The Southern African Regional Science Initiative (SAFARI 2000): wet season campaigns

L.B. Otter[a*], R.J. Scholes[b], P. Dowty[c], J. Privette[d], K. Caylor[c], S. Ringrose[e], M. Mukelabai[f], P. Frost[g], N. Hanan[h], O. Totolo[i] and E.M. Veenendaal[e]

The Southern African Regional Science Initiative (SAFARI 2000) involved two wet season and one dry season field campaigns. This paper reports on the wet season campaigns. The first was conducted at five sites along the Kalahari Transect in Zambia (Kataba Forest) and Botswana (Pandamatenga, Maun, Okwa River Crossing, Tshane) during February 2000 and concentrated primarily on characterizing the land surface with respect to exchanges of matter and energy with the atmosphere. The second, conducted in February 2001, focused on fluxes of water, gases and energy between the canopy and the atmosphere at Maun, Botswana, and at Skukuza in the Kruger National Park, South Africa. Eddy covariance measurements at Skukuza and Maun were designed to collect a near-continuous record of the seasonality and inter-annual variability in savanna carbon, water and energy exchanges in representative savanna ecosystems. This paper gives brief descriptions of the sites, the measurements made, and the methods used. It highlights some preliminary results, particularly from the first campaign, and outlines the next stages of the SAFARI 2000 project.

Introduction

The Southern African Regional Science Initiative (SAFARI 2000) is an experiment involving atmospheric chemists, plant physiologists, ecologists and meteorologists from 18 countries, with measurements taken during the period from 1999 to 2001.[1] It uses the presence of a semi-closed atmospheric circulation pattern over southern Africa to organize a series of mass-balance studies on the exchange of trace gases and aerosols between the land and the atmosphere across the subcontinent. Its predecessor, SAFARI-92,[2] focused almost exclusively on trace gases resulting from the burning of biomass in wildfires, and showed that other trace gas sources, notably from the soil,[3] plants,[4] industries and domestic fires,[5] contributed substantially to the atmospheric load.[6] One of its hypotheses was that the conspicuous build-up of tropospheric ozone over southern Africa during the spring is a consequence of an interaction between atmospheric constituents derived from dry season fires and dust, with constituents produced by soils and plants following the first rains. SAFARI 2000 aims to improve our understanding of these other sources of trace gases and aerosols, their chemical transformation in the atmosphere, and their transboundary transport in southern Africa.[1]

SAFARI 2000 was designed as an integrated experiment, covering all the major sources and sinks of the reactive substances. This required significant observational effort both in the dry season, with the emphasis on fires and dust, and in the wet season, focused on biogenic processes. Observations were made at various spatial scales, and measurements were taken at ground (up to 1 km^2) and tower (21–30 m high, <20 km^2) levels, from aircraft (local to regional scale), and from satellites (1000s of km^2 to global scale). There were numerous field studies of short duration, and investigations where data were collected continuously or at regular intervals over several years, but most activities occurred during three major field campaigns: wet season campaigns during February/March 2000 and 2001 and the September 2000 dry season campaign.[7] This paper outlines the wet season campaigns and discusses some of the preliminary data, showing overall patterns or trends (a complete analysis of the data is beyond the scope of this article).

[a]Climatology Research Group, University of the Witwatersrand, Private Bag 3, WITS, 2050 South Africa
[b]Division of Water, Environment and Forestry Technology, CSIR, Pretoria, South Africa.
[c]Global Environmental Change Program, University of Virginia, Charlottesville, VA, U.S.A.
[d]NASA Goddard Space Flight Center, Greenbelt, MD, U.S.A.
[e]Harry Oppenheimer Okavango Research Centre, University of Botswana, Maun, Botswana.
[f]Zambian Meteorology Department, Mongu, Zambia.
[g]Institute for Environmental Studies, University of Zimbabwe, Harare, Zimbabwe.
[h]Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO, U.S.A.
[i]Department of Environmental Sciences, University of Botswana, Gaborone, Botswana.
*Author for correspondence:
E-mail: luanne@crg.bpb.wits.ac.za

March 2000 Kalahari Transect campaign

The deep, aeolian sands of the Kalahari Basin cover about a third of southern Africa. The substrate is relatively uniform, but occurs over a wide rainfall gradient (200–1000 mm/yr mean annual rainfall), providing an excellent natural experiment for examining climate–vegetation–soil interactions. This potential led the International Geosphere–Biosphere Programme (IGBP) to designate the 'Kalahari Transect' (KT) as one of several terrestrial transects along which global change phenomena could be studied.[8–12] These transects are sets of field sites covering large areas (in the order of 1000 m across) and spanning significant variation in major environmental or land-use factors. While some homogeneity is acknowledged, the Botswana portion of the transect is known to be heterogeneous in terms of climate and cover density.[13,14] Conceptually, the KT extends from equatorial forest in Congo-Brazzaville to the subtropical, arid shrubland of the Kalahari desert in South Africa.

In February 2000, approximately 40 researchers (the number varied from site to site) travelled from Mongu, Zambia, to Tshane in Botswana, spending an average of four days at each of five sites (Table 1) en route.[18] All five sites are on the southern African plateau, with elevations between 929 and 1115 m (Table 1) (Fig. 1), and were selected to span a significant portion of the rainfall gradient in the region. Immediately before the campaign, the field sites in Botswana had received above-average rainfall, associated with tropical cyclone Eline, an Indian Ocean storm, which led to flooding in the eastern part of the region. By contrast, the Mongu site had received slightly below-normal rainfall at the time of the campaign.

The main objective was to collect accurate data relating to vegetation structure and composition, partitioning of solar radiation, soil nitrogen turnover, ex-

Table 1. The five sites visited during the February/March 2000 campaign. They are listed from north to south.

Site	GPS location	Elevation (m a.s.l.)	Mean annual rainfall (mm)	Vegetation	Additional site information
Kataba Forest Reserve	15.44°S, 23.25°E	1084	950	Kalahari woodland dominated by *Brachystegia spiciformis* with sparse woody understorey	EOS validation core site; 30-m tower
Pandamatenga Agricultural Research Station	18.66°S, 25.5°E	1065	630	Open woodland dominated by *Ricenodendron* rautanenii, *Baikiaea plurijuga* and *Burkea africana*	Adjacent to large agricultural areas that are subject to light grazing
Harry Oppenheimer Okavango Research Centre	19.92°S, 23.59°E	929	460	*Colophospermum mopane* woodland	Focus area was 3 km away from a walk-up flux tower and here tree height was lower with patches of *Terminalia sericea*
Okwa River Crossing	22.41°S, 21.71°E	1089	407	Open Kalahari shrubland dominated by *Acacia mellifera, Terminalia sericea* and *Grewia flava*	Somewhat anomalous site on Pleistocene drainage line
Tshane	24.16°S, 21.89°E	1115	365	Open savanna dominated by *Acacia leuderitzii* and *Acacia mellifera*	Land-use gradient: away from the site in the direction of Tshane, the grazing intensity increased

change of CO_2, volatile organic carbons (VOCs) and water between vegetation and the atmosphere for the sites along the transect. Table 2 summarizes the measurements made and the techniques used during this experiment. Further details are given in the Earth Observer report[16] and forthcoming individual journal articles. The effects of land use on vegetation and soils at Tshane were also investigated, since grazing pressures increase as one moves away from Tshane towards the village of Hukuntsi.

The campaign coincided with the first remotely sensed measurements of Earth from the Terra satellite, launched by NASA in December 1999.[17] Detailed vegetation measurements are being used to help validate products from the MODIS, ASTER and MISR sensors on the satellite, so the five sites were among the first areas specifically targeted by these instruments (Table 3). Data and products from Landsat 7, NOAA-AVHRR, SPOT, TOMS, Meteosat and SeaWiFS satellites, and fine-resolution (1 m) images from the IKONOS satellite, were also acquired.

As part of the MODIS validation, a 30-m flux tower was erected at the Mongu site (Fig. 2), and used for measuring radiation and gaseous fluxes in and above the Kalahari Woodland canopy. A tower (21 m) was also erected at the Skukuza site (Fig. 2). Located on the ecotone between two different vegetation types, it thus measures the exchanges between *Combretum* savanna and the atmosphere when the wind is from the northwest, and *Acacia* woodland when it blows from the southeast.[15] Following the Kalahari Transect campaign, some researchers visited the Skukuza site to measure soil moisture, canopy CO_2 and H_2O fluxes, canopy structure (TRAC and LAI 2000), albedo and scene component spectra (for instance, of grass and shrubs) around the tower site. Soil samples were also collected from the burn trial plots for ^{15}N analysis.

February 2001 campaign

The February 2001 campaign focused on the areas around the towers at Maun and Skukuza. The main objective was to investigate and compare canopy fluxes of CO_2/H_2O and VOCs at these two very different sites. Researchers at each location also had other objectives as discussed below.

Maun, February 2001

The team at Maun consisted of researchers from the Harry Oppenheimer Okavango Research Centre (HOORC, Botswana), CSIR (S.A.), University of Natal (S.A.), National Center for Atmospheric Research (NCAR) (U.S.A), and Lancaster University (U.K.). The tower at Maun is operated by HOORC in collaboration with the Max Planck Institute for Biogeochemistry in Jena. It is equipped with a sonic anemometer and a CO_2/H_2O analyser, which have been recording canopy fluxes over the last two years. During this campaign, a second 3D sonic anemometer, linked to a Relaxed Eddy

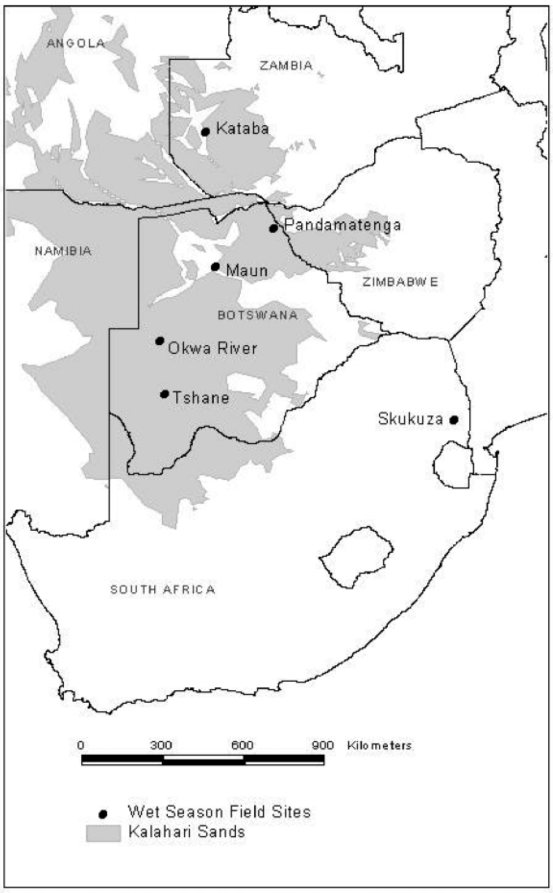

Fig. 1. Map of field sites and the extent of Kalahari sands as delineated in the FAO Soil Map of the World.

Table 2. Activities and measurement techniques used during the February/March 2000 Kalahari Transect campaign.

Activity grouping	Measurement interval or sample collection procedure	Parameter or process	Instrument or technique
Meteorology	30-min intervals 30-min averages	Temperature, humidity, wind speed and direction	Wet and dry bulb temperatures; mercury thermometer Weather station on portable tower
Leaf and canopy radiation	3 parallel transects extending 750 m, separated by 250 m and marked at 25-m intervals	Canopy properties (canopy transmission, leaf area, leaf orientation and clumping, % cover)	Licor plant canopy analyser LAI-2000 TRAC Decagon Accupar ceptometer Nikon digital hemispherical camera ASD field spectrometer Kipp and Zonen albedometer (near-infrared, shortwave) Kipp and Zonen net radiometer (tower mount)
		Component spectra (e.g. leaves, soil), canopy transmission spectra	ASD field spectrometer, Licor 1800 spectrometer
Vegetation structure and composition		Tree/shrub cover/basal area and composition	Stem map Line transects Circular sample plots Spherical densiometer
		Landscape-scale composition/structure	Line transects
		Grass composition	Line transects Circular sample plots
		Grass biomass	Quadrat clipping
		Root distribution	Soil pit profile/root excavation
		Tree age structure	Tree cores
Leaf processes	Measurements made on dominant tree species at the various sites	CO_2 and light response curves of photosynthesis and dark respiration at 3 temperatures	Licor 6400 portable photosynthetic system
		Leaf-specific area and mass	Calipers, balance, leaf area meter
		VOC emissions	Samples from leaf enclosures collected on absorbent cartridges and analysed by GC-FID and mass spectrometry
Canopy fluxes	Measurements made from flux towers	Canopy energy, water and carbon fluxes	Open path CO_2/H_2O analyser, hygrometer, 3D sonic anemometer, net radiometer, air temperature/humidity probe, pyrgeometer
Nitrogen cycling	Analyses done on soil samples and leaves of dominant trees and grasses from the various sites; additional samples along a land-use gradient at HOORC and Tshane sites were also collected and analysed	N mineralization	*In situ* isotope dilution method: soil extracts analysed in the laboratory
		Nitrification	*In situ* isotope dilution method: soil extracts analysed in the laboratory
		Nitrogen fixation by soil microorganisms-soil crusts	*In situ* acetylene reduction assay: gas samples analysed the laboratory
		Nitrogen content of leaves, twigs, roots, and soil	Combustion technique using a gas chromatograph
		Soil NO_3^- and NH_4^+	KCl extraction and colorimetry
		NO fluxes from soils	Dynamic laboratory soil incubation chamber technique linked to a chemiluminescence NO/NO_2 analyser
Atmospheric aerosols	30-min intervals	Aerosol characterization and optical thickness	Handheld multispectral sun photometer
	8–12 h TSP samples	Total suspended particulate (TSP) matter	High volume pump and glass-fibre filters
Soil moisture and heat flux	30-min averages – at portable tower	Soil temperature	Soil heat flux plates (5 cm) and thermocouples (2.5 and 7.5 cm)
		Soil moisture	TDR soil moisture probes (0–30 cm)
	30-min averages – at Kataba Forest Reserve flux tower	Soil moisture	TDR soil moisture probes (5, 15, 30, 60, 125 cm)
		Soil temperature	Thermisters (5, 15, 30, 60, 125 cm); soil heat flux plate (10 cm)
	Surface (0–30 cm) measurements over a 1-hectare plot at Kataba Forest Reserve, Pandamatenga, Okwa River Crossing	Spatial variability in soil moisture	Handheld TDR probe
Soil characterization		Texture and particle size distribution	Hydrometer
		Bulk density	Gravimetric methods

Table 3. Characteristics of the various satellite sensors and the data collected during the Kalahari campaign. Satellite data are being collected throughout the SAFARI 2000 campaign.

Sensor	Pixel size (m)	Frequency	Characteristic*
MODIS	250, 500 and 1000	Daily	36 bands, wide range of land products including LAI, FPAR, albedo, surface type, vegetation indices, surface temperature, fire detection
MISR	275, 1100	1/9 days (repeat)	4 spectral bands, 9 view angles, various radiation products
ASTER	15, 30, 90	1/16 days (repeat; requested/approved scenes only)	15 spectral bands, including multispectral thermal infrared
Landsat 7 ETM+	15, 30, 60	1/16 days (repeat, requested/approved scenes only)	8 spectral bands
AVHRR	1100	Daily	5 spectral bands, unique SAFARI products
SeaWiFS	1100	Daily	8 spectral bands
IKONOS	1 (pan), 4 (spectral)	Variable depending on view angle limits (requested/approved scenes only)	4 spectral bands

*A complete list of EOS products by sensor is available online (http://spsosun.gsfc.nasa.gov/download.html).

Accumulation (REA) system, was set up for sampling canopy VOC emissions, whose concentrations were determined by gas chromatography and a flame ionization detector. An aerosol sampling head containing quartz-fibre filters was also installed on the tower (as well as one at the research station) for collecting atmospheric aerosols. At ground level the branch enclosure technique[4] was used to collect VOC samples in absorbent cartridges from dominant woody species in the area. Physiological variables (such as leaf temperature, photosynthetic rates, stomatal conductance and photosynthetically active radiation), measured with a Licor 6200 instrument, and water stress data were also collected.

Skukuza, February 2001

An eddy covariance system linked to a closed-path CO_2/H_2O analyser, jointly run by the CSIR and Colorado State University, was installed on the tower in April 2000 to measure the canopy fluxes. A REA system, similar to that at Maun, was temporarily installed by the researchers from NCAR for the 2001 campaign period to collect canopy VOC samples. Approximately 150 woody species were screened for isoprene emissions using a Licor 6400 leaf cuvette system linked to a portable gas chromatograph. Samples from dominant species and from species that showed some emissions in the screening phase were collected on cartridges that will be analysed at NCAR for the concentration of all VOCs. At the tower site, physiological measurements (photosynthetic and transpiration rates, light intensity, stomatal conductance) on plants were made by the National Botanical Institute, South Africa, with a Licor 6400.

Preliminary results

KT campaign

This section shows some of the preliminary results from the Kalahari Transect campaign, whose analysis is continuing. Further information will be presented in more detail in the future.

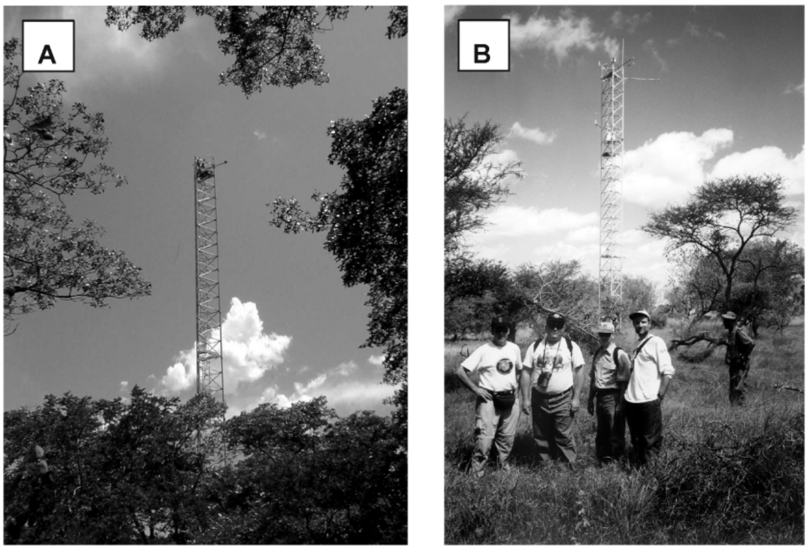

Fig. 2. The 30-m and 21-m walk-up towers in Kataba Forest Reserve, Mongu, Zambia (**A**) and Skukuza, Kruger National Park, South Africa (**B**), respectively. From the left, Phil Russell (NASA-Ames), Mark Helmlinger (NASA-Jet Propulsion Laboratory), Tim Suttles (Raytheon), Niall Hanan (Colorado State University) and a game guard further back are seen here standing in front of the Skukuza tower.

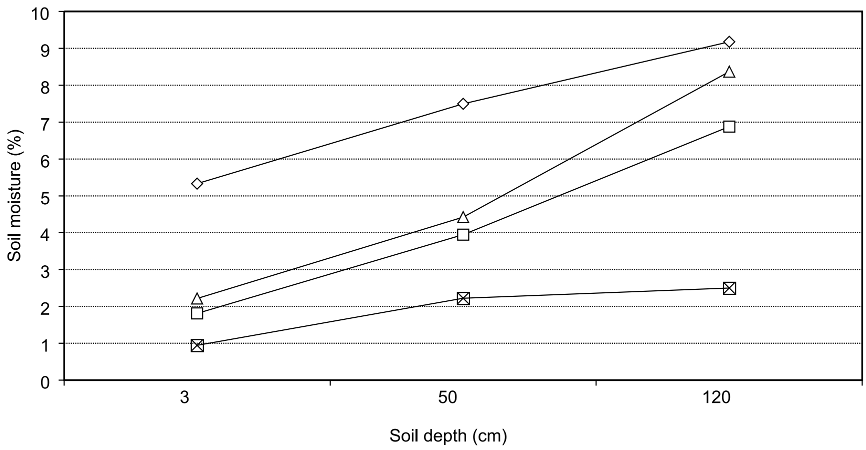

Fig. 3. Change in average soil moisture with depth at Pandamatenga (diamonds), Maun (squares), Okwa River Crossing (triangles) and Tshane (stars).

Soil moisture

There was a significant decline in soil moisture between Pandamatenga and Tshane at the time of the campaign (with slightly higher values at Okwa River Crossing than at Maun (Fig. 3)). At all sites soil moisture increased with depth.

Vegetation structure and composition

Spatial analysis indicates significant aggregation across all individuals in the vegetation communities at moister northern sites, and random spatial distributions at southern arid sites. Understorey individuals were more highly aggregated than overstorey individuals. In addition, the spatial pattern of understorey trees in relation to canopy dominants shows a marked transition along the moisture gradient, indicating changing tradeoffs

Table 4. Site and plot-level characteristics of woody vegetation at the sampling locations along the Kalahari Transect. Leaf area values are derived from allometric leaf biomass relationship found in Goodman.[23]

Site	Site-level characteristics[a]				Plot-level characteristics[b]				
	Basal area (m^2/ha)	Biomass (kg/ha)	Leaf area (m^2/m^2)	Stem density (stems/ha)	Plot size (m^2)	Basal area (m^2/ha)	Biomass (kg/ha)	Leaf area (m^2/m^2)	Average no. stems per individual
Kataba	8.47	42 064	1.703	336	2 500	10.5	57 650	2.79	1.7
Pandamatenga	15.24	49 766	1.675	432	5 000	11.9	62 180	2.02	1.2
Maun	8.65	22 105	0.738	2 622	2 500	10.1	36 200	1.86	3.6
Okwa	1.93	2 822	0.190	7 000					
Tshane	5.32	15 175	0.509	4 547	10 000	3.0	13 000	0.51	6.1

[a]Characteristics determined from a 300 x 350 m area, with vegetation sampled in 42 circular plots of radius 5 m.
[b]Characteristics of woody vegetation derived from detailed stem-map data of overstorey and understorey vegetation for a smaller area within the larger 300 x 350-m grid.