SAFARI 2000 Fire Emission Data, Dry Season 2000

Abstract

As part of the Southern Africa Regional Science Initiative (SAFARI 2000), the University of Montana participated in both ground-based and airborne campaigns during the southern African dry season of 2000 to measure trace gas emissions from biofuel production and use and savanna fires, respectively.

During the airborne campaign, stable and reactive trace gases were measured over southern Africa with an airborne Fourier transform infrared spectroscopy (AFTIR) onboard the University of Washington Convair-580 research aircraft in August-September of 2000. The measurements included vertical profiles of CO_2, CO, H_2O, and CH_4 up to 5.5 km on 6 occasions above instrumented ground sites and below the TERRA satellite and ER-2 high-flying research aircraft as well as trace gas emissions from ten African savanna fires. These measurements are the first broad characterization of the most abundant trace gases in nascent smoke from African savanna fires (i.e., including oxygen- and nitrogen-containing species) and are used to calculate emission factors for savanna fires that can be used for regional emissions estimates.

The investigators also measured trace gas emissions from the production and use of biofuels using ground-based open-path Fourier transform infrared spectroscopy (OP-FTIR) in September of 2000. The data set for ground-based OP-FTIR measurements is archived at ORNL DAAC at ftp://daac.ornl.gov/data/safari2k/atmospheric/biofuel_emissions/.

Background Information

Investigators:

Robert J. Yokelson (byok@selway.umt.edu)

Project: SAFARI 2000

Data Set Title: SAFARI 2000 Fire Emission Data, Dry Season 2000

Site: Southern Africa
Westernmost Longitude: 12° E
Easternmost Longitude: 36° E
Northernmost Latitude: 14° S
Southernmost Latitude: 27° S

Data Set Citation:

Yokelson, R. J. 2004. SAFARI 2000 Fire Emission Data, Dry Season 2000. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A.

Web Site: https://www.umt.edu/chemistry/faculty/yokelson.htm

Data File Information

This data set provides emission ratios and emission factors from the aircraft sampling effort for the following trace gases: carbon dioxide (CO_2); carbon monoxide (CO); methane (CH_4); acetylene (C_2H_2); ethene (C_2H_4); acetic acid (CH_3COOH); methanol (CH_3OH); formaldehyde (HCHO); hydrogen cyanide (HCN); formic acid (HCOOH); ammonia (NH_3); nitric oxide (NO); and nitrogen dioxide (NO_2). The file is an ASCII text file in comma-separated-value format. All emission factor units are grams of compound emitted per kilogram of fuel burned (g/kg) for the savanna fires investigated. Emission ratios are dimensionless.

Data file information for savanna_fire_emiss_aftir.csv is provided below:

Column Name	Description	Units
UW Flight Number	UW CV-580 flight number	numeric
Date	Date of flight	ddmmyyyy
Fire	The name or location of the fire	none
CO2 EF	CO_2 Emission Factor	g/kg
CO/CO2 ER	CO Emission Ratio	dimensionless
CO EF	CO_2 Emission Factor	g/kg
MCE	Modified Combustion Efficiency $\Delta CO_2/(\Delta CO_2+\Delta CO)$	dimensionless
NO/CO2 ER	NO Emission Ratio	dimensionless
NO2/CO2 ER	NO_2 Emission Ratio	dimensionless
NO2 as NO EF	NO_2 Emission Factor	g/kg
CH4/CO ER	CH_4 Emission Ratio	dimensionless
CH4 EF	CH_4 Emission Factor	g/kg
C2H4/CO ER	C_2H_4 Emission Ratio	dimensionless
C2H4 EF	C_2H_4 Emission Factor	g/kg
C2H2/CO ER	C_2H_2 Emission Ratio	dimensionless
C2H2 EF	C_2H_2 Emission Factor	g/kg
HCHO/CO ER	HCHO Emission Ratio	dimensionless

HCHO EF	HCHO Emission Factor	g/kg
CH3OH/CO ER	CH_3OH Emission Ratio	dimensionless
CH3OH EF	CH_3OH Emission Factor	g/kg
CH3COOH/CO ER	CH_3COOH Emission Ratio	dimensionless
CH3COOH EF	CH_3COOH Emission Factor	g/kg
HCOOH/CO ER	HCOOH Emission Ratio	dimensionless
HCOOH EF	HCOOH Emission Factor	g/kg
NH3/CO ER	NH_3 Emission Ratio	dimensionless
NH3 EF	NH_3 Emission Factor	g/kg
HCN/CO ER	HCN Emission Ratio	dimensionless
HCN EF	HCN Emission Factor	g/kg

Chemical formulas and names used in the data file are provided below:

Trace Gas Chemical Name	Chemical Formula
carbon dioxide	CO_2
carbon monoxide	CO
methane	CH_4
acetylene	C_2H_2
ethene	C_2H_4
acetic acid	CH_3COOH
methanol	CH_3OH
formaldehyde	HCHO
hydrogen cyanide	HCN
formic acid	HCOOH
ammonia	NH_3
nitric oxide	NO
nitrogen dioxide	NO_2

The table below defines some of the terms commonly used in the discussion of biomass burning in general and in this documentation file specifically. (Also see, http://www.umt.edu/chemistry/faculty/yokelson/firetermbob.htm.)

Biomass Burning Term	Definition
Biofuel	This term has been used most often to denote biomass that is used as a (renewable) domestic or industrial energy source (cooking, heating, lighting, etc.) instead of fossil fuels. It may confuse people to use "biofuel" as a term equivalent to biomass.

Emission Factor (EF)	Grams compound emitted per kg of fuel burned (on a dry mass basis). EF * fuel consumption * burned area = the total emissions of a compound from a burned area.
Emission Ratio (ER)	Dimensionless molar ratio between two emitted compounds measured at a fire. Most often reported as $\Delta X/\Delta Y$ where "ΔX" and "ΔY" refer to excess mixing ratios (defined as the mixing ratio of a species in the smoke minus the mixing ratio of that species in the background air) and "Y" is usually CO or CO_2.
Combustion Efficiency (CE)	Defined as the fraction of fuel carbon converted to carbon as CO_2. Historically, combustion engineers want the CE of their reactors to equal 1 to maximize energy delivered by the fuel.
Modified Combustion Efficiency (MCE)	Defined as $\Delta CO_2/(\Delta CO_2+\Delta CO)$ and abbreviated as MCE. Related to CE, but easier to measure in the real world. MCE has a further advantage, in that other carbonaceous compounds can be plotted vs. MCE as independent variables. Pure flaming usually has MCE of 0.97-0.99, and pure smoldering usually has MCE of 0.75-0.85. CE and MCE are higher when the ratio of flaming to smoldering combustion is higher.

Introduction

To help address crucial gaps in our knowledge of southern African fire emissions, the University of Montana participated in both ground-based and airborne dry season campaigns as part of the Southern Africa Regional Science Initiative (SAFARI 2000). In the airborne campaign, trace gases, mostly in smoke and haze from savanna fires, were measured with an airborne FTIR (AFTIR) during 19 flights (>86 hours) between 14 August and 14 September aboard the University of Washington's (UW) Convair-580 research aircraft (UW Convair-580). The complete set of instruments for measuring trace gases and particles aboard the UW Convair-580 is described by Hobbs (2003).

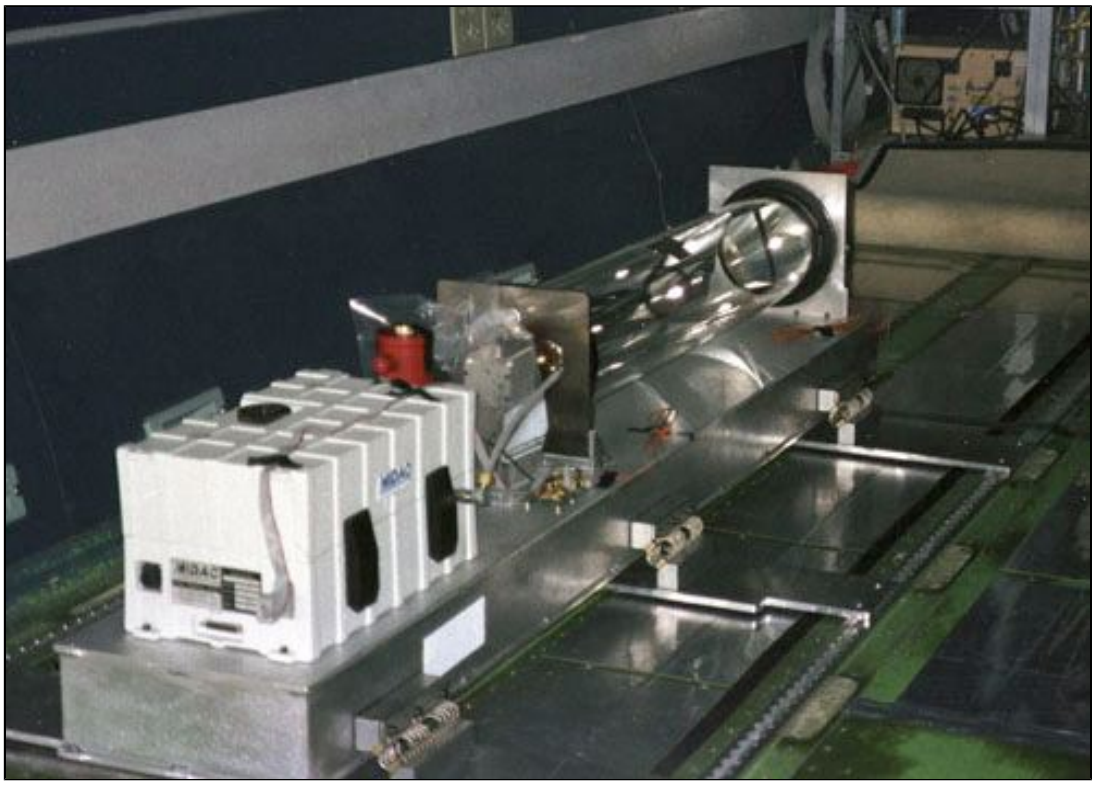
AFTIR measurements acquired on the UW Convair-580

Trace gas measurements collected onboard the CV-580 include vertical profiles of CO_2, CO, CH_4, and H_2O below 5.5 km in the regional haze layers that dominate southern Africa during the dry season due mostly to emissions from biomass burning. The profiles were measured above instrumented ground sites in association with overpasses by the Terra satellite and the ER-2 aircraft.

The University of Washington Convair-580 aircraft

Also measured were the first broad characterization of the most abundant trace gases in nascent smoke from African savanna fires (i.e. including oxygen- and nitrogen-containing species). These measurements (which include fires in the humid savanna region) are used to calculate emission factors for savanna fires that can be used for regional emissions estimates.

Additionally, comparisons of nascent and downwind smoke samples reveal intriguing post-emission changes in smoke composition due to photochemistry and cloud processing. This demonstrates the need to measure smoke less than a few moments in age to properly determine the 'initial emissions' from fires and the value of measuring older smoke to understand plume chemistry and characterize regional impacts.



Airborne FTIR (AFTIR) instrument, before installing protective mesh rack, is anchored to the floor of the University of Washington Convair-580 research aircraft.

Additional photographs that complement the airborne FTIR measurements are archived with this data set. They are described in the excel file: ftp://daac.ornl.gov/data/safari2k/atmospheric/fire_emissions/comp/aftir_photo_index.xls.

Measurement Strategy

The AFTIR system is designed to obtain FTIR spectra of air flowing through, or detained within, a multipass cell inside an aircraft (Yokelson et al., 1999; Goode et al.,

2000). On the UW Convair-580, outside air samples were forced by ram pressure into a forward-facing inlet [25 mm internal diameter (i.d.)] with an opening 22 cm from the outer skin of the aircraft cabin roof. The air flowed next through 10 m of 25 mm i.d. Teflon bellows; a 16 liter, Pyrex, multipass cell; and ~5 m of 25 mm i.d. tubing to a rear-facing outlet. Fast-acting valves (19 mm i.d.) on the inlet and outlet lines of the cell were used to temporarily trap the cell contents for signal averaging at desired times. In addition, closing the inlet and outlet valves reduced the noise in the 900-1100 cm -1 region of the AFTIR spectrum providing lower detection limits for many species (Yokelson et al., 1999). At the aircraft research speed (80 m/s) the flow rate through the system was ~ 100 l/min. The 1/*e* decay time for a signal when exchanging the cell contents was 4-5 s, indicating a faster flow in the center of the cell where most of the optical path is located. The residence time in the exterior inlet tubing was only about 2.5 ms. Sampling artifacts were further guarded against by coating all the metal surfaces in the system with a nonreactive halocarbon wax (Webster et al., 1994). Recent tests in our laboratory showed that this wax imparts Teflon-like properties to metal surfaces (Yokelson and Bertschi, 2002).

Infrared spectra of the cell contents were acquired continuously (every 0.83 s) throughout most of each flight and the flow-control valves were normally open, which flushed the cell with ambient air. The aircraft was flown into the smoke plume to temporarily trap 'grab' samples and then the valves were closed when the cell was well flushed with smoke. The valves remained closed for 1-3 minutes while several hundred spectra of the detained smoke sample were acquired. The valves were then opened, which flushed the cell. Background grab samples were trapped at the same altitude just outside the plume and processed in the same way. The cells were usually flushed for one to many minutes before closing the valves for a smoke or background air sample. The low-noise spectra, acquired with the valves closed, were later averaged together (by sample) to further improve the signal-to-noise ratio. To measure initial emissions from a fire, smoke less than several minutes old was sampled by penetrating the rapidly rising column of smoke just above the flame front. 'Aged' smoke samples were acquired within the plumes up to 30 km downwind. The age of downwind samples was computed from GPS and wind speed measurements. Vertical profiles of trace gases in regional haze layers, and in the free troposphere, were obtained by continuous sampling during rapid ascent/descent, or from a series of detained samples obtained during the horizontal legs of a 'ladder' type flight profile.

Calculation of Emission Ratios and Emission Factors

The excess mixing ratios (ΔX, the mixing ratio of species 'X' in the smoke minus the mixing ratio of 'X' in the background air) that are observed in biomass-burning studies reflect the degree of dilution of the smoke at the point of measurement. Thus, a more widely-used, derived quantity is the normalized excess mixing ratio where ΔX is compared to a simultaneously-measured smoke tracer such as ΔCO or ΔCO_2. A

measurement of $\Delta X/\Delta CO$ or $\Delta X/\Delta CO_2$ made in nascent smoke (< ~5 minutes old) is an emission ratio (ER). Fire-integrated excess mixing ratios were used to calculate fire-average emission ratios.

Additional Sources of Information

Ground-based open-path Fourier transform infrared spectroscopy (OP-FTIR) was used to quantify 18 of the most abundant trace gases emitted by wood and charcoal cooking fires and an earthen, charcoal-making kiln in Zambia. The data set for the ground-based OP-FTIR measurements is archived at ORNL DAAC at ftp://daac.ornl.gov/data/safari2k/atmospheric/biofuel_emissions/.

A detailed description of the airborne FTIR (AFTIR) system and the ground-based Open Path FTIR (OP-FTIR) system can be found in Yokelson et al. (2003) and Bertschi et al. (2003a), respectively.

References

Bertschi, I. T., R. J. Yokelson, D. E. Ward, T. J. Christian, and W. M. Hao. 2003a. Trace gas emissions from the production and use of domestic biofuels in Zambia measured by open-path Fourier transform infrared spectroscopy. J. Geophys. Res., 108, NO. D13, 8469, doi:10.1029/2002JD002158.

Bertschi, I. T., R. J. Yokelson, D. E. Ward, R. E. Babbitt, R. A. Susott, J. G. Goode, and W. M. Hao. 2003b. Trace gas and particle emissions from fires in large-diameter and belowground biomass fuels. J. Geophys. Res., 108, NO. D13, 8472, doi:10.1029/2002JD002100.

Hobbs, P. V., P. Sinha, R. J. Yokelson, T. J. Christian, D. R. Blake, S. Gao, T. W. Kirchstetter, T. Novakov, and P. Pilewskie. 2003. Evolution of gases and particles from a savanna fire in South Africa. J. Geophys. Res., 108, NO. D13, 8485, doi:10.1029/2002JD002352.

Sinha, P., P. V. Hobbs, R. J. Yokelson, I. T. Bertschi, D. R. Blake, I. J. Simpson, S. Gao, T. W. Kirchstetter, and T. Novakov. 2003. Emissions of trace gases and particles from savanna fires in southern Africa. J. Geophys. Res., 108, NO. D13, 8487, doi:10.1029/2002JD002325.

McMillan, W. W., M. L. McCourt, H. E. Revercomb, R. O. Knuteson, T. J. Christian, B. G. Doddridge, P. V. Hobbs, J. V. Lukovich, P. C. Novelli, S. J. Piketh, L. Sparling, D. Stein, R. J. Swap, and R. J. Yokelson. 2003. Tropospheric carbon monoxide measurements from the Scanning High-Resolution Interferometer Sounder on 7 September 2000 in southern Africa during SAFARI 2000. J. Geophys. Res., 108, NO. D13, 8492, doi:10.1029/2002JD002335.

Swap, R. J., H. J. Annegarn, J. T. Suttles, J. Haywood, M. C. Helmlinger, C. Hely, P. V. Hobbs, B. N. Holben, J. Ji, M. King, T. Landmann, W. Maenhaut, L. Otter, B. Pak, S. J. Piketh, S. Platnick, J. Privette, D. Roy, A. M. Thompson, D. Ward, and R. Yokelson. 2002. The Southern African Regional Science Initiative (SAFARI 2000): Dry-Season Field Campaign: An Overview. S. Afr. J. Sci., 98, 125-130.

Bertschi, I. T., R. J. Yokelson, D. E. Ward, T. J. Christian, and W. M. Hao. 2003a. Trace gas emissions from the production and use of domestic biofuels in Zambia measured by open-path Fourier transform infrared spectroscopy, J. Geophys. Res., 108, NO. D13, 8469, doi:10.1029/2002JD002158.

Bertschi, I. T., R. J. Yokelson, D. E. Ward, R. E. Babbitt, R. A. Susott, J. G. Goode, and W. M. Hao. 2003b. Trace gas and particle emissions from fires in large-diameter and belowground biomass fuels, J. Geophys. Res., 108, NO. D13, 8472, doi:10.1029/2002JD002100.

Brocard, D., C. Lacaux, J. P. Lacaux, G. Kouadio, and V. Yoboué. 1996. Emissions from the combustion of biofuels in western Africa. In: Levine, J. S. (ed.). Biomass Burning and Global Change, pp. 350-360, MIT Press, Cambridge, MA.

Hobbs, P. V., P. Sinha, R. J. Yokelson, T. J. Christian, D. R. Blake, S. Gao, T. W. Kirchstetter, T. Novakov, and P. Pilewskie. 2003. Evolution of gases and particles from a savanna fire in South Africa. J. Geophys. Res., 108, NO. D13, 8485, doi:10.1029/2002JD002352.

Kaoma, J., and G. Kasali. 1994. Efficiency and emission characteristics of two Zambia cookstoves using charcoal and coal briquettes. Stockholm Environment Institute, Stockholm, 25 pp.

Kituyi, E., L. Marufu, S. O. Wandiga, I. O. Jumba, M. O. Andreae, and G. Helas. 2001. Carbon monoxide and nitric oxide from biofuel fires in Kenya. Energy Conversion and Management, 42: 1517-1542.

Lacaux, J. P., D. Brocard, C. Lacaux, R. Delmas, B. Ajoua, V. Yoboué, and M. Koffi. 1994. Traditional charcoal making: an important source of atmospheric pollution in the African tropics. Atmos. Research, 35: 71-76.

Ludwig, J., L. T. Marufu, B. Huber, M. O. Andreae, and G. Helas. Domestic combustion of biomass fuels in developing countries: A major source of atmospheric pollutants, in press, J. Atmos. Chem., 2002.

McMillan, W. W., M. L. McCourt, H. E. Revercomb, R. O. Knuteson, T. J. Christian, B. G. Doddridge, P. V. Hobbs, J. V. Lukovich, P. C. Novelli, S. J. Piketh, L. Sparling,

D. Stein, R. J. Swap, and R. J. Yokelson. 2003. Tropospheric carbon monoxide measurements from the Scanning High-Resolution Interferometer Sounder on 7 September 2000 in southern Africa during SAFARI 2000. J. Geophys. Res., 108, NO. D13, 8492, doi:10.1029/2002JD002335.

Pennise, D. M., K. R. Smith, J. P. Kithinji, M. E. Rezende, T. J. Raad, J. Zhang, and C. Fan. 2001. Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. J. Geophys. Res,. 106, 24,143-25,155.

Sinha, P., P. V. Hobbs, R. J. Yokelson, I. T. Bertschi, D. R. Blake, I. J. Simpson, S. Gao, T. W. Kirchstetter, and T. Novakov. 2003. Emissions of trace gases and particles from savanna fires in southern Africa, J. Geophys. Res., 108, NO. D13, 8487, doi:10.1029/2002JD002325.

Smith, K. R., R. Uma, V. V. N. Kishore, K. Lata, V. Joshi, J. Zhang, R. A. Rasmussen, and M. A. K. Khalil. 2000. Greenhouse gases from small-scale combustion devices in developing countries: Household stoves in India. U.S. Environmental Protection Agency (EPA) report, EPA-600/R-00-052, Research Triangle Park, NC.

Swap, R. J., H. J. Annegarn, J. T. Suttles, J. Haywood, M. C. Helmlinger, C. Hely, P. V. Hobbs, B. N. Holben, J. Ji, M. King, T. Landmann, W. Maenhaut, L. Otter, B. Pak, S. J. Piketh, S. Platnick, J. Privette, D. Roy, A. M. Thompson, D. E. Ward, and R. J. Yokelson. 2002. The Southern African Regional Science Initiative (SAFARI 2000) Dry-Season Field Campaign: An Overview. S. Afr. J. Sci., 98: 125-130.

Yokelson, R. J., I. T. Bertschi, T. J. Christian, P. V. Hobbs, D. E. Ward, and W. M. Hao. 2003. Trace gas measurements in nascent, aged, and cloud-processed smoke from African savanna fires by airborne Fourier transform infrared spectroscopy (AFTIR). J. Geophys. Res., 108, NO. D13, 8478, doi:10.1029/2002JD002322.

Point of Contact:

Dr. Robert J. Yokelson
Department of Chemistry
University of Montana
Missoula, MT 59812 USA
E-mail: byok@selway.umt.edu
Phone: +01 406 329-4812
Fax: +01 406 329-4863

Revision Date: Thursday, August 19, 2004