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The SAFARI 2000 – Kalahari Transect Wet Season Campaign of year 2000

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Abstract

Over 50 scientists from eight different countries coordinated research efforts in the Kalahari sand mass in Zambia and Botswana during the 2000 wet season as a part of the Southern African Regional Science Initiative – Kalahari Transect Wet Season Campaign (S2K-KT Wet Season Campaign). The work focused on change in ecological processes along the International Geosphere–Biosphere Programme-designated Kalahari Transect (KT). Topics included ecosystem structure, function, biogeochemistry, and modeling at the patch, landscape and regional scale. The KT of southern and central Africa follows a sharp precipitation gradient within an otherwise climatically and geographically similar region that contains a widely distributed, physically uniform soil and relatively little variation in elevation. This paper outlines the focus of the SAFARI 2000 research campaign as it relates to this study area and provides references to archived data sets generated during the study. It also describes vegetation patterns, climate, and 2000 wet season meteorological conditions for the region.

Keywords: Africa, climate, ENSO, Kalahari, Savanna, vegetation, woodland

Introduction

The Kalahari region lies in the interior of central and southern Africa primarily between latitudes 12°–28°S and longitudes 15°–27°E. The main physical feature throughout the region is the relatively uniform soil, the Kalahari sands, which are distributed within a high plateau that rises in all directions from a low point of about 1000 m in the Kgalagadi to a general level of 1200 m above sea level (FAO, 1995). Along the eastern boundary, the plateau rises to over 3000 meters to form the Drakensburg Mountains.

In February, 2000, in the middle of the wet season, a group of over 50 scientists from research organizations in eight different countries conducted an intensive coordinated investigation at five sites starting in Kataba Forest Reserve in Zambia (15.44°S, 23.25°E) and moving southward through Botswana to Pandamatenga (18.66°S, 25.5°E), Maun (19.92°S, 23.59°E), Okwa River Crossing (22.41°S, 21.71°E), and finally to Tshane (24.16°S, 21.89°E) (Fig. 1). All of these sites are between elevations of 929–1115 m. The northernmost, Kataba Forest Reserve site receives an average of 950 mm of rain per year. The rain decreases systematically toward the south with the southernmost Tshane site receiving a mean annual rainfall of 365 mm.

The Southern African Regional Science Initiative – Kalahari Transect Wet Season Campaign (SAFARI; S2K-KT) was a jointly coordinated international regional field campaign that drew heavily from both the International Geosphere–Biosphere Programme (IGBP) Kalahari Transect (KT) megatransect study (Scholes & Parsons, 1997) and the SAFARI science research program (SAFARI 2000) that was conceived to identify and understand the relationships between the physical, chemical, biological and anthropogenic processes that underlie the biogeophysical and biogeochemical systems of southern Africa (Swap *et al.*, 2002a, b; 2003). Regional and international scientific communities have been particularly interested in the influence of aerosol and trace gas emissions on regional climate and meteorology, their sites of eventual deposition, and the effects of deposition on ecosystems. As part of the goals of SAFARI 2000, specific emphasis was given to understanding biogenic, pyrogenic, and anthropogenic aerosol and trace gas emissions from their sources to their sinks. Given the need to understanding regional

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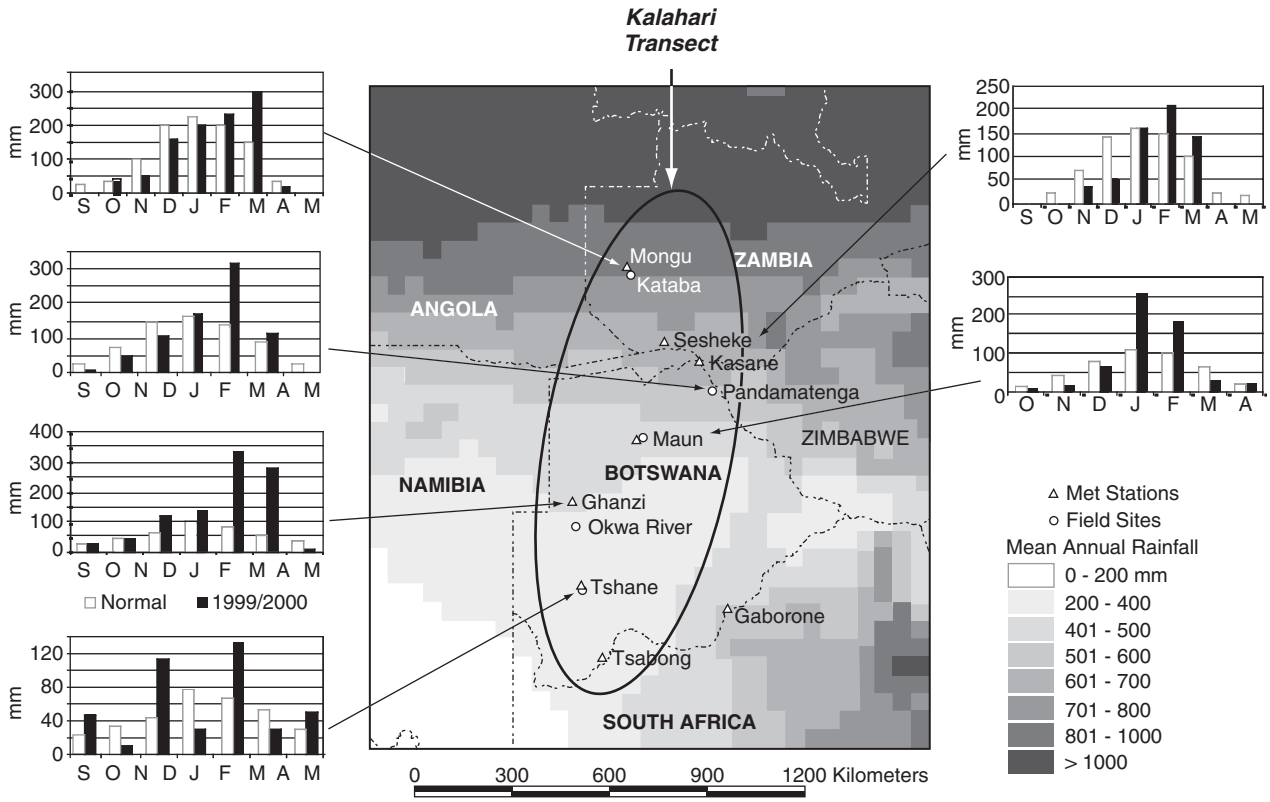

Fig. 1 Map of the Kalahari Transect showing mean annual rainfall (1961–1990) and site locations mentioned in the text. Rainfall data are from in New *et al.* (1999). The small insets are for the monthly 1999–2000 rainfall relative to normal for selected stations in western Zambia and Botswana.

productivity as it relates to the production of fuel for seasonal biomass burning, SAFARI 2000 leadership recognized that intensive ground-based and *in situ* observation of the southern African system during the wet season was imperative for the success of SAFARI 2000 overall.

S2K-KT, as initially documented by Otter *et al.* (2002), was an effort to characterize ecological processes during the growing season, particularly those processes that generate biomass fuels for the fires of the dry season. However, the project was motivated toward several overarching goals:

1. Characterizations of a major global transect – basic information on spatial patterns of vegetation, soils and plant physiology were collected to provide a basic characterization of the KT (Bird & Veenendaal, this issue; Midgley *et al.*, this issue; Privette *et al.*, this issue). A useful compendium of the synoptic characterization of the KT can be found in a special issue of Journal of Arid Environments (Vol. 54(2)) and in Scholes *et al.* (2002).
2. Simultaneous collection of ecosystem process information – the S2K-KT Wet Season campaign emphasized measurements relating plant function to ecosystem fluxes of heat, water and carbon dioxide. In addition, stable isotopes of nitrogen were measured to give a characterization of the patterns of nitrogen transfer and sources of ecosystem nitrogen (Aranibar *et al.*, this issue; Swap *et al.*, this issue). Mobile micrometeorological flux towers provided a whole canopy integration that could be tied to direct vegetation measurements at the same sites while sampling the range of environmental conditions along the transect (Scanlon & Albertson, this issue). The short-duration, spatially extensive micrometeorological-tower observations were anchored by long-term tower information from the Maun site (Veenendaal *et al.*, this issue).
3. Calibration of MODIS (Moderate Resolution Imaging Spectroradiometer) satellite sensors – data collection was timed to agree with the launch of the first MODIS satellite, now called the EOS Terra satellite. This satellite carries an array of sensors designed to sample the large-scale environmental variables with direct relevance to the understanding of the global environmental systems and global change (Justice *et al.*, 1998; Kaufman *et al.*, 1998). Thus, the testing of

models to be used in conjunction with the data products of this satellite, the development of measurements of radiative fluxes and of leaf area to calibrate satellite measurements with variable involved with surface function were important topics to be supported by the S2K-KT Wet Season campaign (Caylor *et al.*, this issue; Privette *et al.*, this issue; Scholes *et al.*, this issue). Additional information is reported in the SAFARI 2000 Special Issue of the Journal of Geophysical Research (Swap *et al.*, 2003).

4. Test data for dynamic global vegetation models (DGVMs) are becoming a mainstay for interpreting the consequences of predicted global climate changes and more recently feeding these changes into atmospheric general circulation models. While the models have been regularly compared (e.g., Cramer *et al.*, 2001) or matched against existing data (Melillo *et al.*, 1993), they have been relatively rarely tested against independent data. The ability to duplicate the biophysical performance of vegetation along a gradient such as the KT can be used as an independent test of a DGVM. Several of the DGVM groups were invited to a 'blind' model test using the data collected during S2K-KT. The proposition was to provide any necessary data for model parameterization and to reserve data for a model test (Jolly & Running, this issue; Woodward & Lomas, this issue). The testing of DGVMs against novel independent data is a necessary step toward progress in modeling global change. The S2K-KT Wet Season campaign represents one way of developing model tests that simultaneously engage modelers and field scientists in a testing protocol.

The information collected during S2K-KT Wet Season campaign will be of considerable value for other modeling studies and field comparisons in the future. Accordingly, effort has been made to store information from the study in permanent digital archives. The KT Wet Season campaign was conducted in February and March 2000 emphasizing the five stations mentioned above: Kataba Forest (Mongu, Zambia), Pandamatenga Agricultural Station (Pandamatenga, Botswana), Harry Oppenheimer Okavango Research Centre (Maun, Botswana), Okwa River Crossing (Botswana), and Tshane (Botswana). Data were collected on a range of environmental and ecological topics, including: soil nitrogen (bulk and ^{15}N abundance); soil carbon (bulk and ^{13}C abundance), leaf nitrogen, vegetation structure (e.g., tree basal area, tree height, tree crown size, tree species abundance, tree species distribution, tree cover, and grass biomass), and high-resolution carbon flux, water flux, soil temperature, soil moisture, and basic eddy flux (e.g., wind, atmospheric moisture, air temperature, surface albedo, and net radiation). Many of the original data sets are now housed in the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC), and are accessible on the SAFARI 2000 CD-ROM Data Series (Privette *et al.*, 2001; Nickeson *et al.*, 2002).

For much of Africa, instrumental meteorological measurements are not available for more than about 40 years (Moron *et al.*, 1995; Laurent *et al.*, 1998; Verschuren *et al.*, 2000). In recent years, however, a considerable amount of work has gone into acquiring and organizing climatological and ecological data for southern Africa, in general, and the Kalahari region in particular. In addition to station-based instrumental records and satellite-derived data sets, the SAFARI 2000 generated data that inform our understanding of contemporary land–atmosphere dynamics in southern Africa (Privette *et al.*, 2001; Swap *et al.*, 2002a, b; Otter *et al.*, 2002; Nickeson *et al.*, 2002). Available climatological data for the region include:

1. Daily climate data available from station sites – the NOAA/NCEP CD-ROM Data Base of African Weather Data for 1987–1995 (Thiaw & Kumar, 1996) provide station-based, daily resolved, climatological data for all of Africa, including the Kalahari region. Variables reported on a daily basis include maximum temperature, minimum temperature, reported precipitation, vapor pressure, and potential evapotranspiration.
2. Monthly mean climate data available in gridded format – The primary source of mean monthly climatological data describing the Kalahari region is the climatic research unit (CRU) Global Climate Data set (New *et al.*, 1999), available via the IPCC Data Distribution Centre (http://link6.cru.uea.ac.uk/cru_data/examine/cru_climate.html).

The KT

The KT is one of a set of global 'megatransects' designated by the IGBP to explore the continental-scale links among climate, biogeochemistry, and ecosystem structure and function (Scholes & Parsons, 1997). The KT is manifested as a set of study sites, beginning in Zambia and running southerly through Botswana to terminate in Namibia and the Republic of South Africa (Fig. 1). Although there is significant local site variation (see Ringrose *et al.*, 1998) over its subcontinental extent, the KT displays a strong moisture gradient across a topographically level region with similar soil throughout. The vegetation and soils of the KT have been described elsewhere and will be briefly summarized in the section that follows as a preamble to the coordinated studies described in this special issue. The climate of the KT and the conditions antecedent to the

period of intensive study during S2K-KT are less available and is reported in more detail to put the studies in their climatic context. The following climate summary is important because the year of this study was a particularly wet growing season in the climatic context of much of the region.

The Kalahari sand mass and vegetation patterns of the KT

The 2.5 million ha Kalahari sand sheet spreads from 29°S to the equator and 14–28°E. It lies in the elevated interior basin of southern Africa. The basin initially formed from tectonic events associated with the break-up of Gondwanaland (140 million years ago) and it filled with aeolian sands about 10 million years ago (Thomas & Shaw, 1991). The sands of the Kalahari sand sheet (which are 100–200 m deep at the center of the basin have been redistributed several times in the past million years to form a one of the largest sand seas in the world (McKee 1979). South of 20°S, there is an extensive region with 600 mm or less of rainfall, in generally freely draining sands, and with no permanent surface water. This latter region is popularly known by the misnomer 'Kalahari Desert' – a term that is consistent neither with the climate nor the vegetation. The relative homogeneity of the sandy substrate, the level topography and the untransformed nature of much of the land surface make the Kalahari an ideal environment for studying large-scale trends in vegetation structure and function (Scholes *et al*., 2002).

The key determinants of structure and composition of savanna vegetation include patterns of rainfall, nutrient availability, fire and herbivory (Huntley & Walker, 1982; Scholes & Walker, 1993). Only a small part of the Kalahari has been is transformed by humans through crop agriculture or settlement. Nonetheless, human action has been an important determinant of vegetation structure. People are the major agent of fire ignition throughout, and probably have been for millennia. Most of the valuable timber species in the northern woodlands have been heavily logged. There is increasing grazing pressure in the center and south as cattle replaces migratory wildlife, following the introduction of fences and boreholes. Ringrose *et al*. (1998) provide the most extensive report on the vegetation pattern over the Kalahari gradient, with information from 57 sites spanning the Botswana portion of the KT. These data provide estimates of woody, live and dead herbaceous and litter cover as well as soil organic carbon. These parameters also show a weak positive relationship with mean annual rainfall with high variability, especially in herbaceous cover.

Vegetation types on deep, well-drained sand occupy the largest fraction of the landscape (Scholes *et al*., 2002) and form a relatively orderly progression of increasing woody plant cover and height from south to north. The fine-leafed savannas (also referred to as arid, eutrophic or nutrient-rich savannas by some authorities) give way to broad-leafed savanna woodlands (also called moist/dystrophic/nutrient-poor savannas) along a line extending NW–SE through Botswana. This corresponds to the division by White (1983) between the Highveld–Kalahari Transition Zone and the Zambezian Domain.

Several authors working in the area that is more arid than about 500 mm yr^{-1} make a distinction between the vegetation on the red sands (typically dune-fields) vs. whitish calcareous sands. The sands in the more mesic areas of the Kalahari are also light colored, but seldom calcareous. Although the sands are deep and relatively homogeneous, there is evidence that the particle size distribution in the sand fraction (which makes up in excess of 96% of the soil mass) has some regional variation (Moore & Attwell, 1999). This variation may be related to the distance from the surface to the underlying hard geology, and is reflected in patterns of woody plant composition at the local scale.

Rocky exposures of the underlying bedrock are rare within the main body of the sand sheet. Calcrete ridges are sometimes exposed in the south. These 'hard' geologies typically support woodier vegetation than their sandier surrounds.

Locally, there are regularities in less widespread vegetation types (Scholes *et al*., 2002). The pans and dry river valleys (fossil drainage from Pleistocene times) are prominent in the south and center of the Kalahari and have clay-rich soils. The drainage lines are typically grassy with clumps of trees. The pans often show concentric bands of vegetation that are associated with different flooding and soil environments. Saline areas (such as the vast Makgadigadi Pan) either support halophytic shrubs and grasses or are bare. Nonsaline pans support sedge and grasslands, sometimes with tree-clumps on slightly more elevated ground, for example at Nxai Pan. The banks of perennial rivers (the Okavango, Kwando, Linyanti/Chobe, and Zambezi) and seasonal rivers (such as the Botletele) have fringing forests a few meters wide. Permanent swamps, such as the Okavango Delta, support *Papyrus* in the shallower water, and floating macrophyte communities in the deeper water. Broad seasonally flooded grasslands and sedgelands known as dambos are common in the north (Scholes *et al*., 2002).

Climate of the KT

The Kalahari sands region is arid to semi-arid in the south with a continuous gradient of increasing annual rainfall to the north (Chipanshi and Ringrose, 2001 and

others). Annual rainfall amounts are highly variable both seasonally and annually (Mwangala & Mukelabai, 2000). The mean annual rainfall varies from 1000 mm in the north to a minimum of less than 200 mm in the extreme southwest (Zambia Meteorological Department, 1969; Bhalotra, 1987). Rainfall amounts decrease from the east to west and north to south (Fig. 1). The rainy season typically starts in October and ends in April of the following year over the entire region. The rest of the year (May–August) is dry with little or no rainfall. Sporadic rainfall may occur during the austral winter months but it contributes very little to the annual rainfall. The long-term mean rainfall during these months is less than 10 mm over the region.

General circulation patterns

The subcontinent of subequatorial Africa tapers to the south as it extends into the southern Ocean and the subcontinent's weather is influenced by maritime air from both the Atlantic and Indian Oceans. The northbound, cold Benguela Current flows off the west coast. In the east and southeast are the much warmer waters of the Mozambique and Algulhas Currents flowing southward and eastward from the Indian Ocean.

During both summer and winter seasons, the subtropical high-pressure belt of the southern hemisphere dominates the general atmospheric circulation of the region (Tyson & Crimp, 2000). The wind flow at upper levels during both seasons is dominated by anticyclonic flow throughout southern Africa, which causes large-scale subsidence in the upper atmosphere. The result is the characteristic arid to semi-arid nature of the climate in this area. The anticyclonic belt does not, however, extend vertically into the upper atmosphere. Southern African weather is largely under the influence of the Southern Hemisphere westerly circulation. On the surface, this is manifested by a succession of cyclones and anticyclones moving around the coast (Shulze, 1972).

During the austral winter, the weather is characterized by clear and cold conditions that, to a large extent, are the result of a seasonally strong continental high-pressure cell over Botswana. The main surface synoptic features affecting Botswana during this period are a series of cold fronts associated with westerly depressions in the South Atlantic Ocean. During the summer, the weather is characterized by wet and warm conditions. A number of factors affect the weather during the rainy season including the movements of the zaire air boundary (ZAB), the inter-tropical convergence zone (ITCZ), and midlatitude disturbances traveling with the prevailing westerlies (Schulze, 1972; Tyson, 1986). Tropical cyclones and El Niño-Southern Oscillation (ENSO) are also important factors affecting rainfall in the region.

Tropical cyclones

Tropical storms that affect southern Africa normally form in the southwest Indian Ocean during the austral summer months of December–April, with a peak season between January and March. An average of four cyclones occurs in this region every year, although this varies widely from year to year. Once formed, the storms move southwestward into the Mozambique Channel or curve off the coast of Madagascar and move southeastward to dissipate in the cool waters of the south Indian Ocean.

Tropical storms that move into the Mozambique Channel have a marked influence on rainfall over the subcontinent. Indeed, the occurrence of storms in the channel in April leads to a cessation of rainfall activities as a result of the southeast air currents diverting to nourish the depression. Under these circumstances, precipitation that might otherwise come to eastern Botswana and neighboring states fails to reach land.

Tropical cyclones have on occasion crossed Mozambique and traveled west into the continent. Their lifespan varies with the humidity of the air, the moistness of the underlying surface, and the relief. Some penetrate thousand of kilometers before dissipating. Once overland, the power of the cyclone decreases, but the convergence nonetheless often causes heavy rains across wide areas. Examples include cyclones Emilie of February, 1977, and the more recent Eline of February, 2000, when extraordinary rainfall totals were recorded throughout southern Africa.

El Niño-Southern Oscillation

In recent years, much of the rainfall variability in southern Africa has been attributed to the ENSO (Nicholson & Kim, 1997; Nicholson *et al.*, 2001). The warm episode, in particular, has been interpreted as heralding drought conditions throughout the subcontinent (Ropelewki & Halpert, 1987, 1989). Although most ENSO events are linked to drought over southern Africa, not all anomalies in ENSO years can be attributed to El Niño. Ogallo (1994) has shown that 50% of the interannual variance in eastern and southern Africa precipitation can be linked to ENSO. Moreover, Bhalotra (1987) showed that of 16 ENSO years, only 12 coincided with deficient rainfall in Botswana. However, many of the more extreme anomalies of severe droughts in southern Africa have strong teleconnections to the ENSO events. The severe events of 1983/1984, 1991/1992 and 1998/1999 have all been linked to ENSO (Reason & Rouault 2002).

Rainfall changes over time

Although it is generally believed that climate throughout southern Africa is in the midst of a 'dry period',

other research suggests that current trends are well within the range of accepted historical variation (Nicholson, 2000). Recent droughts in the 1980s were the worst of the century (Nicholson, 1993), but such droughts are an inherent part of the long-term climatic history of Africa (and have occurred previously). Tyson *et al*. (1975) suggest a fluctuation in summer rainfall with a period of 16–20 years which has been confirmed in studies in Botswana (Lesolle & Gopolang, 1997). Whereas others have suggested different periodicities, there is consensus that for available meteorological records in southern Africa, regional rainfall has shown a remarkable degree of organization in both space and time.

The 1999/2000-rainfall situation

The 1999/2000-rainfall season (during which the SAFARI 2000 Kalahari Transect Wet Season field campaign was conducted) was characterized in a general sense by a late start of very heavy rains. The onset of normal to above-normal rains started across the region during the month of December and extended into January. February saw the development of cyclones Damaine and Eline. The latter cyclone brought torrential rains and severe flooding to Botswana while a tropical depression associated with Damaine ushered in heavy rains early in the month. Figure 1 shows the total rainfall received on a month-by-month basis at six stations along the KT and a comparison with the long-term mean is also depicted. The heavy rainfall for January and February are apparent. October is a transition month marking the end of the dry season and the beginning of the rainy season. The first 20 days of the month in 1999 were generally characterized by dry conditions while the continental gyre that dominates the weather in winter was still present. Uncharacteristically, Mongu received rainfall in the first week of October. Sesheke, to the south of Mongu, did not receive rain until the last 10 days of October. Then, the pattern changed dramatically when a westerly trough off the southwestern coast of the subcontinent (in concert with a surface trough over the western parts of the country) induced substantial rain over the southwestern parts of the country. Thus, the Kgalagadi district of Botswana received the highest amounts of rainfall for the season during October, with Werda recording a total of 59 mm.

Dry conditions prevailed in most other parts of the region during October, and continued into the first 20 days of November. During the last 10 days of November, a surface trough controlled the weather over most areas and a series of lows developed to the south and southeast of the region in the afternoons. A highly unstable moist tropical air mass was drawn into the country. The vertical uplift induced by the westerly trough and the easterly wave over the subcontinent ensured that widespread rains covered Botswana. This marked the start of the rains in the east and central parts of the country. By the end of November, rainfall in western Zambia was significantly below normal and somewhat less so in northern Botswana.

The month of December 1999 saw the proximity of the ITCZ move to the northern parts of the subcontinent. Furthermore, midlevel dynamics were dominated by the oscillating easterly wave, which further increased precipitation over the region and resulted in widespread rains that were heavy in places. Monthly total in excess of 200 mm were recorded in Gaborone (267 mm), Gabane (228.6 mm) and Zwenshambe (300.8 mm). However, heavy rains were not uniform across the region in December, as a number of stations recorded below normal monthly totals.

The beginning of the second half of the 1999/2000-rainfall season (January–March 2000) saw a middle level (500hPa) anticyclone centered over the Mozambique Channel during January 2000. This confined the westerly cloud bands over Botswana, giving rise to enhanced rains over most parts of the country. The ITCZ, which was anchored over Angola and the Democratic Republic of Congo (DRC) in the early days of January, started drifting southward during the second week of the month, further inducing appreciable amounts of rains over the region, especially to the north.

February was marked by the dominance of an interior surface low that was rooted in the monsoon trough. A tropical depression that had developed in the Mozambique Channel in the early days of the month migrated into Mozambique and drifted swiftly inland. It covered the eastern and central parts of Botswana around February 7, and resulted in flash floods over these areas during that time. Also, this initiated a period of daily rainfall in Mongu and Sesheke that persisted until March with the exception of one dry spell at Mongu (February 26–28) and two at Sesheke (February 26–28 and March 4–5).

The month of March saw the ITCZ (which had been kept in its southernmost position for much longer than usual by the tropical cyclones over the Indian Ocean) starting to shift northward, thereby reducing the convective activity over most parts of southern Africa. Rainfall ended abruptly at the end of March at Sesheke while light isolated showers continued at Mongu into May. The 1999–2000 wet season over the KT during SAFARI 2000 KT Wet Season campaign as a whole was unusually wet, inviting the possibility of a second comparative campaign which would very likely be under dryer conditions.

Concluding comments

The KT has a sharp precipitation gradient for a climatically similar region with a widely distributed, physically uniform soil and relatively little variation in elevation. The S2K-KT Wet Season campaign illustrates the value of intensive observational campaigns along megatransects coordinated with longer term, lower intensity, ground-based and remote sensing studies. The design of the S2K-KT Wet Season campaign was to collect observations about the biophysical functioning of the KT system as it varies with landcover type across the strong precipitation gradient. This coordinated study of the biophysical performance of the vegetation along this transect illustrates the potential of transect to test global and regional scale vegetation models, to calibrate satellite sensors intended to monitor global change and to coordinate field studies in time and space. When utilized by regional and global ecological modelers, the results of this special volume present the potential of an approach that allows for the analysis of the impacts of global change at the regional scale

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