCHO in the megacities Cairo (Egypt), Lagos (Nigeria), and Kinshasa (DRC) suggest increasing emissions of NMVOCs (De Smedt et al., 2010). Similarly, increases in tropospheric $NO_2$ in Cairo, Lagos, and Algiers (Algeria) imply growth in $NO_x$ sources (Schneider and van der A, 2012; Hilboll et al., 2013). Other African cities will likely join this list, as the world's fastest growing cities are in Africa (UN, 2014).

Using a 15-year record of satellite AOD Boys et al. (2014) identified a robust increase in $PM_{2.5}$ in southern Africa where there is also a positive trend in biomass area burned (Andela and van der Werf, 2014). $PM_{2.5}$ appears to be declining in Nigeria, but data coverage is limited due to cloudy conditions during the West African monsoon (Boys et al., 2014).

## An African Geostationary Observation Platform

LEO sensors have been invaluable for investigating seasonal and multiannual variability in Africa (Section 2), but knowledge of diurnal evolution of atmospheric composition in Africa is limited.

Figure 2 shows the spatial extent of the planned (pre-2020 launch) constellation of Earth observing geostationary (GEO) sensors TEMPO (Chance et al., 2013), Sentinel-4 (Ahlers et al., 2011), and GEMS (Kim, 2012). Coverage is largely limited to the northern hemisphere. The Sentinel-4 viewing domain will vary seasonally, extending over much of North Africa in boreal winter. GEO satellites are positioned ~36 000 km above the Earth's equator and the planned instruments will observe the same point every hour at higher resolution than the deployed LEO satellites. The ground footprint of TEMPO, for example, is 2 km × 5 km at the center of the North American domain (Chance et al., 2013).

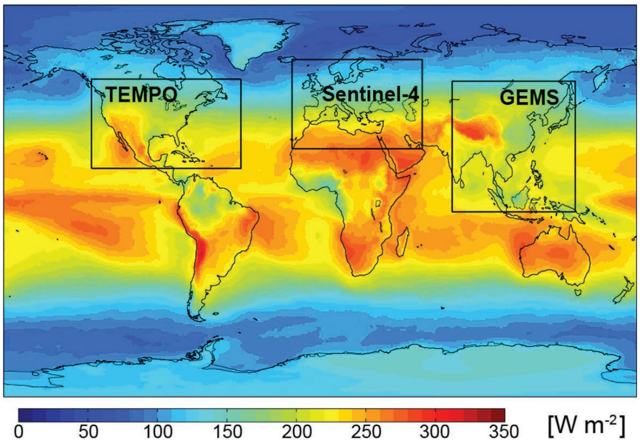


***Figure 2**: MERRA 2006-2007 all-sky incident solar radiation overlaid with sampling domains of planned GEO Earth observation platforms.*

Planned GEO sensors sacrifice spatial coverage (Figure 2) for fine spatial and temporal (hourly) resolution. Higher sampling frequencies and spatial resolution increase signal-to-noise and the number of clear-sky observations. Finer spatial resolution of a GEO instrument would resolve sub-urban features, heterogeneous vegetation cover, and the many political boundaries in Africa. Hourly measurements provide information about diurnal evolution of emissions, chemistry, and pollution transport dynamics. Information gained from a GEO satellite will better constrain air quality models that are being developed at increasingly fine resolution.

Current LEO sensors have limited sensitivity to surface $O_3$ (Zhang et al., 2010) that will be addressed with TEMPO by extending the spectrum to include the visible Chappuis $O_3$ band (Chance et al., 2013).

The underlying map in Figure 2 is annual mean incident solar radiation flux (Appendix), used here as a proxy for sampling frequency of a remote UV-visible instrument. GEO satellites located above the Equator are ideally positioned to view Africa. Africa also has year-round sun, with some reduction in coverage over West Africa due to persistent clouds during the monsoon season. Large portions of the planned GEO sensors will go dark in boreal winter.

Already South Korea has launched the GEO GOCI satellite to monitor ocean color in the Korean Sea at 500 m spatial resolution (Choi et al., 2012). GEO satellites can be expensive and high mission costs of the US GEO-CAPE instrument (~$2 billion) have delayed that project (Fishman et al., 2012). The cost to launch TEMPO is reduced by including the instrument as a hosted payload on a commercial satellite (http://science.nasa.gov/missions/tempo/), and contracting simultaneous build and design of TEMPO and GEMS (Brown, 2013).

Africa has successfully deployed Earth observing multispectral imaging satellites either as independent countries or through the African Union (Ngcofe and Gottschalk, 2013). Data from these satellites are invaluable for disaster risk management, food security, and urban planning, but African nations need to invest in an instrument that monitors air quality across a continent already experiencing rapid growth. Skills scarcity on the continent can be addressed by training scientists at overseas institutions that specialize in retrieval and interpretation of remote sensing data. Instrument design and build can be outsourced to a private company, as is the case with TEMPO and GEMS (Chance et al., 2013).

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## Appendix

Data used in this work are version 2 gridded monthly mean OMI tropospheric $NO_2$ (http://www.temis.nl/airpollution/no2.html); updated OMI HCHO and OMI CHOCHO products described in González Abad et al. (2015) and Miller et al. (2014), respectively; and NASA version 3 level 3 OMI PBL $SO_2$ (http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omso2e_v003.shtml). Net solar radiation flux is the NASA reanalysis MERRA product, version 2.3, obtained with the Giovanni visualization tool (http://disc.sci.gsfc.nasa.gov/giovanni).

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