Atmospheric Environment 99 (2014) 32–40

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Anthropogenic emissions in Nigeria and implications for atmospheric ozone pollution: A view from space

E.A. Marais [a, *], D.J. Jacob [a, b], K. Wecht [a], C. Lerot [c], L. Zhang [b, d], K. Yu [b], T.P. Kurosu [e, 1], K. Chance [e], B. Sauvage [f]

[a] Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA
[b] School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA
[c] Belgian Institute for Space Aeronomy (BIRA-IASB), Brussels, Belgium
[d] Department of Atmospheric and Oceanic Sciences & Laboratory for Climate and Ocean-Atmosphere Studies, School of Physics, Peking University, China
[e] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
[f] Laboratoire d'Aérologie, CNRS, Université de Toulouse III, Toulouse, France

HIGHLIGHTS

- Interpret Nigerian air pollution with satellite and aircraft observations.
- Per capita NMVOC emissions are higher than emissions in China.
- December–February surface ozone exceeds 70 ppbv.
- Open fires, fuel emissions, and restricted ventilation contribute to high ozone.

ARTICLE INFO

Article history:
Received 27 July 2014
Received in revised form
17 September 2014
Accepted 19 September 2014
Available online 22 September 2014

Keywords:
Nigeria
NMVOC
Atmospheric ozone pollution
Satellite
AMMA

ABSTRACT

Nigeria has a high population density and large fossil fuel resources but very poorly managed energy infrastructure. Satellite observations of formaldehyde (HCHO) and glyoxal (CHOCHO) reveal very large sources of anthropogenic nonmethane volatile organic compounds (NMVOCs) from the Lagos megacity and oil/gas operations in the Niger Delta. This is supported by aircraft observations over Lagos and satellite observations of methane in the Niger Delta. Satellite observations of carbon monoxide (CO) and nitrogen dioxide (NO_2) show large seasonal emissions from open fires in December–February (DJF). Ventilation of central Nigeria is severely restricted at that time of year, leading to very poor ozone air quality as observed from aircraft (MOZAIC) and satellite (TES). Simulations with the GEOS-Chem chemical transport model (CTM) suggest that maximum daily 8-h average (MDA8) ozone exceeds 70 ppbv over the region on a seasonal mean basis, with significant contributions from both open fires (15–20 ppbv) and fuel/industrial emissions (7–9 ppbv). The already severe ozone pollution in Nigeria could worsen in the future as a result of demographic and economic growth, although this would be offset by a decrease in open fires.

1. Introduction

Nigeria is Africa's most populous country (170 million people as of 2012). Its population grew 60% between 1990 and 2008 and is projected to reach 0.5–1 billion people by 2100 (UN, 2013). Nigeria's 2012 GDP growth rate of 7% per year, forecast to continue (PwC, 2013), is amongst the highest in the world. The Nigerian economy recently surpassed South Africa as the largest on the continent (Magnowski, 2014).

* Corresponding author. Now at School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA.
E-mail address: emarais@seas.harvard.edu (E.A. Marais).
[1] Now at Earth Atmosphere Science, Jet Propulsion Laboratory, Pasadena, CA, USA.

http://dx.doi.org/10.1016/j.atmosenv.2014.09.055

This rapid growth in Nigeria elicits a range of environmental concerns including air quality. Pollution from mobile sources is exacerbated by inefficient vehicles, disorganized road networks, traffic congestion, and fuel adulteration (Hopkins et al., 2009; Osuji et al., 2009; Assamoi et al., 2010). The megacity Lagos has higher emissions of nonmethane volatile organic compounds (NMVOCs) than megacities in China and India (Hopkins et al., 2009). Baumbach et al. (1995) measured average benzene concentrations in Lagos of 80 ppbv, which is 8 times more than the highest concentrations found by Barletta et al. (2005) in Chinese cities. The oil and gas sector is also a large source of air pollution due to flaring (Ologunorisa, 2001; Osuji and Avwiri, 2005), illegal oil refining (EIA, 2012), gas leakage and venting (Hopkins et al., 2009), and frequent pipeline explosions (Minga et al., 2010; Fadeyibi et al., 2011). In the densely populated Niger Delta, where oil and gas extraction is concentrated, carcinogenic polycyclic aromatic hydrocarbon (PAH) concentrations are amongst the highest in the world (Ana et al., 2012). In addition, inadequate electricity distribution results in dependence of industries and households on diesel-powered backup generators (BUGs), kerosene, and fuelwood (Ikeme and Ebohon, 2005; Akinlo, 2009).

Satellites provide a unique resource for observing air quality in a region such as Nigeria where ground-based information is sparse. In a recent continental-scale study for Africa we used formaldehyde (HCHO) observations from the space-based Ozone Monitoring Instrument (OMI) to map emissions of isoprene, a NMVOC emitted by vegetation (Marais et al., 2012). However, we found that we could not retrieve isoprene emissions over Nigeria because of extremely high HCHO of apparently anthropogenic origin, comparable to levels observed over industrial regions of China (Fu et al., 2007).

Here we conduct a comprehensive analysis of satellite observations of atmospheric composition over Nigeria, including not only HCHO but also carbon monoxide (CO), nitrogen dioxide (NO_2), glyoxal (CHOCHO), methane (CH_4), and ozone (O_3). We also use aircraft measurements obtained during the African Monsoon Multidisciplinary Analysis (AMMA) campaign in 2006 (Hopkins et al., 2009; Redelspeger et al., 2006) and the Measurement of Ozone and Water Vapor aboard Airbus In-service Aircraft (MOZAIC) program in 2003–2004 (Marenco et al., 1998; http://www.iagos.fr/mozaic). We interpret these data with the GEOS-Chem chemical transport model (CTM) in terms of the information they provide for Nigerian emissions and air quality.

2. Pollution sources and transport in Nigeria

Fig. 1 shows the major population centers and industrial point sources in Nigeria. The highest population densities are in the northern state Kano, the southwestern state Lagos, and the Niger Delta states in the southeast. Metropolitan Lagos has a population of 21 million people with a growth rate of 670 000 people per year (Cocks, 2013). The majority of Nigeria's industry is concentrated in 5 cities – Kano and Kaduna in the north, Lagos in the southwest, and Warri and Port Harcourt in the Niger Delta.

Oil and gas production is concentrated in the Niger Delta. Production in 2011 was 2.1 million bpd (barrels per day) of crude oil (3% of global production) and 28 billion m^3 of natural gas (0.9%). Up to 70% of extracted natural gas is lost by venting, leakage, and flaring (Ashton-Jones, 1998). Extensive pipeline networks transport crude oil from wells to export terminals and also link wells to refineries, but the latter only operate at 20% capacity due to mismanagement, poor maintenance, and pipeline vandalism (EIA, 2012). Low refining capacity has forced Nigeria to import more than 80% of its refined products, while more than 80% of extracted crude oil is exported accounting for >95% of Nigeria's export earnings (EIA, 2012). Theft of crude oil at pipelines is between

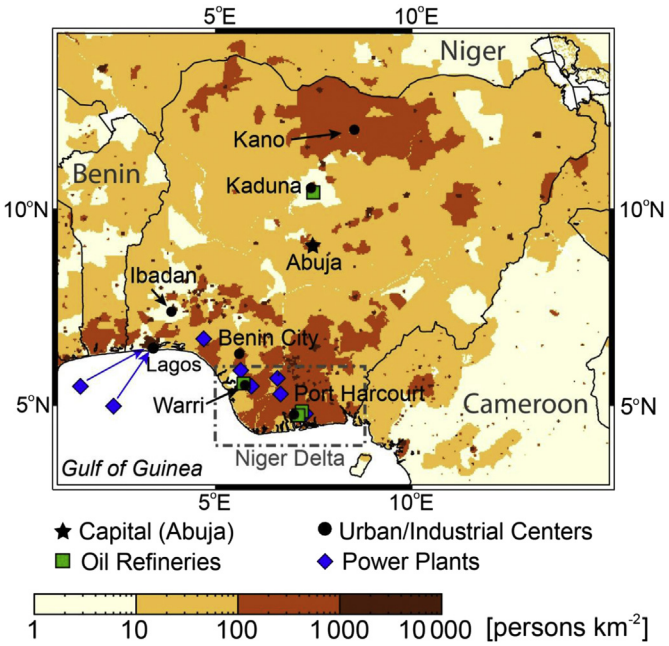

Fig. 1. Map of Nigeria highlighting major emission centers. The population density map is for 2000 (CIESN, 2005).

100 000 and 400 000 bpd and much of this is refined illegally in the Niger Delta for local and international sale of kerosene, diesel, and bitumen (EIA, 2012).

Electricity generation in Nigeria includes oil- and gas-fueled thermal power plants and hydropower. Hydroelectric plants are concentrated in central Nigeria, while thermal power plants are close to industry in Lagos and oil extraction facilities in the Delta (Fig. 1). Although coal fueled the industrialization of Nigeria in the early 20th century, most coal mines were abandoned following the Nigerian-Biafran civil war (1967–1970) (Oguejiofor, 2010). Inadequate supply of electricity and regular power outages lead to dependence on diesel for BUGs and kerosene for lighting. BUGs are used by 97% of businesses and in 1990 accounted for 30% of the nation's grid capacity (Ikeme and Ebohon, 2005). Fuelwood and waste burning, a source of energy for illegal oil refining in the Niger Delta and domestic use by rural populations, accounts for >80% of the country's energy consumption (Hyman et al., 1994; Maconachie et al., 2009; EIA, 2012).

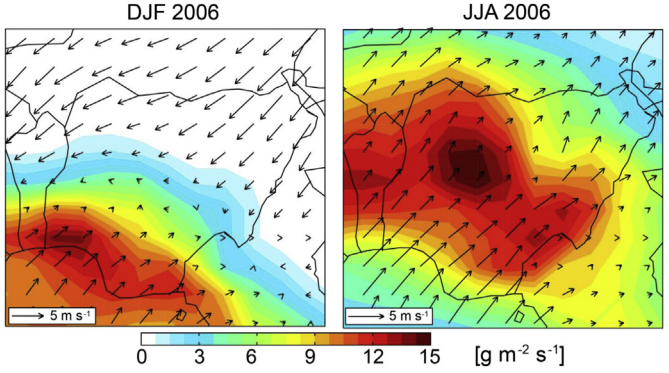

Fig. 2. Surface winds and deep convection over Nigeria. Mean 0–1 km wind vectors (arrows) and 500 hPa convective mass fluxes (contours) are shown for the dry season (December–February) and wet season (June–August) of 2006. Data are from NASA MERRA (Rienecker et al., 2011).

Fig. 2 shows 2006 surface winds and 500 hPa convective mass fluxes for the dry season (December–February – DJF) and wet season (June–August – JJA). The West African Monsoon (WAM) is a prominent feature in JJA and effectively ventilates the region. In DJF, by contrast, winds are stagnant over central Nigeria and vertical ventilation is suppressed by a strong temperature inversion at 900–750 hPa due to warm northeasterly Harmattan winds at that altitude blowing from the Sahara (Sauvage et al., 2005). The lack of ventilation is illustrated in Fig. 3 with a GEOS-Chem simulation of ^{222}Rn, a chemically inert continental tracer with uniform source from non-frozen soil and e-folding lifetime of 5.5 days (Jacob et al., 1997; Liu et al., 2001). Surface air ^{222}Rn concentrations in DJF in West Africa are the highest in the world, highlighting the potential for accumulation of pollution.

3. Atmospheric composition over Nigeria observed from space

Fig. 4 shows DJF mean satellite observations of atmospheric composition over Nigeria mapped on a 0.5 × 0.5° grid: CO from AIRS, tropospheric NO_2 and HCHO from OMI, CH_4 from SCIAMACHY, and CHOCHO from GOME-2. Values for JJA are shown for OMI NO_2 only; other data are excessively noisy in that season because of cloud cover. Sources of data are given in Table 1. AIRS CO columns are weighted towards the mid-troposphere (McMillan et al., 2011) while other variables have uniform vertical sensitivity in the tropospheric column (after air mass factor correction). Observations are averaged over 2005–2007, except for CHOCHO which is 2007 only as GOME-2 was launched in October 2006. MODIS Terra fire counts at 1 × 1 km^2 resolution are superimposed on AIRS CO.

CO and NO_2 (DJF) show maxima in central Nigeria from seasonal open fires. Urban and industrial activity in Lagos and the Niger Delta is also apparent in the DJF observations for NO_2 but not for CO, possibly reflecting the weak boundary layer sensitivity of the AIRS instrument. NO_2 concentrations in JJA are considerably lower than in DJF over most of Nigeria, reflecting the lack of fire influence but also the more efficient ventilation. The exception is northern Nigeria (Sahel), where higher NO_2 in JJA may be due to stimulation of NO_x emissions by precipitation at the onset of the wet season (Yienger and Levy, 1995; Jaeglé et al., 2004). The JJA NO_2 maximum in the northeastern corner of Nigeria may be due to crop cultivation and receding shorelines of Lake Chad (Batello et al., 2004).

HCHO in Nigeria, offset from the open fire NO_2 and CO enhancement, is highest in the Niger Delta and is also high over Lagos, indicating a dominant source from anthropogenic NMVOCs. This is in sharp contrast to the rest of Africa where HCHO observed from space is mainly from open fires and isoprene (Stavrakou et al., 2009; Marais et al., 2012). CH_4 peaks in the Niger Delta, indicative of the oil/gas source, with high values also along the distribution line to Lagos. By contrast, CHOCHO is higher over Lagos than over the Delta. CHOCHO is not produced from oxidation of alkanes (a large fraction of oil/gas emissions; Gilman et al. (2013)) but has a high yield from oxidation of aromatics associated with vehicle emissions (Fu et al., 2008; Liu et al., 2012).

The satellite data indicate HCHO:NO_2 molar ratios of 6–8 over Lagos, whereas values for megacities in China and the US tend to be less than unity (Martin et al., 2004; Duncan et al., 2010; Witte et al., 2011). This reflects an unusually high NMVOC/NO_x emission ratio in Lagos, as would be expected from the very inefficient energy infrastructure and lack of pollution control.

4. Constraints on Nigerian emissions

We use the GEOS-Chem global 3-D CTM (see Appendix) to simulate atmospheric composition over Nigeria and compare with aircraft and satellite observations. Table 2 shows Nigerian emissions in the model, including corrections on the basis of observations as discussed below.

Some information on anthropogenic emissions from Lagos is available from atmospheric composition measurements made onboard the AMMA BAe-146 aircraft on Thursday 8 August 2006 at 1530–1700 local time. The NMVOC measurements imply very high emissions (Hopkins et al., 2009). Fig. 5 compares observed and simulated (GEOS-Chem) boundary layer (<1 km) NMVOC and CO concentrations. The standard GEOS-Chem simulation uses RETRO (Schultz et al., 2007) as its default global inventory for anthropogenic NMVOC emissions, except for ethane which is from Xiao et al. (2008). We find that CO, ethane, propane, and acetone are well simulated. Other NMVOCs including higher alkanes and aromatics are underestimated several-fold, likely reflecting missing sources in the RETRO emission inventory from vehicles, BUGs, and industry and consistent with other observations of elevated concentrations in Lagos (Baumbach et al., 1995). Successful simulation of CO and short alkanes suggests that the model bias for NMVOCs reflects error in emissions rather than transport or dilution. We corrected anthropogenic emissions throughout Nigeria by the corresponding factor bias and results are shown in Fig. 5. The residual error is from chemical non-linearity and is within the uncertainty in the comparison.

The resulting corrected anthropogenic NMVOC emissions in Nigeria for 2006 are 6.4 Tg C a^{-1}, 4 times the RETRO inventory (Table 2). From the stoichiometry of speciated emissions this translates into 8.4 Tg NMVOCs a^{-1} (49 kg NMVOCs per capita) and

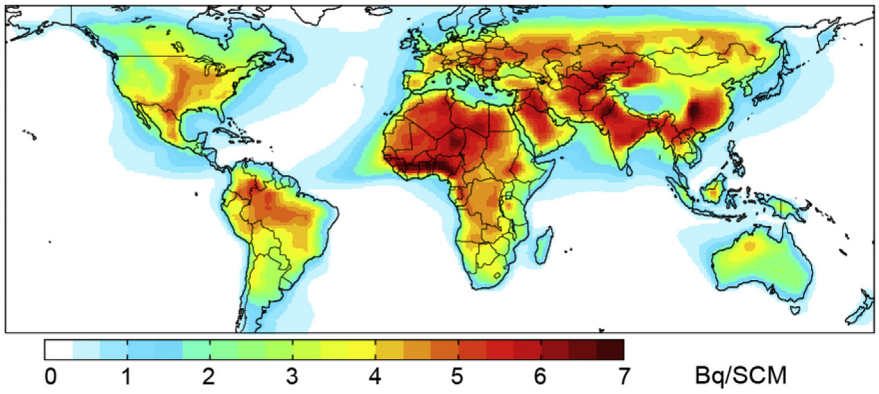

Fig. 3. Mean ^{222}Rn mixing ratios in surface air simulated by GEOS-Chem for December–February 2006.

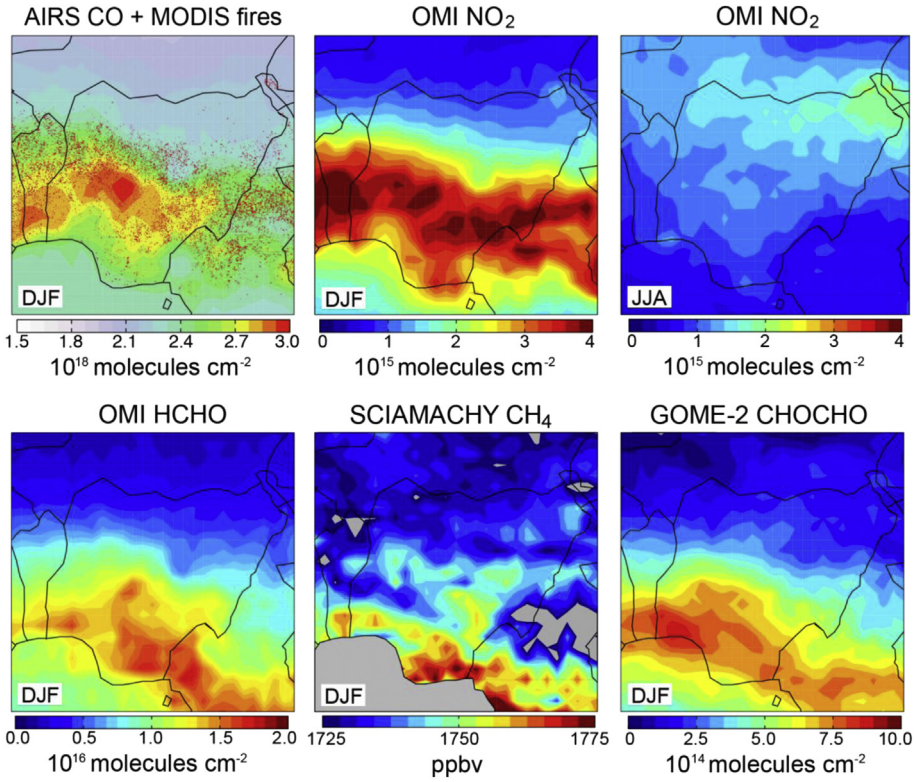

Fig. 4. Satellite observations of atmospheric composition over Nigeria: 2005–2007 December–February (DJF) means (2007 only for CHOCHO) and June–August (JJA) means for NO_2. Data are atmospheric columns except for NO_2 (tropospheric column) and CH_4 (column-averaged mixing ratio). Individual fire counts at 1×1 km^2 are also shown. Gray indicates missing data. See Table 1 for sources of data.

Table 1
Satellite data used in this work.

Species	Instrument	Product[a]	Reference
CO	AIRS[b]	NASA v5 L2	McMillan et al. (2011)
NO_2	OMI	ESA TEMIS v2 L2	Boersma et al. (2007)
CH_4	SCIAMACHY[c]	SRON/JPL v5.5	Frankenberg et al. (2011)
HCHO	OMI	NASA v2 L3	Kurosu (2008)
CHOCHO	GOME-2	Research product	Lerot et al. (2010)
Fire Counts	MODIS	NASA v5 L3	Giglio et al. (2003)
O_3	TES[d]	v005	Bowman et al. (2006)

[a] v = version; L = level.
[b] Only daytime data are used as these have higher quality than nighttime data (Kopacz et al., 2010). A 10% downward correction is applied to correct for positive bias (Yurganov et al., 2008, 2010; Warner et al., 2010; McMillan et al., 2011).
[c] Data are for land only and include a bias correction dependent on water vapor (Wecht et al., 2014).
[d] Reprocessed to a fixed a priori profile for West Africa and filtered for data quality following Zhang et al. (2010).

can be compared to an estimated anthropogenic source of 23 Tg NMVOCs a^{-1} from China (18 kg NMVOCs per capita) (Zhang et al., 2009).

Fig. 6 shows the simulation by GEOS-Chem of the satellite observations in Fig. 4. The simulation includes the above correction to anthropogenic NMVOC emissions as well as other corrections applied as scale factors to the standard GEOS-Chem emissions (Table 2 and Appendix). Model values are means for DJF 2006 (and JJA for NO_2 only) sampled at the satellite overpass times, and including AIRS CO and SCIAMACHY CH_4 averaging kernels. The model has a horizontal resolution of $2 \times 2.5°$ while the observations in Fig. 4 are on a $0.5 \times 0.5°$ grid, so that fine-scale features in the observations are diluted in the model.

Table 2
Annual emissions in Nigeria (2006).[a]

Species	Emission inventory	Emissions	
		Standard	Corrected
NO_x [Tg N a^{-1}]		**0.60**	**1.1**
Fossil fuel	EDGAR v2.0	0.10	0.21[b]
Biofuel	Yevich and Logan (2003)	0.073	0.073
Open fires	GFED v2	0.096	0.27[c]
Soils	Yienger and Levy (1995)	0.33	0.52[d]
CO [Tg CO a^{-1}]		**15**	**49**
Fossil fuel	EDGAR v2.0	3.2	5.4[b]
Biofuel	Yevich and Logan (2003)	5.3	5.3
Open fires	GFED v2	6.2	38[c]
NMVOCs [Tg C a^{-1}]		**2.7**	**7.4**
Fuel	RETRO[e]	1.6	6.4[f]
Open fires	GFED v2	0.35	0.35
Biogenic	MEGAN	0.79	0.65[g]
CH_4 [Tg a^{-1}]		**8.2**	**8.2**
Oil and Gas	EDGAR v4.2	1.7	1.7
Livestock	EDGAR v4.2	1.3	1.3
Waste	EDGAR v4.2	0.90	0.90
Wetlands	Picket-Heaps et al. (2011)	2.7	2.7
Other	EDGAR v4.2	1.6	1.6

[a] "Standard" emissions are those in the standard version of GEOS-Chem (v9-01-03) using the emission inventories indicated. "Corrected" emissions are modified on the basis of additional information and constraints from observations as described in the text.
[b] Including additional emissions from motorcycles and back-up generators (see Appendix).
[c] Increased to improve agreement with MOZAIC CO, AIRS CO, and OMI NO_2.
[d] Increased to improve agreement with OMI NO_2 in northern Nigeria in JJA.
[e] Except ethane, which is from Xiao et al. (2008).
[f] Increased on the basis of AMMA aircraft observations.
[g] Decreased across the Sahel to match the HCHO and CHOCHO satellite data.

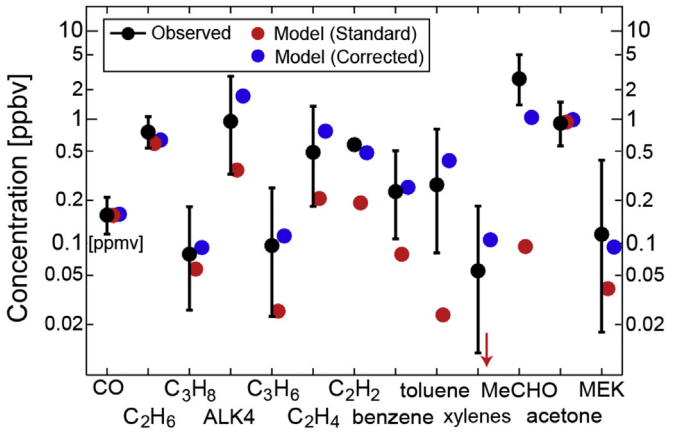

Fig. 5. Concentrations of CO and NMVOCs over Lagos on 8 August 2006 at 1530–1700 local time. Observations from the AMMA aircraft at <1 km altitude (black) are compared to GEOS-Chem results sampled at the time and location of the aircraft observations, using the standard GEOS-Chem emission inventories (red) and after scaling of emissions to correct for the bias (blue) (Table 2). Values are geometric means, with geometric standard deviations for the observations. Model points are offset for clarity. CO concentrations are ppmv. ALK4 ≡ ≥C_4 alkanes, MeCHO ≡ acetaldehyde, MEK ≡ methyl ethyl ketone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

GEOS-Chem roughly reproduces the spatial distribution and magnitude of NO_2 and CO after increasing GFED v2 open fire emissions of NO_x and CO (Table 2). The previously discussed increase of model anthropogenic NMVOC emissions to fit the AMMA data enables simulation of the observed OMI HCHO maximum over Lagos and the Niger Delta. The model roughly reproduces the CHOCHO observations over Lagos but is too high in the Delta. Aromatics are the dominant anthropogenic source of CHOCHO (Liu et al., 2012), and were greatly increased in the model to match the AMMA aircraft data over Lagos (Fig. 5). It may be that such an increase is not appropriate for the Delta as oil/gas emissions are dominated by alkanes. The CHOCHO and HCHO enhancement east of Nigeria is from oxidation of isoprene emitted in central Africa that is still too high after decreasing emissions there (see Appendix).

The high CH_4 levels in the Niger Delta, observed by SCIAMACHY and reproduced in GEOS-Chem, are dominated by emissions from the oil and gas industry. According to EDGAR v4.2 (EC-JRC/PBL, 2011), the default anthropogenic inventory for CH_4 emissions in GEOS-Chem, oil/gas emissions account for 75% of DJF CH_4 emissions in the Niger Delta (oil/gas extraction) and 40–50% across coastal Nigeria (pipeline network linking the Delta and Lagos). Wetlands are also a major source of CH_4 in the Delta (18–30%).

5. Implications for ozone air quality

Clear skies, stagnant air, and strong temperature inversions over central Nigeria in DJF imply a particular propensity for air quality problems. Observations allow us to place some constraints on surface O_3, a major respiratory irritant produced by photochemical oxidation of VOCs and CO in the presence of NO_x. Field and model studies have found elevated surface O_3 concentrations in West Africa in DJF due to seasonal open fires (Helas et al., 1995; Marufu et al., 2000; Sauvage et al., 2005; Aghedo et al., 2007). Here we test the GEOS-Chem simulation of O_3 with aircraft observations from MOZAIC (Thouret et al., 1998) and satellite observations from TES, and examine the implications for O_3 pollution over Nigeria now and in the future.

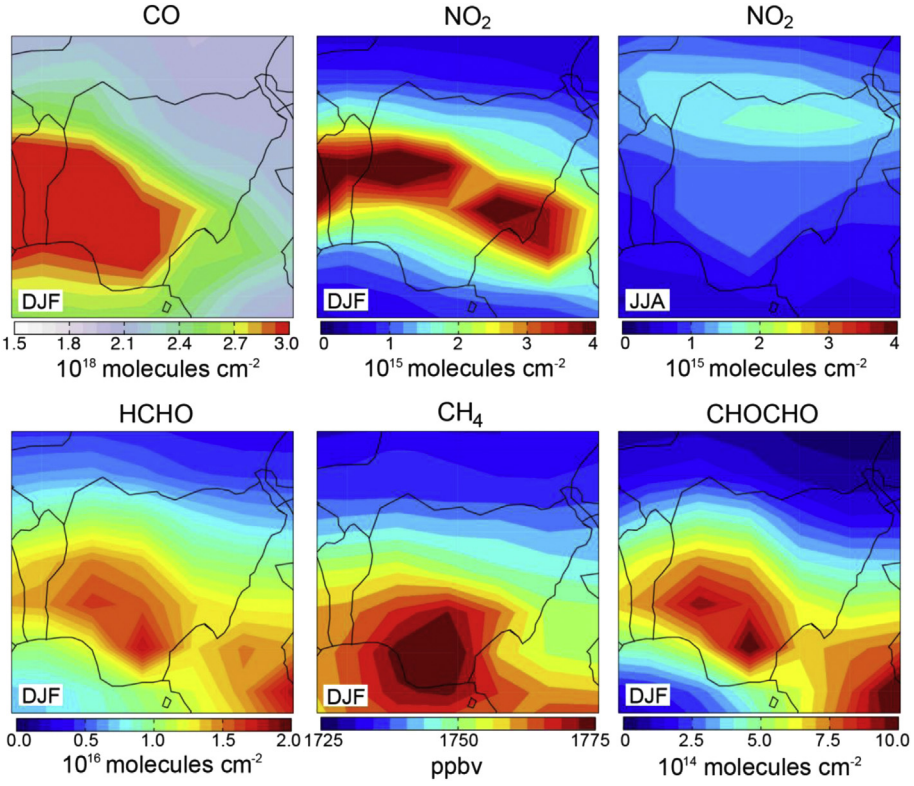

Fig. 6. GEOS-Chem simulation of the satellite observations in Fig. 4 after applying corrections to the emission inventories (Table 2). Values are means for December–February 2006 and include total column CO weighted by the AIRS averaging kernels, tropospheric NO_2 column, HCHO column, column average CH_4 mixing ratios weighted by the SCIAMACHY averaging kernels, and CHOCHO column. The model is sampled during the satellite overpass times. The horizontal resolution is 2 × 2.5°.

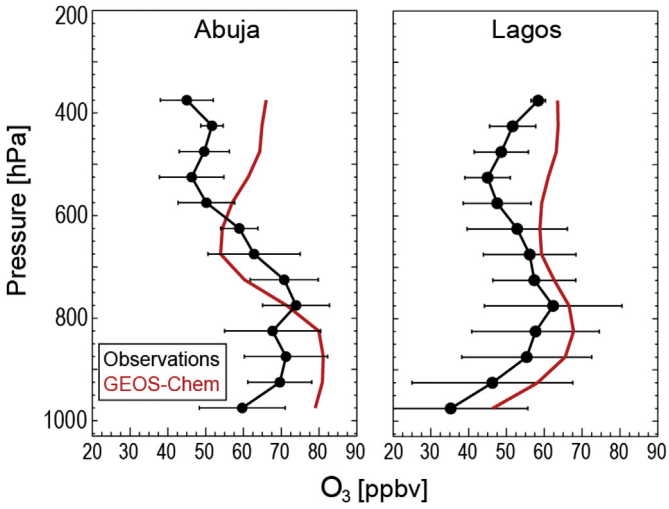

Fig. 7. Mean vertical profiles of O_3 concentrations over Abuja and Lagos in January–February. MOZAIC observations are for 3 descent flights over Abuja and 16 over Lagos at 18–19 and 18–21 local time, respectively, in 2003–2004. Horizontal lines are 1σ standard deviations. Corresponding GEOS-Chem profiles are means for January–February 2006 at the same local time.

MOZAIC observations of vertical O_3 profiles from commercial flights are available for Lagos and Abuja in January–February 2003–2004 at 18–21 and 18–19 local time, respectively. These are shown in Fig. 7 together with the corresponding mean model profiles for January–February 2006 sampled at the same local time. The observations at Abuja show mean concentrations of 60–75 ppbv from the surface to 700 hPa. Such high values are due to a combination of fires and anthropogenic emissions, as discussed below. The model is about 10 ppbv higher than the observations below 800 hPa. It does not capture the drop at the surface, which could be due to poor model representation of stratified conditions near the surface after sunset (Jacob et al., 1993). Lower O_3 concentrations in the Abuja profile above 700 hPa are associated with the African Easterly Jet (AEJ) (Sauvage et al., 2007). Concentrations over Lagos differ from those over Abuja mostly below 900 hPa, reflecting the influx of clean oceanic air (Fig. 2). Above 900 hPa the Harmattan northeasterly winds carry O_3 pollution from central Nigeria over Lagos. This is again roughly reproduced by the model, with a 10 ppbv positive bias.

TES is a thermal IR instrument with sensitivity to O_3 in the lower free troposphere. Fig. 8 shows the TES O_3 retrieval at 825 hPa, representing a tropospheric column concentration with maximum sensitivity at 800–700 hPa (left panel). Retrievals nearer the surface have a similar vertical pattern of sensitivity but weaker signal. O_3 at 800–700 hPa is strongly affected by the Harmattan winds transporting O_3-rich air from central to coastal Nigeria, as is apparent from the vertical profiles over Abuja and Lagos (Fig. 7). Deep convection over coastal Nigeria (Fig. 2) then transports that O_3-rich air to high altitude. The TES observations show a maximum over Lagos, consistent with that transport pattern. GEOS-Chem results sampled with TES sensitivity (Fig. 8) show a more muted effect of this transport with little gradient from central to coastal Nigeria, consistent also with the aircraft profiles of Fig. 7.

Fig. 9 shows mean surface daily maximum 8-h average (MDA8) O_3 concentrations simulated by GEOS-Chem in surface air for DJF 2006. Values in central Nigeria exceed 80 ppbv. Even allowing for a possible ~10 ppbv positive bias in the model, these are very high values and suggest that Nigeria has presently a major O_3 air quality problem. We are unaware of an official O_3 air quality standard in Nigeria, but the US health-based standard of 75 ppbv (MDA8) would be routinely exceeded.

The band of elevated O_3 pollution in the GEOS-Chem simulation across central Nigeria follows the pattern of seasonal open fires but also the transport of pollution from coastal anthropogenic sources (Fig. 2) and meteorological stagnation (Fig. 3). GEOS-Chem sensitivity simulations with zeroed sources indicate that open fires increase mean MDA8 O_3 in central Nigeria in DJF by 15–20 ppbv while anthropogenic sources (fuel) increase it by 7–9 ppbv, consistent with the previous model study by Aghedo et al. (2007). A sensitivity simulation zeroing emissions from NMVOC anthropogenic emissions only indicate that these contribute half of the anthropogenic MDA8 O_3 increase.

Anthropogenic emissions in Nigeria are expected to increase in the future following economic growth. The Representative Concentration Pathways (RCP) scenarios (van Vuuren et al., 2011)

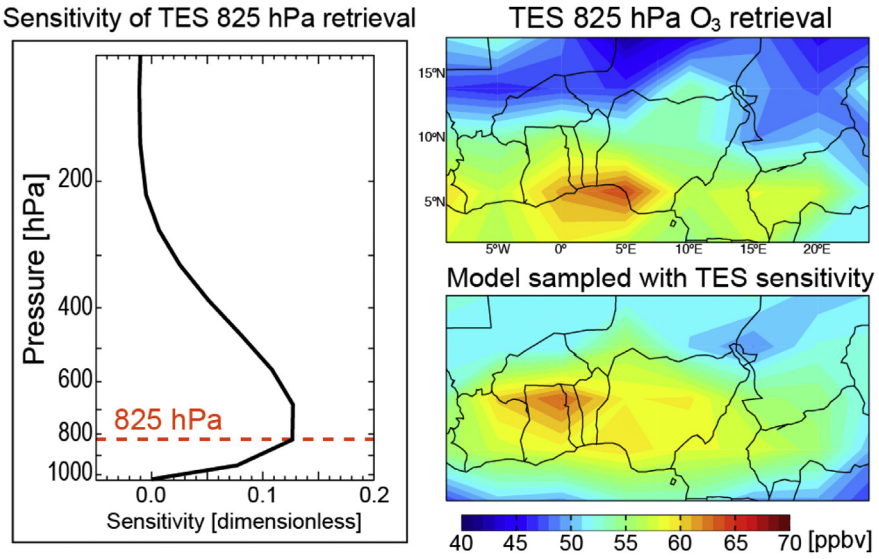

Fig. 8. O_3 concentrations measured by TES in the lower free troposphere in DJF 2006. The left panel shows the vertical sensitivity of the TES 825 hPa retrieval (mean averaging kernel matrix row for Abuja). The right panels show the TES retrievals and the GEOS-Chem O_3 values sampled along the TES orbit tracks at the overpass time (0130 and 1330 local) and smoothed by the TES sensitivity. The TES data were reprocessed to use a fixed a priori (Zhang et al., 2010) so that the structure in the figure is solely from the observations.

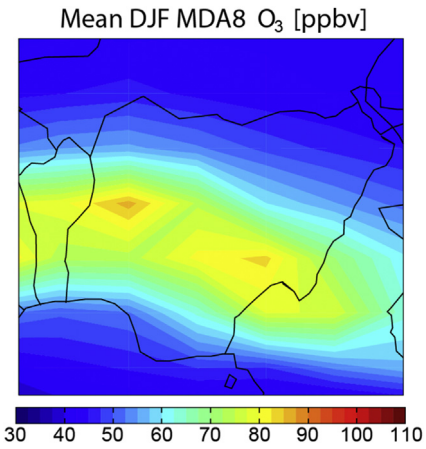

Fig. 9. Mean daily maximum 8-h average (MDA8) O_3 concentrations simulated by GEOS-Chem in surface air over Nigeria for December–February 2006.

project anthropogenic NO_x emissions in Nigeria of 0.2–0.5 Tg N a^{-1} by 2050, compared to 0.2 Tg N a^{-1} for 2000, but these assume strong regulation of air pollution in the future. A less optimistic scenario where fuel emissions scale with power generation would imply an order-of-magnitude increase in anthropogenic emissions if Nigeria's economy were to rise to the current level of BRICS nations (i.e. Brazil, Russia, India, China, and South Africa). On the other hand, economic growth would likely be associated with decreased fire activity. Arino et al. (2012) find significant decrease in Nigerian fires over 1995–2009 from ATSR satellite measurements. Thus the future of O_3 air quality in Nigeria depends on the likely opposite trends of anthropogenic and fire emissions.

6. Conclusions

Nigeria has a large and rapidly growing population, a massive oil/gas exploitation sector, and a poorly functioning energy sector. Little information is available on its air quality. Here we used an ensemble of satellite observations of atmospheric composition together with aircraft observations and the GEOS-Chem model to better understand pollution sources and ozone air quality in Nigeria. Particulate matter and carcinogens such as benzene also degrade air quality in Nigeria, but observations of these pollutants near source regions are very limited.

Satellite observations of HCHO and CHOCHO indicate extremely high NMVOC emissions in the Lagos megacity and in the Niger Delta where oil and gas extraction is concentrated. HCHO is highest over the Delta while CHOCHO is highest over Lagos and downwind. The HCHO data indicate extensive leakage of NMVOCs (mostly alkanes) from oil/gas extraction, as corroborated by satellite observations of CH_4. The CHOCHO data imply considerable emissions of aromatic NMVOCs in Lagos, consistent with limited in situ data. We estimate an anthropogenic NMVOC source of 6.4 Tg C a^{-1} for Nigeria – higher on a per capita basis than China.

Anthropogenic NO_x emissions in Nigeria are lower than in comparable urban/industrial areas of China or the US, reflecting the very inefficient power production system. There is however a large NO_x source from open fires in December–February (DJF). Together with severely restricted ventilation this leads to poor O_3 air quality in central Nigeria. Model results suggest that the daily maximum 8-h average surface (MDA8) O_3 exceeds 70 ppbv over much of the region on a seasonal mean basis, and this is supported by satellite (TES) and aircraft (MOZAIC) data. Sensitivity simulations indicate that open fires and fuel/industrial emissions enhance MDA8 O_3 by 15–20 and 7–9 ppbv, respectively, over central Nigeria in DJF. Future economic growth with associated increase of fuel/industrial emissions would worsen O_3 air quality although this might be compensated by decreasing fire activity.

Acknowledgments

This work was funded by NASA through the Aura Science Team and by a South African National Research Scholarship for Study Abroad awarded to EAM. The authors grately acknowledge James Hopkins and Claire Reeves for access to the NMVOC measurements obtained onboard the BAe-146 aircraft as part of the AMMA campaign in July–August 2006. The authors acknowledge the strong support of the European Commission, Airbus, and the Airlines (Lufthansa, Air-France, Austrian, Air Namibia, Cathay Pacific, Iberia and China Airlines so far) who carry the MOZAIC or IAGOS equipment and perform the maintenance since 1994. MOZAIC is presently funded by INSU-CNRS (France), Météo-France, CNES, Université Paul Sabatier (Toulouse, France) and Research Center Jülich (FZJ, Jülich, Germany). IAGOS has been and is additionally funded by the EU projects IAGOS-DS and IAGOS-ERI. The MOZAIC-IAGOS data are available via CNES/CNRS-INSU Ether web site http://www.pole-ether.fr.

Appendix. GEOS-Chem description

We use the GEOS-Chem chemical transport model (version 9-01-03, http://geos-chem.org) driven by GEOS-5 assimilated meteorological data from the NASA Global Modeling and Assimilation Office (GMAO). The GEOS-5 meteorological data have a native horizontal resolution of 0.5 × 0.67° with 72 vertical pressure levels and 6-h temporal frequency (3-h for surface variables and mixing depths). We use data for year 2006 and degrade the horizontal resolution to 2 × 2.5° and 47 pressure levels for input to GEOS-Chem. GEOS-Chem results use a one year spinup for chemical initialization.

The simulations presented here include the standard GEOS-Chem representation of oxidant-aerosol chemistry as described for example by Mao et al. (2010). We added chemical mechanisms for the oxidation of benzene, toluene, and xylenes (Calvert et al., 2002), and ethylene and acetylene (Saunders et al., 2003), as these are important reactive NMVOCs in Nigeria. We also conducted a separate GEOS-Chem simulation of CH_4 (Picket-Heaps et al., 2011) for comparison with the SCIAMACHY CH_4 data.

Emissions used in the model are listed in Table 2. Anthropogenic emissions of CO and NO_x in the standard GEOS-Chem simulation are from the EDGAR v2.0 inventory (Olivier et al., 1996) and biofuel NO_x and CO emissions are from the Yevich and Logan (2003) inventory. NO_x emissions from soils and fertilizer use are from Yienger and Levy (1995) as implemented by Wang et al. (1998) and are increased by 60% to improve agreement with OMI tropospheric NO_2. Open fire emissions are from GFED v2 with 8-day temporal resolution (van der Werf et al., 2006). We impose a cap of 1 g C m^{-2} d^{-1} on the biomass burn rate in central Africa to avoid spuriously high emissions. We also increase open fire emissions of CO and NO_2 in Nigeria to better match CO from MOZAIC (Abuja and Lagos flights) and AIRS, and NO_2 from OMI. Anthropogenic NMVOC emissions, including biofuel use, are from the RETRO inventory (Schultz et al., 2007), except ethane emissions which are from Xiao et al. (2008). Isoprene and biogenic acetone, ethene, and propene emissions are calculated with the MEGAN v2.1 inventory (Guenther et al., 2006) including modifications described in Marais et al. (2012) and a 50% emissions reduction in central Africa and the Sahel (Marais et al., 2014).

Anthropogenic emission inventories for Nigeria do not properly account for motorcycles and diesel-powered backup generators (BUGs). Assamoi and Liousse (2010) developed a black carbon and organic carbon aerosol emission inventory for motorcycles in West Africa. Here we include these emissions and emissions of carbonyls, aromatic VOCs, NO_x, and CO using emission factors available for Vietnam (Oanh et al., 2012). We derive BUG emissions in Nigeria using the 2400 MW installed capacity for 1999 estimated by the Nigerian Energy Commission (www.energy.gov.ng/) and emission factors from Gullet et al. (2006) and Sawant et al. (2007).

Further adjustments of emissions on the basis of the aircraft and satellite data over Nigeria are described in the text and in Table 2.

References

Aghedo, A.M., Schultz, M.G., Rast, S., 2007. The influence of African air pollution on regional and global tropospheric ozone. Atmos. Chem. Phys. 7, 1193–1212.

Akinlo, A.E., 2009. Electricity consumption and economic growth in Nigeria: evidence from cointegration and co-feature analysis. J. Policy Model. 31, 681–693. http://dx.doi.org/10.1016/j.jpolmod.2009.03.004.

Ana, G.R.E.E., Sridhar, M.K.C., Emerole, G.O., 2012. Polycyclic aromatic hydrocarbon burden in ambient air in selected Niger Delta communities in Nigeria. J. Air Waste Manage 62, 18–25. http://dx.doi.org/10.1080/10473289.2011.628900.

Arino, O., Casadio, S., Serpe, D., 2012. Global night-time fire season timing and fire count trends using the ATSR instrument series. Remote Sens. Environ. 116, 226–238. http://dx.doi.org/10.1016/j.rse.2011.05.025.

Ashton-Jones, N., 1998. The Human Ecosystem of the Niger Delta: an ERA Handbook. Environmental Rights Action (ERA), Ibadan, Nigeria, p. 137.

Assamoi, E.-M., Liousse, C., 2010. A new inventory for two-wheel vehicle emissions in West Africa for 2002. Atmos. Environ. 44, 3985–3996. http://dx.doi.org/10.1016/j.atmosenv.2010.06.048.

Barletta, B., Meinardi, S., Rowland, F.S., Chan, C.-Y., Wang, X., Zou, S., Chan, L.Y., Blake, D.R., 2005. Volatile organic compounds in 43 Chinese cities. Atmos. Environ. 39, 5979–5990. http://dx.doi.org/10.1016/j.atmosenv.2005.06.029.

Batello, C., Marzot, M., Touré, A.H., 2004. The Future is an Ancient Lake. FAO, Rome, Italy.

Baumbach, G., Vogt, U., Hein, K.R.G., Oluwole, A.F., Ogunsola, O.J., Olaniyi, H.B., Akeredolu, F.A., 1995. Air pollution in a large tropical city with a high traffic density – results of measurements in Lagos, Nigeria. Sci. Total Environ. 169, 25–31.

Boersma, K.F., Eskes, H.J., Veefkind, J.P., Brinksman, E.J., van der, A.,R.J., Sneep, M., van den Oord, G.H.J., Levelt, P.F., Stammes, P., Gleason, J.F., Bucsela, E.J., 2007. Near-real time retrieval of tropospheric NO_2 from OMI. Atmos. Chem. Phys. 7, 2103–2118. http://dx.doi.org/10.5194/acp-7-2103-2007.

Bowman, K.W., Rodgers, C.D., Kulawik, S.S., Worden, J., Sarkissian, E., Osterman, G., Steck, T., Lou, M., Eldering, A., Shephard, M., Worden, H., Lampel, M., Clough, S., Brown, P., Rinsland, C., Gunson, M., Beer, R., 2006. Tropospheric emission spectrometer: retrieval method and error analysis. IEEE T. Geosci. Remote 44, 1297–1307.

CIESN (Center for International Earth Science Information Network), 2005. Gridded Population of the World, Version 3 (GPWv3) Data Collection. Columbia University, New York. http://sedac.ciesin.columbia.edu/gpw/index.jsp.

Calvert, J., Atkinson, R., Becker, K.H., Kamens, R.M., Seinfeld, J.H., Wallington, T.J., Yarwood, G., 2002. The Mechanisms of Atmospheric Oxidation of Aromatic Hydrocarbons. Oxford University Press, New York.

Cocks, T. Will Nigerian Boom Babies Feed Prosperity or Entrench Poverty?, Reuters, http://www.reuters.com/article/2013/04/09/us-africa-summit-population-idUSBRE9380DH20130409, 9 April 2013, (accessed 08.07.13.).

Duncan, B.N., Yoshida, Y., Olson, J.R., Sillman, S., Martin, R.V., Lamsal, L., Hu, Y., Pickering, K.E., Retscher, C., Allen, D.J., Crawford, J.H., 2010. Application of OMI observations to a space-based indicator of NO_x and VOC controls on surface formation. Atmos. Environ. 44, 2213–2223. http://dx.doi.org/10.1016/j.atmosenv.2010.03.010.

EC-JRC/PBL (European Commission, Joint Research Centre/Netherlands Environmental Assessment Agency PBL), 2011. Emission Database for Global Atmospheric Research (EDGAR), Release Version 4.2. http://edgar.jrc.ec.europa.eu.

EIA (US Energy Information Administration), Nigeria, http://www.eia.gov/countries/analysisbriefs/Nigeria/nigeria.pdf, Last Updated: October 16, 2012, (accessed 15.01.13.).

Fadeyibi, I.O., Jewo, P.I., Opoola, P., Babalola, O.S., Ugburo, A., Ademiluyi, S.A., 2011. Burns and fire disasters from leaking petroleum pipes in Lagos, Nigeria: an 8-year experience. Burns 37, 145–152. http://dx.doi.org/10.1016/j.burns.2010.06.012.

Frankenberg, C., Aben, I., Bergamaschi, P., Dlugokencky, E.J., van Hees, R., Houweling, S., van der Meer, P., Snel, R., Tol, P., 2011. Global column-averaged methane mixing ratios from 2003 to 2009 as derived from SCIAMACHY: trends and variability. J. Geophys. Res. 116, D04302. http://dx.doi.org/10.1029/2010JD014849.

Fu, T.-M., Jacob, D.J., Palmer, P.I., Chance, K., Wang, Y.X., Barletta, B., Blake, D.R., Stanton, J.C., Pilling, M.J., 2007. Space-based formaldehyde measurements as constraints on volatile organic compound emissions in east and south Asia and implications for ozone. J. Geophys. Res. 112, D06312. http://dx.doi.org/10.10292/2006JD007853.

Fu, T.-M., Jacob, D.J., Wittrock, F., Burrows, J.P., Vrekoussis, M., Henze, D.K., 2008. Global budgets of atmospheric glyoxal and methylglyoxal, and implications for formation of secondary organic aerosols. J. Geophys. Res. 113, D15303. http://dx.doi.org/10.1029/2007JD009505.

Giglio, L., Descloitres, J., Justice, C.O., Kaufman, Y.J., 2003. An enhanced contextual fire detection algorithm for MODIS. Remote Sens. Environ. 87, 273–282. http://dx.doi.org/10.1016/S0034-4257(03)00184-6.

Gilman, J.B., Lerner, B.M., Kuster, W.C., de Gouw, J.A., 2013. Source signature of volatile organic compounds from oil and natural gas operations in northeastern Colorado. Environ. Sci. Technol. 47, 1297–1305. http://dx.doi.org/10.1021/es304119a.

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P.I., Geron, C., 2006. Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). Atmos. Chem. Phys. 6, 3181–3210. http://dx.doi.org/10.5194/acp-6-3181-2006.

Gullet, B.K., Touati, A., Oudejans, L., Ryan, S.P., 2006. Real-time emission characterization of organic air toxic pollutants during steady state and transient operation of a medium duty diesel engine. Atmos. Environ. 40, 4037–4047. http://dx.doi.org/10.1016/j.atmosenv.2006.03.031.

Helas, G., Lobert, J., Scharffe, D., Schäfer, L., Goldammer, J., Baudet, J., Ahoua, B., Ajavon, A.-L., Lacaux, J.-P., Delmas, R., Andreae, M.O., 1995. Ozone production due to emissions from vegetation burning. J. Atmos. Chem. 22, 163–174.

Hopkins, J.R., Evans, M.J., Lee, J.D., Lewis, A.C., Marsham, J.H., McQuaid, J.B., Parker, D.J., Stewart, D.J., Reeves, C.E., Purvis, R.M., 2009. Direct estimates of emissions from the megacity of Lagos. Atmos. Chem. Phys. 9, 8471–8477. http://dx.doi.org/10.5194/acp-9-8471-2009.

Hyman, E.L., 1994. Fuel substitution and efficient woodstoves: are they the answers to the fuelwood supply problem in northern Nigeria. Environ. Manag. 18, 23–32. http://dx.doi.org/10.1007/BF02393747.

Ikeme, J., Ebohon, O.J., 2005. Nigeria's electric power sector reform: what should form the key objectives? Energ. Policy 33, 1213–1221. http://dx.doi.org/10.1016/j.enpol.2003.11.018.

Jacob, D.J., Logan, J.A., Yevich, R.M., Gardner, G.M., Spivakovsky, C.M., Wofsy, S.C., Munger, J.W., Sillman, S., Prather, M.J., Rodgers, M.O., Westberg, H., Zimmerman, P.R., 1993. Simulation of summertime ozone over North America. J. Geophys. Res. 98 (D8), 14 797–14 816.

Jacob, D.J., Prather, M.J., Rasch, P.J., Shia, R.-L., Balkanski, Y.J., Beagley, S.R., Bergmann, D.J., Blackshear, W.T., Brown, M., Chiba, M., Chipperfield, M.P., de Grandpré, J., Dignon, J.E., Feichter, J., Genthon, C., Grose, W.L., Kasibhatla, P.S., Köhler, I., Kritz, M.A., Law, K., Penner, J.E., Ramonet, M., Reeves, C.E., Rotman, D.A., Stockwell, D.Z., Van Velthoven, P.F.J., Verver, G., Wild, O., Yang, H., Zimmerman, P., 1997. Evaluation and intercomparison of global atmospheric transport models using ^{222}Rn and other short-lived tracers. J. Geophys. Res. 102 (D5), 5 953–955 970. http://dx.doi.org/10.1029/96JD02955.

Jaeglé, L., Martin, R.V., Chance, K., Steinberger, L., Kurosu, T.P., Jacob, D.J., Modi, A.I., Yoboué, V., Sigha-Nkamdjou, L., Galy-Lacaux, C., 2004. Satellite mapping of rain-induced nitric oxide emissions from soils. J. Geophys. Res. 109, D21310. http://dx.doi.org/10.1029/2004JD004787.

Kopacz, M., Jacob, D.J., Fisher, J.A., Logan, J.A., Zhang, L., Megretskaia, I.A., Yantosca, R.M., Singh, K., Henze, D.K., Burrows, J.P., Buchwitz, M., Khlystova, I., McMillan, W.W., Gille, J.C., Edwards, D.P., Eldering, A., Thouret, V., Nédélec, P., 2010. Global estimates of CO sources with high resolution by adjoint inversion of multiple satellite datasets (MOPITT, AIRS, SCIAMACHY, TES). Atmos. Chem. Phys. 10, 855–876. http://dx.doi.org/10.5194/acp-10-855-2010.

Kurosu, T.P., 1 May 2008. OMI HCHO Readme File. http://www.cfa.harvard.edu/atmosphere/Instruments/OMI/PGEReleases/READMEs/OMHCHO_README.pdf (accessed 01.08.09.).

Lerot, C., Stavrakou, T., De Smedt, I., Müller, J.-F., Van Roozendael, M., 2010. Glyoxal vertical columns from GOME-2 backscattered light measurements and comparisons with a global model. Atmos. Chem. Phys. 10, 12059–12072.

Liu, H., Jacob, D.J., Bey, I., Yantosca, R.M., 2001. Constraints from ^{210}Pb and ^{7}Be on wet deposition and transport in a global three-dimensional chemical tracer model driven by assimilated meteorological fields. J. Geophys. Res. 106 (D11), 12 109–112 128. http://dx.doi.org/10.1029/2000JD900839.

Liu, Z., Wang, Y., Vrekoussis, M., Richter, A., Wittrock, F., Burrows, J.P., Shao, M., Chang, C.-C., Liu, S.-C., Wang, H., Chen, C., 2012. Exploring the missing source of glyoxal (CHOCHO) over China. Geophys. Res. Lett. 39, L10812. http://dx.doi.org/10.1029/2012GL051645.

Maconachie, R., Tanko, A., Zakariya, M., 2009. Descending the energy ladder? Oil price shocks and domestic fuel choices in Kano, Nigeria. Land Use Policy 26, 1090–1099. http://dx.doi.org/10.1016/j.landusepol.2009.01.008.

Magnowski, D., 7 April 2014. Nigerian Economy Overtakes South Africa's on Rebased GDP. Bloomberg. http://www.bloomberg.com/news/2014-04-06/nigerian-economy-overtakes-south-africa-s-on-rebased-gdp.html (accessed 07.04.14.).

Mao, J., Jacob, D.J., Evans, M.J., Olson, J.R., Ren, X., Brune, W.H., St Clair, J.M., Crounse, J.D., Spencer, K.M., Beaver, M.R., Wennberg, P.O., Cubison, M.J., Jimenez, J.L., Fried, A., Weibring, P., Walega, J.G., Hall, S.R., Weinheimer, A.J., Cohen, R.C., Chen, G., Crawford, J.H., McNaughton, C., Clarke, A.D., Jaeglé, L., Fisher, J.A., Yantosca, R.M., Le Sager, P., Carouge, C., 2010. Chemistry of hydrogen oxide radicals (HO_x) in the Arctic troposphere in spring. Atmos. Chem. Phys. 10, 5823–5838. http://dx.doi.org/10.5194/acp-10-5823-2010.

Marais, E.A., Jacob, D.J., Kurosu, T.P., Chance, K., Murphy, J.G., Reeves, C., Mills, G., Casadio, S., Millet, D.B., Barkley, M.P., Paulot, F., Mao, J., 2012. Isoprene emissions in Africa inferred from OMI observations of formaldehyde columns. Atmos. Chem. Phys. 12, 6219–6235. http://dx.doi.org/10.5194/acp-12-6219-2012.

Marais, E.A., Jacob, D.J., Guenther, A., Chance, K., Kurosu, T.P., Murphy, J.G., Reeves, C.E., Pye, H.O.T., 2014. Improved model of isoprene emissions in Africa using OMI satellite observations of formaldehyde: implications for oxidants and particulate matter. Atmos. Chem. Phys. 14, 7693–7703. http://dx.doi.org/10.5194/acp-14-7693-2014.

Marenco, A., Thouret, V., Nédélec, P., Smit, H., Helten, M., Kley, D., Karcher, F., Simon, P., Law, K., Pyle, J., Poschmann, G., Von Wrede, R., Hume, C., Cook, T., 1998. Measurement of ozone and water vapor by airbus in-service aircraft: the MOZAIC airborne program, an overview. J. Geophys. Res. 103 (D19), 25 631–25 642. http://dx.doi.org/10.1029/98JD00977.

Martin, R.V., Fiore, A.M., Van Donkelaar, A., 2004. Space-based diagnosis of surface ozone sensitivity to anthropogenic emissions. Geophys. Res. Lett. 31, L06120. http://dx.doi.org/10.1029/2004GL019416.

Marufu, L., Dentener, F., Lelieveld, J., Andreae, M.O., Helas, G., 2000. Photochemistry of the African troposphere: influence of biomass-burning emissions. J. Geophys. Res. 105 (D11), 14 513–514 530. http://dx.doi.org/10.1029/1999JD901055.

McMillan, W.W., Evans, K.D., Barnet, C.D., Maddy, E.S., Sasche, G.W., Diskin, G.S., 2011. Validating the AIRS version 5 CO retrieval with DACOM *in situ* measurements during INTEX-A and -B. IEEE Geosci. Remote 49, 2802–2813. http://dx.doi.org/10.1109/TGRS.2011.2106505.

Minga, A., Thouret, V., Saunois, M., Delon, C., Serça, D., Mari, C., Sauvage, B., Mariscal, A., Leriche, M., Cros, B., 2010. What caused extreme ozone concentrations over Cotonou in December 2005? Atmos. Chem. Phys. 10, 895–907. http://dx.doi.org/10.5194/acp-10-895-2010.

Oanh, N.T.K., Phuong, M.T.T., Permadi, D.A., 2012. Analysis of motorcycle fleet in Hanoi for estimation of air pollution emission and climate mitigation co-benefit of technology implementation. Atmos. Environ. 59, 438–448. http://dx.doi.org/10.1016/j.atmosenv.2012.04.057.

Oguejiofor, G.C., 2010. Modeling of linear and exponential growth and decay equations and testing them on pre- and post-war-coal production in Nigeria: an operations research approach. Energ. Source Part B 5, 116–125.

Olivier, J.G.J., Bouwman, A.F., van der Maas, C.W.M., Berdowski, J.J.M., Veldt, C., Bloos, J.P.J., Visschedijk, A.J.H., Zandveld, P.Y.J., Haverlag, J.L., 1996. Description of EDGAR Version 2.0: a Set of Global Emission Inventories of Greenhouse Gases and Ozone-depleting Substances for all Anthropogenic and Most Natural Sources on a Per Country Basis and on 1×1° Grid. Bilthoven, The Netherlands.

Ologunorisa, T.E., 2001. A review of the effects of gas flaring on the Niger Delta environment. Int. J. Sust. Dev. World 8, 249–255.

Osuji, L.C., Avwiri, G.O., 2005. Flared gases and other pollutants associated with air quality in industrial areas of Nigeria: an overview. Chem. Biodivers. 2, 1277–1289. http://dx.doi.org/10.1002/cbdv.200590099.

Osuji, L.C., Ogali, R.E., Usen, M.U., 2009. Effect of petroleum condensate/gasoline mixture on automotive engines. Helv. Chim. Acta 92, 328–334.

PwC (Pricewaterhouse Coopers), http://www.pwc.com/en_GX/gx/world-2050/assets/pwc-world-in-2050-report-january-2013.pdf, World in 2050. The BRICs and Beyond: Prospects, Challenges and Opportunities, (accessed 26.04.13.).

Picket-Heaps, C.A., Jacob, D.J., Wecht, K.J., Kort, E.A., Wofsy, S.C., Diskin, G.S., Worthy, D.E.J., Kaplan, J.O., Bey, I., Drevet, J., 2011. Magnitude and seasonality of wetland methane emissions from the Hudson Bay Lowlands (Canada). Atmos. Chem. Phys. 11, 3773–3779. http://dx.doi.org/10.5194/acp-11-3773-2011.

Redelsperger, J.-L., Thorncroft, C.D., Diedhiou, A., Lebel, T., Parker, D.J., Polcher, J., 2006. African Monsoon Multidisciplinary Analysis (AMMA): an international research project and field campaign. Br. Am. Meteorol. Soc. 87, 1739–1746. http://dx.doi.org/10.1175/BAMS-87-12-1739.

Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.-K., Bloom, S., Chen, J., Collins, D., Conaty, A., Da Silva, A., Gu, W., Joiner, J., Koster, R.D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C.R., Reichle, R., Robertson, F.R., Ruddick, A.G., Sienkiewicz, M., Woollen, J., 2011. MERRA: NASA's modern-era retrospective analysis of research and applications. J. Clim. 24, 3624–3648. http://dx.doi.org/10.1175/JCLI-D-11-00015.1.

Saunders, S.M., Jenkin, M.E., Derwent, R.G., Pilling, M.J., 2003. Protocol for the development of the Master Chemical Mechanism, MCM v3 (Part A): tropospheric degradation of non-aromatic volatile organic compounds. Atmos. Chem. Phys. 3, 161–180. http://dx.doi.org/10.5194/acp-3-161-2003.

Sauvage, B., Thouret, V., Cammas, J.-P., Gheusi, F., Athier, G., Nédélec, P., 2005. Tropospheric ozone over Equatorial Africa: regional aspects from the MOZAIC data. Atmos. Chem. Phys. 5, 311–335. http://dx.doi.org/10.5194/acp-5-311-2005.

Sauvage, B., Gheusi, F., Thouret, V., Cammas, J.-P., Duron, J., Escobar, J., Mari, C., Mascart, P., Pont, V., 2007. Medium-range mid-tropospheric transport of ozone and precursors over Africa: two numerical case studies in dry and wet seasons. Atmos. Chem. Phys. 7, 5357–5370. http://dx.doi.org/10.5194/acp-7-5357-2007.

Sawant, A.A., Shah, S.D., Zhu, X., Miller, J.W., Cocker, D.R., 2007. Real-world emissions of carbonyl compounds from in-use heavy-duty diesel trucks and diesel Back-Up Generators (BUGs). Atmos. Environ. 41, 4535–4547. http://dx.doi.org/10.1016/j.atmosenv.2006.11.028.

Schultz, M.G., Backman, L., Balkanski, Y., Bjoerndalsaeter, S., Brand, R., Burrows, J.P., Dalsoeren, S., de Vasconcelos, M., Grodtmann, B., Hauglustaine, D.A., Heil, A., Hoelzemann, J.J., Isaksen, I.S.A., Kaurola, J., Knorr, W., Ladstaetter-Weißenmayer, A., Mota, B., Oom, D., Pacyna, J., Panasiuk, D., Pereira, J.M.C., Pulles, T., Pyle, J., Rast, S., Richter, A., Savage, N., Schnadt, C., Schulz, M., Spessa, A., Staehelin, J., Sundet, J.K., Szopa, S., Thonicke, K., van het Bolscher, M., van Noije, T., van Velthoven, P., Vik, A.F., Wittrock, F., August 2007. REanalysis of the TROpospheric Chemical Composition over the Past 40 Years (RETRO) — a Long-term Global Modeling Study of Tropospheric Chemistry: Final Report. Jülich/Hamburg, Germany.

Stavrakou, T., Müller, J.-F., De Smedt, I., Van Roozendael, M., van der Werf, G.R., Giglio, L., Guenther, A., 2009. Evaluating the performance of pyrogenic and biogenic emission inventories against one decade of space-based formaldehyde columns. Atmos. Chem. Phys. 9, 1037–1060. http://dx.doi.org/10.5194/acp-9-1037-2009.

Thouret, V., Marenco, A., Logan, J.A., Nédélec, P., Grouhel, C., 1998. Comparisons of ozone measurements from the MOZAIC airborne program and the ozone sounding network at eight locations. J. Geophys. Res. 103 (D19), 25695–25720. http://dx.doi.org/10.1029/98JD02243.

UN (United Nations) Economic and Social Affairs, 2013. World Population Prospects: the 2012 Revision. New York. http://esa.un.org/unpd/wpp/ (accessed 13.07.13.).

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Clim. Change 109, 5–31. http://dx.doi.org/10.1007/s10584-011-0148-z.

Wang, Y., Jacob, D.J., Logan, J.A., 1998. Global simulation of tropospheric O_3-NO_x-hydrocarbon chemistry, 1. Model formulation. J. Geophys. Res. 103 (D9), 10713–10725. http://dx.doi.org/10.1029/98JD00157.

Warner, J.X., Wei, Z., Strow, L.L., Barnet, C.D., Sparling, L.C., Diskin, G., Sachse, G., 2010. Improved agreement of AIRS tropospheric carbon monoxide products with other EOS sensors using optimal estimation retrievals. Atmos. Chem. Phys. 10, 9521–9533. http://dx.doi.org/10.5194/acp-10-9521-2010.

Wecht, K.J., Jacob, D.J., Sulprizio, M.P., Santoni, G.W., Wofsy, S.C., Parker, R., Bösch, H., Worden, J.R., 2014. Spatially resolving methane emissions in California: constraints from the CalNex aircraft campaign and from present (GOSAT, TES) and future (TROPOMI, geostationary) satellite observations. Atmos. Chem. Phys. Discuss. 14, 4119–4198. http://dx.doi.org/10.5194/acpd-14-4119-2014.

van der Werf, G.R., Randerson, J.T., Giglio, L., Collatz, G.J., Kasibhatla, P.S., Arellano Jr., A.F., 2006. Interannual variability in global biomass burning emissions from 1997 to 2004. Atmos. Chem. Phys. 6, 3423–3441. http://dx.doi.org/10.5194/acp-6-3423-2006.

Witte, J.C., Duncan, B.N., Douglass, A.R., Kurosu, T.P., Chance, K., Retscher, C., 2011. The unique OMI $HCHO/NO_2$ feature during the 2008 Beijing Olympics: implications for ozone production sensitivity. Atmos. Environ. 45, 3103–3111. http://dx.doi.org/10.1016/j.atmosenv.2011.03.015.

Xiao, Y., Logan, J.A., Jacob, D.J., Hudman, R.C., Yantosca, R., Blake, D.R., 2008. Global budget of ethane and regional constraints on U.S. sources. J. Geophys. Res. 113, D21306. http://dx.doi.org/10.1029/2007JD009415.

Yevich, R., Logan, J.A., 2003. An assessment of biofuel use and burning of agricultural waste in the developing world. Glob. Biogeochem. Cycles 17 (4), 1095. http://dx.doi.org/10.1029/2002GB001952.

Yienger, J.J., Levy II, H., 1995. Empirical model of global soil-biogenic NO_x emissions. J. Geophys. Res. 100 (D6), 11447–11464. http://dx.doi.org/10.1029/95JD00370.

Yurganov, L.N., McMillan, W.W., Dzhola, A.V., Grechko, E.I., Jones, N.B., van der Werf, R., 2008. Global AIRS and MOPITT CO measurements: validation, comparison, and links to biomass burning variations and carbon cycle. J. Geophys. Res. 113, D09301. http://dx.doi.org/10.1029/2007JD009229.

Yurganov, L., McMillan, W., Grechko, E., Dzhola, A., 2010. Analysis of global and regional CO burdens measured from space between 2000 and 2009 and validated by ground-based solar tracking spectrometers. Atmos. Chem. Phys. 10, 3479–3494. http://dx.doi.org/10.5194/acp-10-3479-2010.

Zhang, Q., Streets, D.G., Carmichael, G.R., He, K.B., Huo, H., Kannari, A., Klimont, Z., Park, I.S., Reddy, S., Fu, J.S., Chen, D., Duan, L., Lei, Y., Wang, L.T., Yao, Z.L., 2009. Asian emissions in 2006 for the NASA INTEX-B mission. Atmos. Chem. Phys. 9, 5131–5153. http://dx.doi.org/10.5194/acp-9-5131-2009.

Zhang, L., Jacob, D.J., Liu, X., Logan, J.A., Chance, K., Eldering, A., Bojkov, B.R., 2010. Intercomparison methods for satellite measurements of atmospheric composition: application to tropospheric ozone from TES and OMI. Atmos. Chem. Phys. 10, 4725–4739. http://dx.doi.org/10.5194/acp-10-4725-2010.