

This discussion paper is/has been under review for the journal *Atmospheric Chemistry and Physics (ACP)*. Please refer to the corresponding final paper in *ACP* if available.

**Direct estimates of
emissions from
Lagos**

J. R. Hopkins et al.

Direct estimates of emissions from the megacity of Lagos

J. R. Hopkins¹, M. J. Evans², J. D. Lee¹, A. C. Lewis¹, J. H. Marsham²,
J. B. McQuaid², D. J. Parker², D. J. Stewart³, C. E. Reeves³, and R. M. Purvis^{1,4}

¹National Centre for Atmospheric Science, University of York, York, YO10 5DD, UK

²School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

³School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK

⁴Facility for Airborne Atmospheric Measurement, Cranfield, MK43 0AL, UK

Received: 18 January 2009 – Accepted: 3 March 2009 – Published: 1 April 2009

Correspondence to: M. J. Evans (mat@env.leeds.ac.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

We report here top-down emissions estimate for an African megacity. A boundary-layer circumnavigation of Lagos, Nigeria was completed using the FAAM BAe146 aircraft as part of the AMMA project. These observations together with an inferred boundary-layer height allow the flux of pollutants to be calculated. Extrapolation gives annual emissions for CO, NO_x and VOCs of 0.72 Tg C yr⁻¹, 0.02 Tg N yr⁻¹ and 0.28 Tg C yr⁻¹ respectively, consistent with bottom-up estimates for other developing megacities. These emissions are attributed to the evaporation of fuels, mobile combustion and natural gas emissions.

1 Introduction

The world's "megacities" (populations over 10 million) emit a large fraction of global pollutants (Lawrence et al., 2007). The continued growth of urban populations (2.7% yr⁻¹ over the last fifty years, Gurjar and Lelieveld, 2005) has led to an increase in their importance as a pollutant source. Previous projects have investigated Asian (e.g. Gutikunda et al., 2005) and Central American (e.g. Jobson et al., 2004) megacities, but there is little information on African megacities. Here we use observations within the boundary layer of Lagos, Nigeria taken during 2006 as part of the African Monsoon Multidisciplinary Analysis (AMMA, Redelsperger et al., 2006) to infer emissions from the city.

Lagos is Nigeria's commercial capital with ~75% of the country's industries. It is the second most populated and fastest growing city in Africa. Its population in 2005 was 10.8 million (to rise to 16 million by 2015) making it the world's 17th most populated city (UN, 2005). As with the majority of cities, road transport is thought to be the most significant source of anthropogenic emissions (Baumbach et al., 1995). Often dated technologies and poor emission control strategies lead to substantial uncertainties in emission estimates calculated from vehicle number density statistics. The unre-

Direct estimates of emissions from Lagos

J. R. Hopkins et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



liable electrical supply in Lagos has led to an increased reliance on small-scale diesel powered generators and these potentially present a significant source of emissions in Lagos. The uncontrolled open incineration of waste adds a further very poorly constrained emission source within the city. One of the major thermal power stations in Africa and substantial petrochemical activity is within the city limits.

The African Monsoon Multi-disciplinary Analysis (AMMA) was a 5 year programme to understand the impact of the West African monsoon on both the atmosphere and society of Western Africa (Redelsperger et al., 2006). A major intensive field program occurred in the summer of 2006 with the UK FAAM BAe146 research aircraft being based in the Nigerien capital Niamey.

On the 8 August the FAAM BAe146 flew to the city of Cotonou in Benin. From there the aircraft headed north-eastward to arrive over the centre of Lagos. It then descended southward to make a missed approach at Lagos International Airport (minimum altitude: 20 m) and arrived south of the city at ~350 m. The aircraft then made a clockwise circumnavigation of the city at this altitude before climbing over the city and returning to Niamey (see Fig. 1a).

2 Observations

Measurements of carbon monoxide (CO) were performed using a fast response fluorescence instrument, Aero-Laser 5002 fast CO monitor Gerbig et al. (1999). Oxides of nitrogen (NO_x) were measured by two instruments. The first instrument (TECO) measured using a model 42C trace level NO_x , chemiluminescence analyser (Thermo Environmental Instruments, Hemel Hempstead, UK). The instrument sequentially measured nitric oxide (NO) and total NO_x ($\text{NO} + \text{NO}_2$) using a molybdenum catalyst to convert NO_2 to NO. Oxides of nitrogen were also measured by the University of East Anglia NO_{xy} . This measures NO by its chemiluminescence reaction with O_3 and NO_2 by photolytic conversion of NO_2 to NO with subsequent measurement of NO. The instrument is described in detail in Brough et al. (2003). Volatile Organic Compounds

Direct estimates of emissions from Lagos

J. R. Hopkins et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



(VOCs) were measured using silica coated stainless steel canisters (Thames Restek, UK). Samples were collected at approximately 2 min time intervals around the city. Air samples were analysed using a dual channel gas chromatograph with flame ionisation detectors (Hopkins et al., 2003).

5 Figure 1b to f shows the concentration of CO, benzene, acetylene, NO_x (TECO) and O₃ around Lagos. The boundary-layer wind originated from the south west (see Fig. 2.) The highest concentrations can be observed to the north east of the city. Typical in-plume concentrations of CO, NO_x, benzene and acetylene were ~400 ppbv, 6 ppbv, 1 ppbv and 1 ppbv.

10 3 Calculation of emission fluxes from Lagos

Given the approximately closed-loop flight track of the aircraft, a uniform boundary layer and no vertical exchange of compound, the horizontal flux of compound out of the Lagos area can be calculated by adding up the components of the observed pollutant mass fluxes perpendicular to the path of the aircraft i.e. by calculating the flux out of the closed loop at each stage around that loop.

$$F = \int C(x) \left(v(x) \cdot \hat{V}(x) \right) Z(x) dx$$

Where F is the flux in kg s^{-1} , $C(x)$ is the concentration of the compound in kg m^{-3} at position x (m) along the loop, v is the horizontal wind vector (m s^{-1}) at position x along the loop, V is the aircraft horizontal flight vector (m s^{-1}) at position x along the loop, Z is the boundary-layer height (m) at position x along the loop, $\hat{\cdot}$ represents the unit normal operator, \cdot is the dot product operator.

As $\hat{V}(x)$ represents a unit vector in the horizontal perpendicular to the path of the aircraft (i.e. a vector pointing out of the loop around Lagos), $v(x) \cdot \hat{V}(x)$ represents the magnitude of the component of the horizontal wind out of that loop. By multiplying this flow out of the loop by the concentration and the boundary-layer height, and integrating

Direct estimates of emissions from Lagos

J. R. Hopkins et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



over the closed loop, the total flux out of the loop is derived. Other than the boundary-layer height all these parameters are directly observed.

Figure 3 shows the measured profile of potential temperature (θ) during the descent, circuit and ascent. The profile consists of a marine boundary-layer up to 400 m and a continental residual layer ending at 1900 m. θ was found to increase away from the coast. The boundary layer height can therefore be expected to have increased away from the coast due to the surface heat fluxes and the resultant entrainment of residual-layer air. The naively estimated boundary-layer height at x ($z(x)$ in m) depends only the height of the boundary-layer top derived from the profiles (400 m, respectively, Fig. 3), the potential temperature observed on the constant altitude loop around the city ($\theta_{350\text{m}}(x)$) and the increase in θ with height in the residual layer (214 m K^{-1} , the dotted line in Fig. 3). This gives,

$$z(x) = 400 + (\theta_{350\text{m}}(x) - 298) \times 214$$

However, Carson (1973) shows that the warming of the boundary-layer by entrainment of air from the residual layer above will increase the boundary-layer height from $z(x)$ to $Z(x)$,

$$Z(x) = \frac{1 + 2A}{1 + A} z(x)$$

where A is the entrainment constant, which has a value of roughly 0.3.

Figure 4 shows the calculated boundary-layer height around the Lagos circuit. The boundary-layer height has a minimum of 309 m over the ocean and a maximum of 1100 m over land furthest from the coast. Over the ocean the aircraft was therefore slightly above (350 m) the calculated boundary layer. However, due to the lack of sources in this region this does not introduce great uncertainty into the calculation. The variation in boundary-layer height over land leads to significant entrainment of air from above. We address this by considering the flux of air into a column around the city with a uniform height of the maximum calculated boundary-layer height (Z_{max}). We anticipate much lower vertical fluxes out of the top of this volume compared with

Direct estimates of emissions from Lagos

J. R. Hopkins et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Direct estimates of
emissions from
Lagos**

J. R. Hopkins et al.

the fluxes from the top of the volume described by the spatially varying boundary layer height. The horizontal fluxes into this column around the loop are calculated as being a flow within the boundary layer with the observed concentration of compound and a flow from above the boundary-layer with a “background” concentration (C_{back}) calculated as the value of the 10th percentile of the concentrations observed around the loop. We assume that there is no difference in the wind vectors in these components. Thus the flux is now calculated to be,

$$F = \int C(x) \left(v(x) \cdot \hat{V}(x) \right) Z(x) dx + \int C_{\text{background}} \left(v(x) \cdot \hat{V}(x) \right) (Z_{\text{max}} - Z(x)) dx$$

If the emitted species has no loss within the loop, the flux of species from the loop is equivalent to the emission from the city. For some species this is a good assumption. CO has a lifetime of the order of a month. Thus for the ~ 1 h transit across the city, it can be considered an inert tracer. VOC lifetimes range from minutes to months. A large fraction is emitted as NMHC which degrade to produce oxygenated species. Thus by including the oxygenated species in our calculation we mitigate the impact of VOC loss. NO_x has a short lifetime in the atmosphere (hours) thus NO_x exported out of the loop does not reflect all the NO_x emitted. Observations of speciated NO_y from other cities suggest that the non NO_x components of the NO_y flux are likely to be small ($\sim 20\%$) on the timescales important here (e.g. Neuman et al., 2006). Thus although use of the NO_x observations provides an underestimate of the emissions, it does not add unacceptable uncertainty.

No correction for diurnal or hebdomadal variability is made as these parameters are not known for a city of this type. Studies in countries such as the UK, show that the ratio between maximum and minimum hourly emission are of the order 5, 3.5 and 4 for CO, VOCs and NO_x respectively, variations between weekday and weekend are of the order of 30%, and annual variation of the order of 30% (Jenkin et al., 2000). Given the observations were made in the mid-afternoon (03:00 p.m. local time) on a Tuesday in the tropics (where annual temperature variations are smaller) we probably overestimate the actual annual emission by a factor of around 2–3 depending upon the

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

species. Given no comparable information for Lagos, we do not adjust our value for these variations.

Considering the various approximations described above we anticipate our estimates for annual emissions to be biased in general high and with uncertainties of $^{+100}_{-66}\%$ (i.e. they could be twice or a third of the values quoted here).

4 Results

Table 1 presents the calculated values of annual emissions together with literature values for the emissions from Lagos (Oketola et al., 2007), two developing Asian mega-cities (Guttikunda et al., 2005) and two developed mega-cities (Guttikunda et al., 2005; Mattai et al., 2003).

Our CO estimate (1.44 Tg yr^{-1}) is higher than that calculated by Oketola et al. (2007) (0.81 Tg yr^{-1}) and the summary of other estimations given for Lagos by Butler et al. (2008) (0.771 to 1.006 Tg yr^{-1}). Given the uncertainties in our estimates and in the bottom up estimates (quoted as being for CO $\sim 68\%$ for 95% confidence by Streets et al. (2006) for Asia) the differences are not large. A major source of the low bias in the bottom up estimates may be the population of Lagos. The local government contests the results of the national census claiming a significant undercount (17 rather than 9 million) of its population (http://www.lagosstate.gov.ng/c/portal/layout?p_l.id=PUB.1095.7). This would be consistent with our higher top-down estimate.

Our VOC estimate (0.36 Tg yr^{-1}) is lower than that calculated by Oketola et al. (2007) but appears more consistent than the estimates for megacities especially on a per-person basis. Although these bottom-up assessments do not quote suitable uncertainties for VOC emissions, those calculated from Asian cities are $\sim 130\%$ (Streets et al., 2003). Although significant differences exist between the bottom-up and top-down approaches they are within the range of uncertainties especially given the uncertainty in the population. The higher per person values compared to other mega-cities may reflect the role of petrochemicals for the economy of Lagos.

Direct estimates of emissions from Lagos

J. R. Hopkins et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Direct estimates of
emissions from
Lagos**J. R. Hopkins et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The NO_x emissions (0.03 Tg NO₂ yr⁻¹) derived are more than an order of magnitude smaller than those quoted by Oketola et al. (2007) (0.97 Tg yr⁻¹). Oketola et al. (2007) suggest a *per capita* NO_x emission an order of magnitude higher than a city such as London. This appears inconsistent with our understanding of urban NO_x sources. Our emissions appear more consistent with the other studies, especially when considered *per capita*.

In general our top-down emissions are consistent with the state of understanding of emissions as represented by the bottom up estimates. Significant differences exist, however, given the uncertainties in approaches they are not in tension (other than for the NO_x estimate of Oketola et al., 2007).

5 Sources of emission within Lagos

The range of sources within the city is reflected in the complex relationships between species. For example the maxima in CO, benzene, acetylene and NO_x all lie in different locations around the loop (see Fig. 1b–e). The VOC composition reveals a dominant signature from mono-aromatic compounds and linear and branched chain alkanes; such species are associated primarily with evaporative sources from gasoline and solvent use. The covariance in 1,3 butadiene, CO and NO_x, is strongly indicative of a major vehicle combustion emission within the city. Finally substantial downwind enhancement in ethane suggests fugitive natural gas leakage. In the absence of a domestic distribution network within Lagos, this may be associated with the 1320 MW Egbin natural gas fired thermal power station based within the city.

6 Conclusions

The combination of a coastal location and an on-shore wind makes Lagos an ideal candidate city for emissions estimates via “closed-loop” observations. Annual emis-

sions fluxes for NO_x were found to be comparable to those calculated for selected other megacities, whereas VOC and CO were amongst the highest. Given these observations the predicted future population growth within Lagos will no doubt serve to position Lagos as one of the most polluting cities in the world unless adequate policy measures are implemented.

Acknowledgements. This work was specifically supported by the United Kingdom Natural Environment Research Council via grant NE/B505570/1 and the European Union via Framework Six grant 004089. Based on a French initiative, AMMA was built by an international scientific group and is funded by a large number of agencies, especially from France, the U.K., the U.S.A. and Africa. It has been the beneficiary of a major financial contribution from the European Community's Sixth Framework Research programme. Detailed information on scientific coordination and funding is available on the AMMA international web site <http://www.amma-international.org>.

References

- Baumbach, G., Vogt, U., Hein, K. R. G., Oluwole, A. F., Ogunsola, O. J., Olaniyi, H. B., and Akeredolu, F. A.: Air pollution in a large tropical city with a high traffic density – results of measurements in Lagos, Nigeria, *Sci. Total Environ.*, 169(1–3), 25–31, 1995.
- Brough, N., Reeves, C. E., Penkett, S. A., Stewart, D. J., Dewey, K., Kent, J., Barjat, H., Monks, P. S., Ziereis, H., Stock, P., Huntrieser, H., and Schlager, H.: Intercomparison of aircraft instruments on board the C-130 and Falcon 20 over southern Germany during EXPORT 2000, *Atmos. Chem. Phys.*, 3, 2127–2138, 2003, <http://www.atmos-chem-phys.net/3/2127/2003/>.
- Butler, T. M., Lawrence, M. G., Gurjar, B. R., van Aardenne, J., Schultz, M., and Leliveld, J.: The representation of emission from megacities in global emissions inventories, *Atmos. Environ.*, 42, 703–719, 2008.
- Carson, D.J., (1973), Development of a dry inversion-capped convectively unstable boundary-layer, *Q. J. R. Met. Soc.*, 99, 421, 450–467
- Gerbig, C., Schmitgen, S., Kley, D., Volz-Thomas, A., Dewey, K., and Haaks, D.: An im-

Direct estimates of emissions from Lagos

J. R. Hopkins et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Direct estimates of
emissions from
Lagos**J. R. Hopkins et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

proved fast-response vacuum-UV resonance fluorescence CO instrument, *J. Geophys. Res.*, 104(D1), 1699–1704, 1999.

Gurjar, B. R. and Lelieveld, J.: New Directions: Megacities and global change, *Atmos. Environ.*, 39(2), 391–393, 2005.

5 Guttikunda, S. K., Tang, Y. H., Carmichael, G. R., Kurata, G., Pan, L., Streets, D. G., Woo, J. H., Thongboonchoo, N., and Fried, A.: Impacts of Asian megacity emissions on regional air quality during spring 2001, *J. Geophys. Res.*, 110, D20301, doi:10.1029/2004JD004921, 2005.

Hopkins, J. R., Lewis, A. C., and Read, K. A.: A two-column method for long-term monitoring of non-methane hydrocarbons (NMHCs) and oxygenated volatile organic compounds (o-VOCs), *J. Environ. Monitor.*, 5(1), 8–13, 2003.

Jenkin, M. E, Murrells, T. P., and Passant, N. R.: The Temporal Dependence of Ozone Precursor Emissions: Estimation and Application, Report to the UK Dept. Energy Trade and the Regions, Air and Environmental Quality Division, AEAT/R/ENV/0355, online available at: <http://www.naei.org.uk/reports.php>, last access: February 2009, 2000.

15 Jobson, B. T., Berkowitz, C. M., Kuster, W. C., Goldan, P. D., Williams, E. J., Fesenfeld, F. C., Apel, E. C., Karl, T., Lonneman, W. A., and Riemer, D.: Hydrocarbon source signatures in Houston, Texas: Influence of the petrochemical industry, *J. Geophys. Res.*, 109(D24), 2004.

Lawrence, M. G., Butler, T. M., Steinkamp, J., Gurjar, B. R., and Lelieveld, J.: Regional pollution potentials of megacities and other major population centers, *Atmos. Chem. Phys.*, 7, 3969–3987, 2007, <http://www.atmos-chem-phys.net/7/3969/2007/>.

Mattai, J. and Hutchinson, D.: London Atmospheric Emissions Inventory 2003, Second Report, Greater London Authority, City Hall, London, UK, SE1 2AA, 2006.

25 Neuman, J. A., Parrish, D. D., Trainer, M. H., et al.: Reactive nitrogen transport and photochemistry in urban plumes over the North Atlantic Ocean, *J. Geophys. Res.*, 111, D23S54, doi:10.1029/2005JD007010, 2006.

Oketola, A. A and Osibanjo, O.: Estimating sectoral pollution load in Lagos by Industrial Pollution Projection System (IPPS), *Sci. Total Environ.*, 377, 125–141, 2007.

30 Otter, L., Guenther, A., Wiedinmyer, C., Fleming, G., Harley, P., and Greenberg, J.: Spatial and temporal variations in biogenic volatile organic compound emissions for Africa south of the equator, *J. Geophys. Res.*, 108(D13), 8505, doi:10.1029/2002JD002609, 2003.

Redelsperger, J.-L., Thorncroft, C. D., Diedhiou, A., Lebel, T., Parker, D. J., and Polcher, J.:

African Monsoon Multidisciplinary Analysis: An International Research Project and Field Campaign, B. Am. Meteorol. Soc., 87, 1739–1746, 2006.

Streets, D. G., Bond, T. C., Carmichael, G. R., et al.: An inventory of gaseous and primary aerosol emissions in Asia in the year 2000, J. Geophys. Res., 108(D21), 8809, doi:10.1029/2002JD003093, 2003.

Streets, D. G., Zhang, Q., Wang, L., He, K., Hao, J., Wu, Y., Tang, Y., and Carmichael, G. R.: Revisiting China's CO emissions after the Transport and Chemical Evolution over the Pacific (TRACE-P) mission: Synthesis of inventories, atmospheric modeling, and observations, J. Geophys. Res., 111, D14306, doi:10.1029/2006JD007118, 2006.

UN: World Population Prospects: The 2005 Revision, vol. I, Comprehensive Tables, (United Nations publication, Sales No. E.05.XIII.5), ESA/P/WP/2005, online available at: <http://www.un.org/esa/population/publications/WUP2005/2005wup.htm>, 2005.

ACPD

9, 8667–8682, 2009

Direct estimates of emissions from Lagos

J. R. Hopkins et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 1. Scaled up annualised emissions fluxes from the city of Lagos in Tg yr^{-1} of compound (other than for NO_x species which is in Tg N yr^{-1}) and comparison of emissions observed in this study with those calculated for other megacities along with a calculation of CO , NO_x and VOC emissions per capita.

	Lagos		Lagos Tg yr^{-1}	Beijing Tg yr^{-1}	Calcutta Tg yr^{-1}	Tokyo Tg yr^{-1}	London Tg yr^{-1}
	Tg yr^{-1}	Tg C/N yr^{-1}					
CO	1.4400	0.7200	0.8100	1.2300	0.6310	0.4610	0.1300
Alkanes	0.1356	0.1141					
Alkenes	0.0263	0.0227					
Alkynes	0.0159	0.0147					
Aromatics	0.0723	0.0660					
Oxygenates	0.1196	0.0660					
Total VOC	0.3696	0.2835	0.7260	0.2250	0.2330	0.1970	0.0782
NO_x^d	0.0346	0.0161	0.9700	0.0359	0.0187	0.0536	0.0800
City Population (2005) ^e	10 886 000	10 886 000	10 717 000	14 227 000	35 197 000	8 505 000	
Emissions per person							
NO_x kg person ⁻¹ yr ⁻¹	3.2	89	3.3	1.3	1.5	9.4	
CO kg person ⁻¹ yr ⁻¹		132	74	115	44	13	15.3
VOC kg person ⁻¹ yr ⁻¹	34	67	21	16	5.6	9.1	
Reference	This Study		a	b	b	b	c

^a Oketola et al. (2007)

^b Guttikunda et al. (2005)

^c Mattai et al. (2003)

^d This is the mean of the TECO NO_x and UEA NO_{xy} instruments

^e UN (2005)

Direct estimates of emissions from Lagos

J. R. Hopkins et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Direct estimates of
emissions from
Lagos

J. R. Hopkins et al.

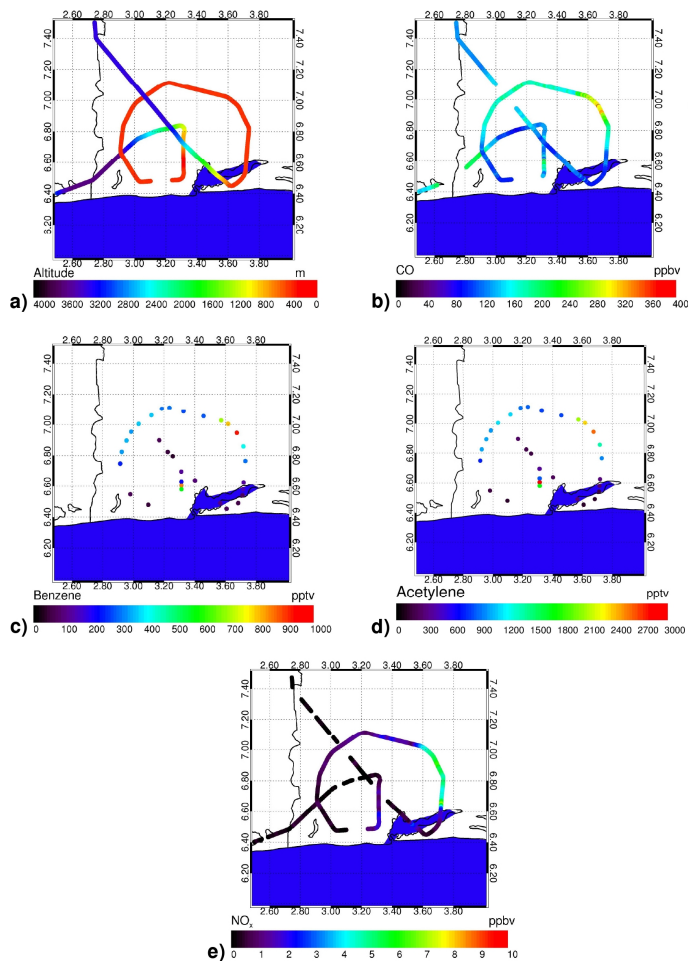


Fig. 1. Observations of altitude (a), CO (b), Benzene (c), Acetylene (d) and TECO NO_x (e) made during the flight around Lagos.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Direct estimates of
emissions from
Lagos**

J. R. Hopkins et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

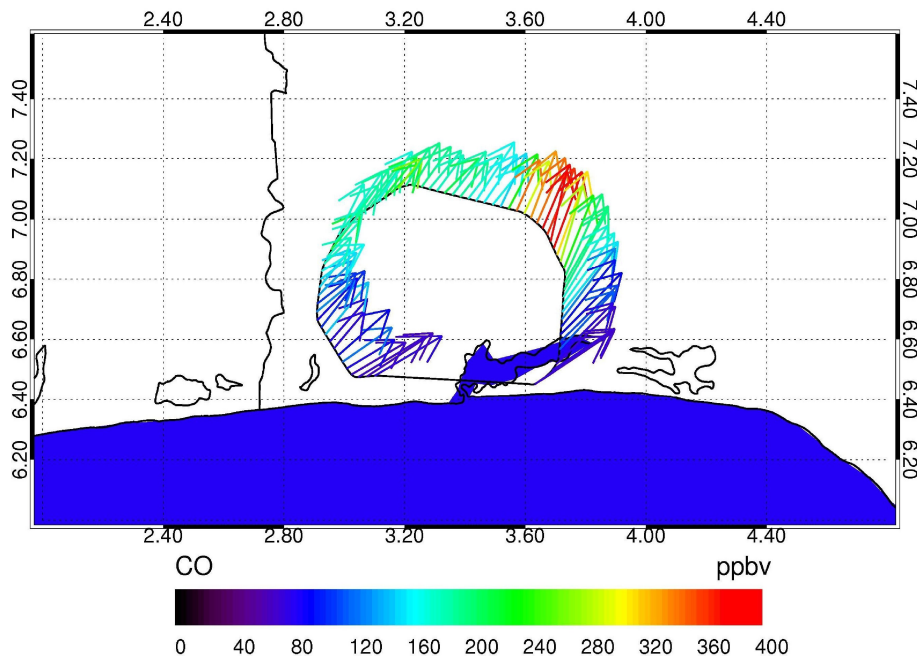
Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Fig. 2.** Wind direction observations from the aircraft coloured by CO concentration.

Direct estimates of
emissions from
Lagos

J. R. Hopkins et al.

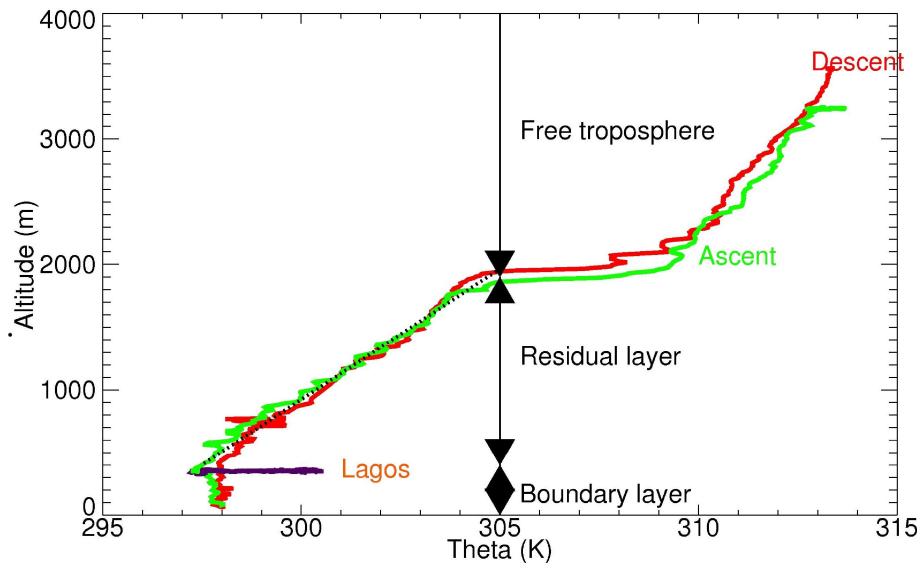


Fig. 3. Profile of θ during descent into (red), circuit of (blue) and ascent out of (green) Lagos. The marine boundary-layer with uniform potential temperature, residual layer and free troposphere are evident. The gradient of θ within the residual layer is the dashed black line.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Direct estimates of
emissions from
Lagos**

J. R. Hopkins et al.

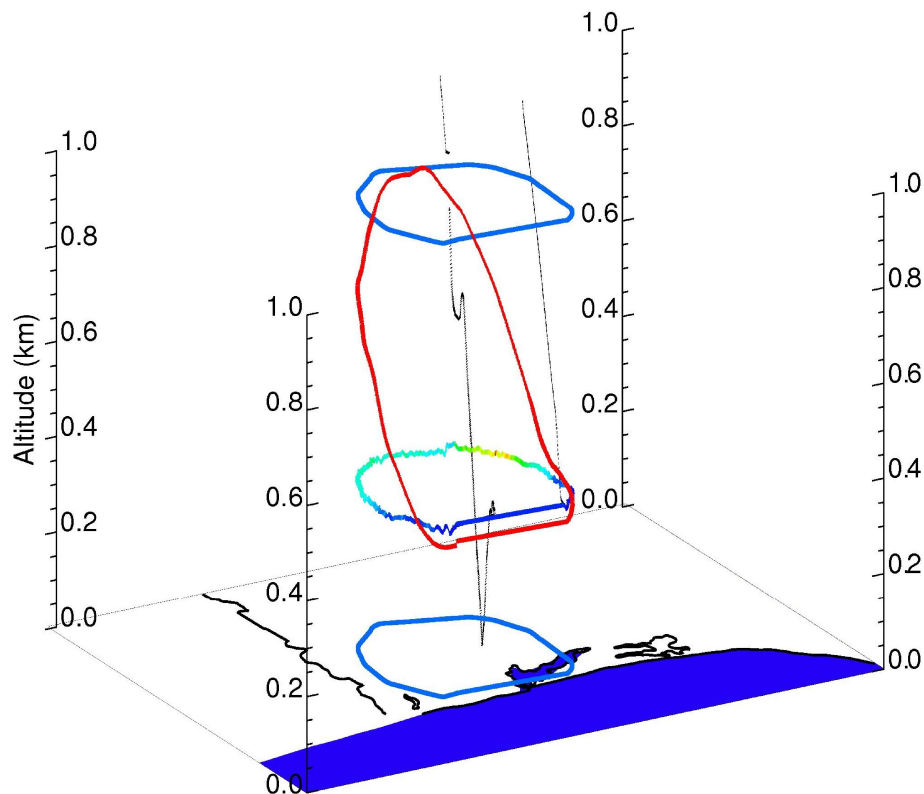


Fig. 4. 3-Dimensional representation of circumnavigation around Lagos. Black line is the aircraft flight track, around the city it is coloured by the CO concentrations; red line is the calculated boundary layer height; the two blue lines are the cylinder considered for the flux calculation.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)