Lusaka, Zambia, during SAFARI-2000: Convergence of local and imported ozone pollution

Anne M. Thompson,1 Jacquelyn C. Witte,2 M. Tal Freiman,3 N. Agnes Phahlane,4 and Gert J. R. Coetzee4

Received 29 April 2002; revised 19 July 2002; accepted 22 July 2002; published 25 October 2002.

[1] In August and September, throughout south central Africa, seasonal clearing of dry vegetation and other fire-related activities lead to intense smoke haze and ozone formation. The first ozone soundings in the heart of the southern African burning region were taken at Lusaka, Zambia (15.5S, 28E) in early September 2000. Maximum surface ozone was over 90 ppbv and column tropospheric ozone exceeded 50 DU. These values are higher than concurrent measurements over Nairobi (1S, 38E) and Irene (25S, 28E, near Pretoria). At least 30% of Lusaka surface ozone appears to be from local sources. A layer at 800–500 hPa has ozone >120 ppbv and originates from transboundary recirculation. Starting out over Zambia, Angola, and Namibia, ozone-rich air travels east to the Indian Ocean, before heading back toward Mozambique, Zimbabwe and Zambia. Thus, Lusaka collects local and imported pollution, consistent with its location within the southern African gyre. INDEX TERMS: 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 9305 Information Related to Geographic Region: Africa. Citation: Thompson, A. M., J. C. Witte, M. T. Freiman, N. A. Phahlane, and G. J. R. Coetzee, Lusaka, Zambia, during SAFARI-2000: Convergence of local and imported ozone pollution, Geophys. Res. Lett., 29(20), 1976, doi:10.1029/2002GL015399, 2002.

1. Introduction: Southern African Ozone and Circulation

[1] Savanna burning is a well-known source of pollutants that lead to ozone formation. During SAFARI-92 (Southern African Fires Atmospheric Research Initiative, September 1992), ozone budgets were determined from ozone soundings and aircraft measurements [Thompson et al., 1996], usually taken downwind from major sources. During SAFARI-2000 [Swap et al., 2002], the first ozonesonde launches were made in the heart of south central African burning, at Lusaka, Zambia (15.5S, 28E). This paper reports on those soundings and compares Lusaka ozone with data from African stations in the SHADOZ (Southern Hemisphere Additional Ozonesondes) network: Irene (25S, 28E) and Nairobi, Kenya (1S, 38E).

[3] Analysis of transport over southern Africa during SAFARI-92 revealed the persistence of anticyclonic flow and “absolutely stable layers,” a term that refers to extreme atmospheric stability including elevated inversions [Cosijn and Tyson, 1996; Garstang and Tyson, 1997]. The lifetime of ozone in these layers may exceed several weeks [Thompson et al., 1996] with ozone being conserved during transport. Indeed, ozone laminae traceable to Africa are well-known over the Pacific [Newell et al., 1999; Oltmans et al., 2001]. We found that the highest ozone concentrations at Lusaka resided in a stable layer at 2–5 km (800–500 hPa) that arrived via easterly winds from the Indian Ocean, Zimbabwe and Mozambique. Wrapped around an anticyclonic high-pressure system, the ozone ultimately originated from fire-rich rural areas of Botswana, South Africa, Namibia, Angola, and western Zambia, making Lusaka a collection point for regional pollution.

2. In-Situ and Remotely Sensed Measurements. Total and Tropospheric Ozone Columns

[4] Ozone and temperature profiles (recorded at 1-s frequency) were determined with an electrochemical concentration cell ozonesonde (ENSCI 2Z) in combination with an RS-80/15 Vaisala radiosonde and a HumiCap humidity sensor, as described in Thompson et al. [2000]. Launches were made at the Zambian Meteorological Department (ZMD) in Lusaka (1.3 km elevation) between 6 and November 2000. Two launches (0800 and 1200 UTC) were made on 7, 9 and 10 September. Soundings were recorded at 8–10 hPa balloon burst; the first 7 September sounding lost sonde signal at 40 hPa when laboratory power failed. AOT (aerosol optical thickness) and total overhead ozone were measured at 1–2 hour intervals from 1–11 September 2000 with a multichannel sun photometer (Solar Light Co.). The 380-nm AOT data are used in this paper. TOMS (Total Ozone Mapping Spectrometer) total ozone data are taken from satellite overpasses closest to Lusaka (shortly before local noon).

[5] Total and tropospheric ozone column amounts (in Dobson Units; 1 DU = 2.69 × 1016 molec/cm2), integrated from the soundings, are shown as a time-series in Figure 1. AOT from the sun photometer is also displayed. In five of six days, agreement of TOMS total ozone with that from the sondes ranges from +7 DU (sonde total ozone greater than TOMS) to −3 DU (TOMS greater than sonde total). This is very good, comparable to the mean agreement (1–2%) recorded at Irene and Nairobi [Thompson et al., 2002a]. All three sites have >1 km elevation, which minimizes one source of TOMS error, a diminished detection efficiency for lower tropospheric ozone [Hudson et al., 1995]. The sun
photometer ozone readings (5–7 per day, not shown) at Lusaka were also in good agreement with sonde and satellite total ozone, bracketing TOMS and sonde total ozone on most days.

The Lusaka soundings show very high tropospheric ozone (54 DU, integrated tropospheric column) during 6–8 September (Figure 1). This is greater than typical September tropospheric ozone at Nairobi and Irene (30 and 35 DU, respectively), although both these stations were more polluted than usual in September 2000 (Section 3). Figure 1 also shows the effect of a localized disturbance that occurred in Lusaka early on 9 September. Between the 8 September (1200 UTC) and 9 September (00 UTC) soundings, the surface wind speed doubled (12 to 24 m/s), dropping to 10 m/s 12 hours later. AOT between 8 and 10 September dropped a factor of two. Between two soundings taken four hours apart on 9 September, tropospheric ozone column declined from 49 DU to 39 DU.

3. Tropospheric Ozone Profiles Over Lusaka. Origins of Surface Ozone

Figure 2 shows high ozone mixing ratios throughout the troposphere over Lusaka on 6 September. Near-surface ozone averaged 90 ppbv and within a double temperature inversion layer (3–5 km), ozone was >120 ppbv. Ozone maxima in the boundary layer and in the inversion layer immediately above coincide with layers of elevated relative humidity. This pattern was typical during the sampling period. Four additional ozone and relative humidity profiles appear in Figure 3.

4. Absolutely Stable Ozone Layers Over Lusaka

Using radiosonde data taken over 4 South African cities and Windhoek, Namibia, Freiman et al. [2002]
showed that absolutely stable layers, similar to those observed during SAFARI-92, persisted on 80% or more of the days in August and September 2000. Absolutely stable layers (gold shading in Figures 3 and 4) appear over Lusaka, with all nine ozone profiles showing at least one layer with ozone >70 ppbv. Following the disturbance between the 8 and 9 September soundings the stable layers were diminished in ozone and drier, but remained intact (10 September profile in Figure 3).

Where does the ozone in the absolutely stable layer over Lusaka come from? The cluster of trajectories shown arriving at Lusaka at 900 hPa on 7 September (orange in Figure 4) shows a typical pattern for the Lusaka sampling area, initialized at 500, 700, and 900 hPa. Clusters of back trajectories were run for five days using a kinematic version of the Goddard trajectory model [Schoeberl and Newman, 1995] to capture uncertainties associated with analyzed winds (NCEP 2.5 × 2.5 deg). Time of trajectory initiation is 12UTC on 7 Sept 2000. These transport patterns are confirmed by trajectories run with winds [Freiman and Riphagen, 2002] from the higher resolution Eta model (0.5 deg, three-hourly data; Black, 1994).

with all nine ozone profiles showing at least one layer with ozone >70 ppbv. Following the disturbance between the 8 and 9 September soundings the stable layers were diminished in ozone and drier, but remained intact (10 September profile in Figure 3).

[11] Where does the ozone in the absolutely stable layer over Lusaka come from? The cluster of trajectories shown arriving at Lusaka at 900 hPa on 7 September (orange in Figure 4) shows a typical pattern for the Lusaka sampling area, initialized at 500, 700, and 900 hPa. Clusters of back trajectories were run for five days using a kinematic version of the Goddard trajectory model [Schoeberl and Newman, 1995] to capture uncertainties associated with analyzed winds (NCEP 2.5 × 2.5 deg). Time of trajectory initiation is 12UTC on 7 Sept 2000. These transport patterns are confirmed by trajectories run with winds [Freiman and Riphagen, 2002] from the higher resolution Eta model (0.5 deg, three-hourly data; Black, 1994).

5-day Back-trajectories arriving over Lusaka, Zambia
Start Date: 7 September, 2000

Figure 4. AVHRR fire counts (red dots) for September 2000, courtesy of (http://shark1.esrinesa.it/ionia/FIRE). Five-day back trajectories from the Lusaka area, initialized at 500, 700, and 900 hPa. Clusters of back trajectories were run for five days using a kinematic version of the Goddard trajectory model [Schoeberl and Newman, 1995] to capture uncertainties associated with analyzed winds (NCEP 2.5 × 2.5 deg). Time of trajectory initiation is 12UTC on 7 Sept 2000. These transport patterns are confirmed by trajectories run with winds [Freiman and Riphagen, 2002] from the higher resolution Eta model (0.5 deg, three-hourly data; Black, 1994).

Figure 3. Ozone and relative humidity profiles over Lusaka 7–10 September 2000. Shading shows absolutely stable layer as classified by Freiman et al. [2002]. On 9 Sept. a disturbance diluted surface ozone and some ozone aloft. By 11 September stagnant conditions returned and surface ozone built up again.

Figure 5. Photo of organized burning in downtown Lusaka, ~200 m from ZMD ozonesonde launch site. Crews set fires to clear debris on both sides of roadway. Each day the crews burn several hundred meters along the road.
(7 September ozone in Figure 3). At 700 hPa (blue in Figure 4) trajectories reveal anticyclonic flow about a subsiding gyre [Jury and Freiman, 2002]. Air parcels at this level, ~2 km (highlighted band in Figure 2), passed over fires throughout southern Africa. The arrival at Lusaka is southeasterly from the Indian Ocean, passing over Mozambique and Zimbabwe (Figure 4), with origins 4–5 days earlier over the Atlantic and fire-rich areas of Angola, Namibia, Botswana, and South Africa. The 500 hPa air parcels (green in Figure 4), corresponding to the upper part of the stable layer in the ozone soundings on 6–8 September 2000 (Figures 2 and 3), were advected over Angola and western Zambia prior to arrival over Lusaka. Thus, although elevated ozone mixing ratios near the surface at Lusaka are partly local, ozone aloft is imported from burning regions in other countries.

5. Summary

[12] The first ozone soundings over Zambia, taken during a typical dry-season burning period in September 2000, showed high ozone concentrations throughout the troposphere. Surface concentrations of 95 ppbv at Lusaka, the highest readings measured to date in southern Africa, were much greater than surface ozone at Nairobi and Irene at the same time. Satellite total column ozone from TOMS agreed well with the sondes and with column measurements from a portable ozone uv-photometer. Free tropospheric ozone over Lusaka was concentrated in absolutely stable layers, a phenomenon that characterized southern African circulation more generally in September 2000. The most prominent stable layer over Lusaka, at 3–5 km (800–500 hPa), was of predominantly imported origins. Ozone from western Zambia and neighboring countries is exported, sometimes via the Indian Ocean, before returning to the continent. In this respect, Lusaka is a collecting point for recirculated trans-boundary pollution within the southern African gyre. During most of the sampling period, Lusaka boundary-layer ozone was a mixture of imported, local background and local pollution origins, approximately one-third of each.

[13] Acknowledgments. Many thanks to the Zambian Meteorological Department (C. Mukula, Z. Mumba, G. Chipeta) and R. Mayers for support during the sounding period and to H. Annegarn, R. J. Swap, J. L. Privette, and L. Otter for logistical help. Comments from R. D. Diab, K. E. Pickering and B. G. Doddridge are greatly appreciated. Special thanks to T. Futrell at the US Embassy in Lusaka. This research was supported by NASA’s EOS validation and ACMAP Programs. The ozonesonde-radiosonde data are available through the SHADOZ (Southern Hemisphere Additional Ozone-sondes) archive (http://code916.gsfc.nasa.gov/Data_services/shadoz) and from SAFARI-2000 at (http://mercury.orml.gov/safari2k).

References


A. M. Thompson and J. C. Witte, NASA/GSFC/Code 916, Greenbelt, MD 20771, USA. (thompson@gator1.gsfc.nasa.gov)
M. T. Freiman, Climatology Research Group, Univ of the Witwatersrand, Private Bag, WITS 2050, Johannesburg, South Africa.