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Botswana water and surface
energy balance research program
Part 1 : Integrated approach and
field campaign results

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BELEIDSCOMMISSIE REMOTE SENSING

**Botswana water and surface energy balance
research program
Part 1 : Integrated approach and field campaign
results**

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1. INTRODUCTION

The "Botswana Water and Surface Energy Balance Research Programme" is a cooperative activity of the Faculty of Earth Sciences of the Vrije Universiteit of Amsterdam (NL), the Hydrological Sciences Branch of NASA/Goddard Space Flight Center in Greenbelt, Maryland (USA) and the Meteorological Services of Botswana. Other participants are the Agricultural University of Wageningen (NL), Queen Mary College of the University of London, and the Remote Sensing Unit of Food and Agriculture Organization (FAO) of the United Nations in Rome. The programme is developed to study and evaluate the integrated use of multi-spectral satellite remote sensing for monitoring the hydrological status of the earth's surface. The overall programme-coordinator is Adriaan A. van de Griend of the Vrije Universiteit, whereas Manfred Owe is responsible for the NASA participation.

This report summarizes the results of the first part of the programme (BOTSWANA-1) which ran officially from 1 January 1988 till 31 December 1990, and of which the Dutch contribution was funded by the Netherlands Remote Sensing Board (BCRS). BOTSWANA-1 consisted of two major, mutually related components, i.e.:

1. A Surface Energy Balance Modelling Component, built around a extensive field campaign, and
2. A Passive Microwave Research Component, which consisted of a retrospective study of large scale soil moisture conditions and Nimbus/SMMR 6.6 GHz and 37 GHz microwave signatures.

This report describes the integrated approach of both components in general and further summarizes the activities performed within the Surface Energy Balance Modelling Component, including the extensive field campaign. The results of the Passive Microwave Research Component are summarized in this report and described in more detail in a separate BCRS-report (Van de Griend and Owe, 1992c).

The terms of the water balance in semi-arid regions can be monitored using different types of remotely sensed information from satellites. Such an integrated approach focuses on the possibilities of monitoring the soil moisture status and evapotranspiration over time from the combination of (a) thermal infrared, (b) visible and near infrared (NIR), and (c) passive microwave remote sensing.

This approach is expected to give better insight into the spatial and temporal variability of soil moisture content and evapotranspiration at different scales, and therefore may contribute to the development of a multiscale monitoring system of the physical status of the earth's surface.

The surface energy balance, which may be modeled using thermal infrared surface temperature observations and large-scale, near-surface synoptic meteorological data, allows the

evaporation to be estimated and the soil moisture status to be inferred together with the water status of the vegetation. This requires a remotely sensed estimate of the vegetation cover and green leaf biomass which may be derived from visible and NIR signatures. Separately, the moisture status of the surface may be derived from passive microwave signatures. This requires an estimate of the green leaf biomass or the vegetation water content in order to determine and model the influence of the vegetation on the microwave signal gathered from space.

2. PURPOSE AND SCOPE

The aim of the project is to study and evaluate the simultaneous use of different satellite remotely sensed signatures (thermal infrared, visible and near-infrared [NIR], and passive microwave) for monitoring the course of soil moisture, primary production of green leaf biomass and various water balance components for semi-arid regions in Botswana, Africa. The research program further aims at the practical application of satellite remote sensing for near real-time monitoring of the physical and hydrological status of the earth's surface, thus providing a basis for regional and large-scale agricultural management, such as sowing date recommendations, early warnings of crop failure, and possible food shortages. The capability of repetitive monitoring of the earth in terms of sensible heat exchange, vegetation conditions and soil moisture availability for latent heat exchange also is expected to play an increasingly important role with respect to Climate Modelling and the internationally recognized issue of Global Change.

The study focuses on the adaptation of hydrometeorologically driven surface energy balance models along with microwave emission and thermal emissivity models for pixel-scale parameterization and subsequent calibration using the remotely sensed signatures. Additionally, the study works toward the development of methodologies for the regionalization of point-scale ground observations for pixel-scale model calibration.

The project goals also fall within the primary objectives of the International Satellite Land Surface Climatology Project (ISLSCP). Savannas are a logical extension to the vegetation continuum that started with the field studies in the Konza Prairie under FIFE, the First ISLSCP Field Experiment (Sellers and Hall, 1987).

2.1 Problem Definition

One of the major problems in water resources management in semi-arid regions is the lack of fundamental knowledge of the spatial variability and temporal dynamics of surface hydrological parameters (such as soil moisture), and key related terms of the water and energy balance such as evapotranspiration and radiative surface temperatures. With remotely sensed data from space becoming regularly available in the nineties and two-thousands (EOS/Columbus, 1991), monitoring of the status of the surface becomes possible in several ways, using different

types of information. However, an integrated approach, which uses the different types of remotely sensed signatures together, undoubtedly has advantages over separate applications of each data type. This integrated approach is being applied to the semi-arid savanna regions of Botswana and emphasis has been placed on the following items:

- (a) estimation of evapotranspiration and soil moisture content by surface energy balance modeling, using thermal infrared signatures and additional estimates of the vegetation characteristics such as leaf area index (LAI);
- (b) estimation of soil moisture content in areas mainly covered with low natural savanna vegetation and intermixed with agricultural fields, using passive microwave signatures; and
- (c) estimation of the vegetation characteristics (such as green leaf biomass, water content and LAI), using visible and NIR signatures.

These research items are mutually complementary in the sense that (b) gives important information to perform both (a) and (c), while (c) gives additional information to perform (a) by reducing the number of degrees of freedom.

Although the basic theory of the physical processes leading to remotely sensed signatures is fairly well understood, application of the above items is not straightforward. Both energy balance and microwave models have been tested and calibrated predominantly using point or local ground observations, assuming spatially homogeneous conditions. Although such models have been applied to pixel-scale signatures (Raffy and Becker, 1986; Owe et al., 1988), little was known about the influence of spatial (within pixel) variability of surface characteristics on model performance and its consequences for the inverse problem (Raffy and Becker, 1985).

Therefore, application of remotely sensed signatures to infer pixel scale information requires fundamental solutions to the problem of pixel scale parameterization and model calibration. In summary, the study aimed at addressing the following points of scientific interest:

1. The influence of heterogeneity of surface-physical conditions on the signal gathered by satellite;
2. The parameterization of physical properties at pixel scale, i.e. $1 \times 1 \text{ km}^2$ for NOAA/AVHRR and $5 \times 5 \text{ km}^2$ for METEOSAT;
3. The influence of heterogeneities of surface physical properties on the performance of mass- and energy balance models; and
4. The implications of these questions for the inverse problem, i.e. the extraction of information about the surface physical status at pixel scale from remotely sensed information.

These questions need to be studied in order to create a sound basis for the development of methodologies for water and energy balance studies from space. The goals of this effort therefore can be summarized as:

1. Development of a methodology to describe the spatial variability of surface characteristics within various-sized resolution cells;
2. Development of a methodology for "model oriented" regionalization of local-scale (point) ground data for pixel-scale calibration;
- 3) Development of a methodology for the discrimination of physiographically significant uniform landscape units, for subsequent selection of (if required) reference areas for the collection of representative ground data and as a basis for regional-scale application of remote sensing models; and finally,
- 4) Development and parameterization of hydrometeorological and/or hydrologically driven surface energy balance models and microwave emission models for pixel-scale interpretation of remotely sensed signatures.

2.2 Integrated Use of Remotely Sensed Signatures

The application of both microwave and thermal infrared methods requires some information on the vegetation and its structure. For passive microwave emission this is needed primarily to model or estimate the transfer of the signal through the canopy, whereas for thermal infrared it forms an integral part of the process of momentum, heat and moisture exchange within the earth-atmosphere interface. This explains the necessity to integrate vegetation information derived from visible and near-infrared data with both microwave and thermal-infrared remote sensing.

The combination of microwave and thermal infrared remote sensing also offers certain advantages. Although thermal infrared remote sensing can be used to determine both evapotranspiration and the thermal inertia of the surface soil, the sensitivity of the surface temperatures to variations in soil moisture content decreases with increasing LAI (Van de Griend and Van Boxel, 1989). Therefore, an independent estimate of the surface soil moisture reduces the number of unknown parameters in the surface energy balance model and may therefore contribute to the accuracy of the estimation of evapotranspiration. The basic structure of this integrated use of the different signals is shown in Fig. 1.

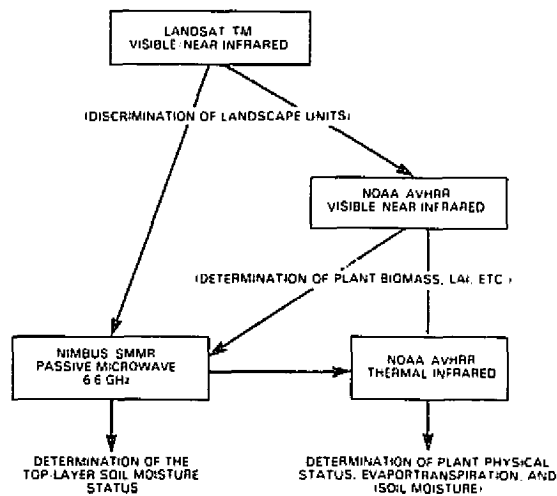


Fig. 1 Schematic representation of the integrated use of different types of remotely sensed signatures for monitoring the physical-hydrological status of the surface in (semi-) arid regions.

2.3 Application to Botswana

The approach described above is being applied to Botswana using data from Landsat/Thematic Mapper (TM), satellite for earth observation (satellite pour l'observation de la terre [SPOT]), NOAA/AVHRR (Advanced Very High Resolution Radiometer), and Nimbus-7/SMMR (Scanning Multichannel Microwave Radiometer). An overview of specifications with respect to spatial and temporal resolutions, applications, and restrictions is given in Table 1.

3. PASSIVE MICROWAVES AND SOIL MOISTURE

The "Passive Microwave Research Component" has been completed and described in a second BCRS-report (Van de Griend and Owe, 1992c). In summary, the microwave study is based on long term and large scale soil moisture observations over the period 1984 till the end of 1987, i.e. until the scanning system of Nimbus-7/SMMR broke down. Large scale soil moisture was estimated using a series of large test areas, where long-term intensive soil moisture sampling takes place. These test areas are approximately 120 km apart, whereas in each area an intensive soil moisture monitoring program has been in progress since 1984, where soil moisture is measured every 10 days by neutron probe. Each test site consists of about 60 access tubes in an area of approximately 12 km long and 0.1 km wide. This soil moisture monitoring program formed the basis for the retrospective analyses which were conducted to evaluate the direct measurement of surface moisture with Nimbus/SMMR and NOAA/AVHRR data. The retrospective study formed the basis for a synergetic inverse modelling approach to infer the soil moisture status from satellite signatures, using the horizontally polarized 6.6 GHz passive microwaves to infer the soil emissivity, and the red and near-infrared bands of NOAA/AVHRR to estimate the vegetation optical depth at 6.6 GHz. The single scattering albedo of the vegetation determines the contribution of the vegetation to the satellite observed microwave signatures. The single scattering albedo could be determined on a theoretical basis from both horizontally (H) and vertically (V) polarized signatures and observed large scale soil moisture. It was found that the single scattering albedos at 6.6 GHz and 37 GHz were very similar and compared extremely well with values determined from laboratory and field experiments.

The Surface Energy Balance Research Component will be described next.

4. SURFACE ENERGY BALANCE RESEARCH COMPONENT

The energy balance modelling approach integrates the visible, near-infrared and thermal infrared signals collected by NOAA/AVHRR (Fig. 1). In addition, Meteorological Satellite

Table 1 Overview of satellites and their specifications used in the integrated approach for monitoring the physical-hydrological status of the surface in semi-arid regions.

Satellite		Sensor Specifications					
Name	Orbit Altitude	Radiometer	Spectral Domain	Wavelength/Frequency	Spatial Resolution	Temporal Resolution	Cloud Penetrating Yes No
Landsat	Polar 918 km	Thematic Mapper (TM)	Visible	0.4–0.8 μm	30 m	18 Days	•
			Near Infrared	0.3–3.0 μm	30 m	18 Days	•
Spot	Polar		Visible	0.49–0.59 μm	20 m	5 Days	•
				0.61–0.71 μm	10 m		•
NOAA	Polar 835 km	Advanced Very High Resolution Radiometer (AVHRR)	Visible/Near Infrared	0.50–0.68 μm	1 km (LAC)/ 4 km (GAC)	12 Hrs	•
				0.73–1.1 μm		12 Hrs	•
			Thermal Infrared	3.55–393 μm	1 km (LAC)	12 Hrs	•
				10.5–11.5 μm	4 km (GAC)	12 Hrs	•
			11.5–12.5 μm		12 Hrs	•	
Nimbus	Polar 1100 km	Scanning Multi-Channel Microwave Radiometer (SMMR)	Microwave	37 GHz	20 km	1 Day	•
				21 GHz			•
				18 GHz	↓	•	
				10.7 GHz		•	
				6.6 GHz	156 km	•	
Meteosat	Geostationary 36,000 km	Vapor Absorption	Visible	0.4–1.1 μm	5 km (NADIR)	30 Minutes	•
		Thermal	Thermal IR	10.5–12.5 μm			•
Name	Allows Physically Based Modelling of the Earth's Physical Status		Applications				
	Yes	No					
Landsat		•	Classification of physiographically different landscape units (1) for selection of control areas for ground truth collection and (2) as a basis for regional scale application of remote sensing models				
NOAA		•	Monitoring of biomass production, leaf area index (LAI), Greenmass etc.				
		•	Thermal infrared modelling of surface energy balance processes to infer information on soil moisture status and heat fluxes				
Nimbus		•	Determination of soil moisture content in the topsoil by direct correlation and calibration or using radiative transfer models				
Spot		•	Classification of Physiographically different landscape units (1) for selection of control areas for ground truth collection and (2) as a basis for regional scale application of remote sensing models				
Meteosat		•	Thermal infrared modelling of surface energy balance processes to infer information on soil moisture status and heat fluxes				

(METEOSAT) data have been collected to determine the daily course of the surface temperature and to study the spatial and temporal variability of the surface temperature at different scales. In support of this research component, an intensive field campaign was held during the period January-March 1989 in south-eastern Botswana, Africa. This report further describes the field campaign and the results achieved so far with respect to the Surface Energy Balance Research Component.

4.1 Climate and Site Characteristics

Botswana is characterized as semi-arid with hot, relatively moist summers, and cool, extremely dry winters. The mean daily air temperature during the summer and winter is approximately 25 °C and 17 °C respectively. Mean annual precipitation is highly variable throughout the country and ranges from a high of almost 700 mm in the extreme north to a low of about 150 mm in the southwest. The variability of annual, seasonal, and single events is high, both spatially and temporally. Precipitation events are generally intense showers of short duration. High runoff rates in the hardveld region and high potential evapotranspiration rates (1500-2000 mm/yr) reduce the recharge effectiveness of the precipitation dramatically.

The southeastern edge of the region has some low hills close to the South African border, and while some of the area may be slightly undulating in places, it is for the most part relatively flat. Most of the region may be classified as tree and shrub/grass savanna, and is often interspersed with cultivated fields in many areas. In some areas, the existing cover is nothing more than sparse grasses, while much is also bare. Relatively dense woodland may be found on some of the better soils along drainages, where trees may average 6-10 meters in height, and will occasionally attain heights of 12 meters or more. Much of the area is used as open range. Vegetation density tends to decrease from SE to N and W, in response to precipitation gradients. Excellent descriptions of the vegetation, topography and land use character of the region are given by Ringrose and Matheson (1987) and Ringrose et al., (1990a; 1990b).

4.2 The Intensive Field Campaign

Acquisition of adequate ground data (e.g., biomass and vegetation structure, soil moisture, soil physical parameters, meteorological and atmospheric data) is a necessity for the described approach. In order to collect such data an international field campaign was performed during the beginning of 1989.

The intensive field campaign was held from 10 January-10 March 1989, at the Mmamashia experimental area near the international airport of Gaborone (Fig. 2). The experimental area consists of hardveld bush/tree-savanna intermixed with agricultural fields. The mean daily air temperature during the field campaign averaged about 28°C. The average daily maxima and minima were approximately 35°C and 20°C, respectively. Above-average precipitation was

SOUTHERN AFRICA

TEST SITE LOCATION

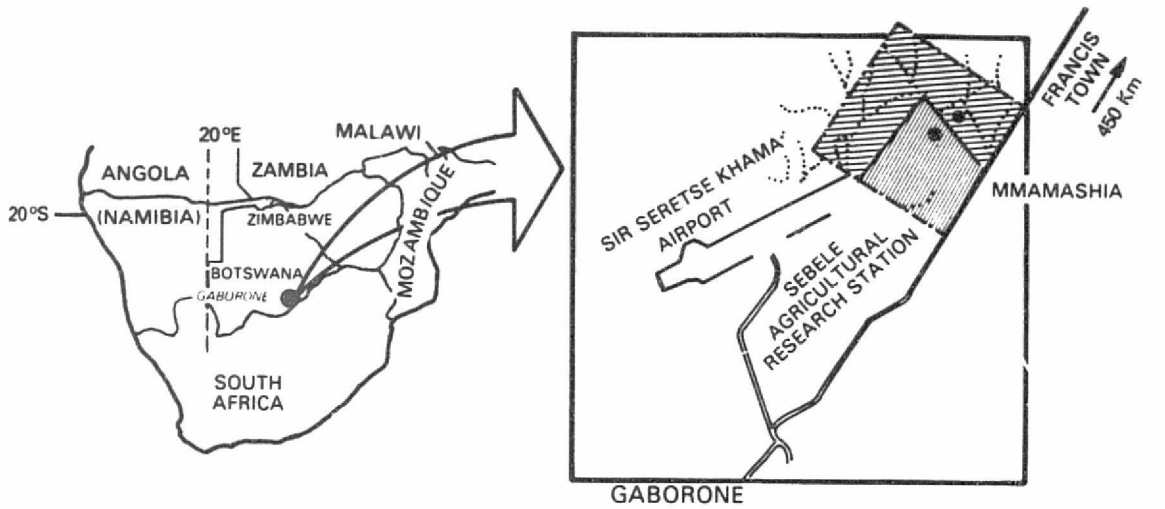


Fig. 2 Map depicting the relative location of the intensive study area.

DISTRIBUTION OF INSTRUMENTS

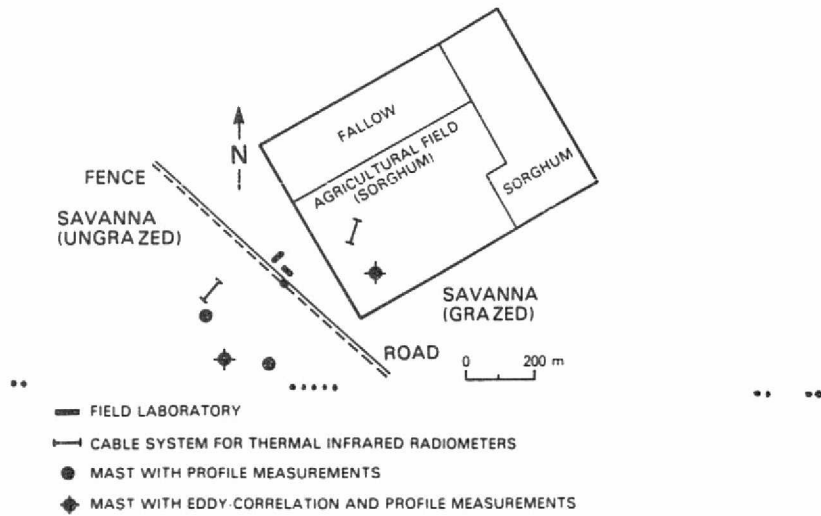


Fig. 3 Map depicting the relative locations of the instruments within the intensive study site.

recorded during the period occurring both as late afternoon thunderstorms as well as from more regional frontal weather systems. Although mornings were usually clear, cloud cover would generally increase by varying degrees throughout the day. This often created problems in scheduling aircraft flights to coincide with the midday NOAA satellite overpass.

During the field campaign all ground data (anticipated to be necessary) has been collected to calibrate surface energy balance models for different surface cover conditions and to incorporate the problems associated with the vegetation. The measurements were performed simultaneously in an agricultural field (sorghum) and in a representative area within the bush/tree-savanna (Fig. 3). The data collection effort was comprised of the activities listed below.

a. Micrometeorological data (Fig. 4)

1) Flux measurements of sensible and latent heat by the eddy correlation method using sonic anemometers and Lyman-alpha hygrometers. The same fluxes were also obtained by the profile method. At the agricultural site, windspeed was measured by cup anemometer at heights of 0.5, 1.5, 2.5, 4.0, 6.0, 8.0, 10.0, and 12.0 m. Dry and wet bulb temperatures were measured by means of aspirated psychrometers at heights of 0.5, 1.5, 4.0, 8.0, and 12.0 m. In the savanna area, three towers were erected. Windspeed was measured at 2.0, 4.0, 5.0, 6.0, 7.5, 9.0, 10.5, and 12.0 m levels, while dry and wet bulb temperatures were measured at 2.0, 4.0, 6.0, 9.0, and 12.0 m levels.

2) CO₂ profiles were measured alternately at the savanna and the agricultural site at six levels.

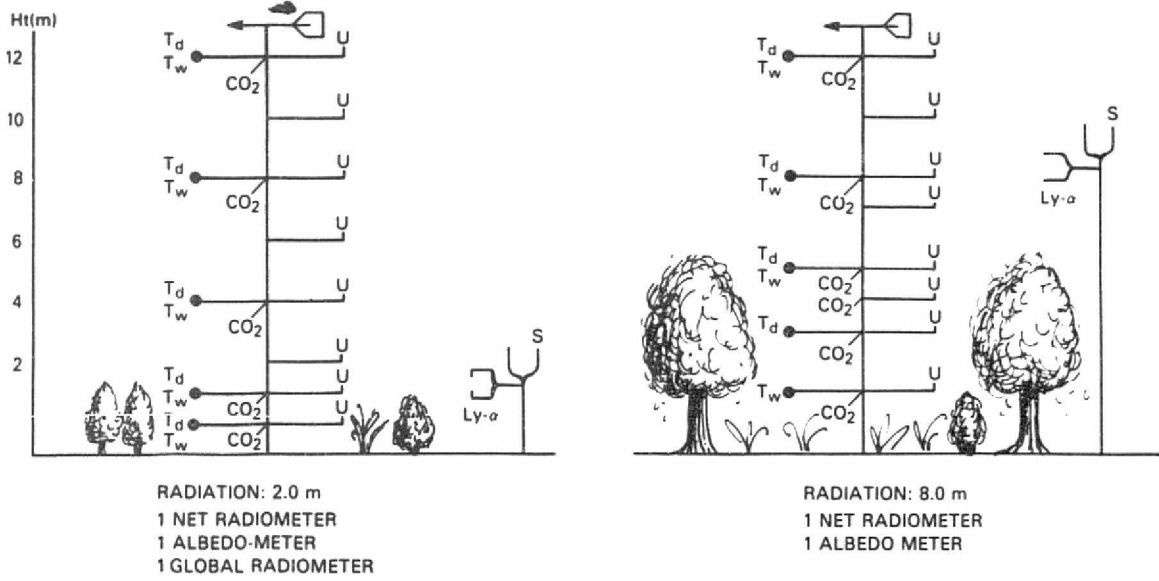
3) Global and net radiation measurements were carried out at both study sites together with albedo measurements. The dataset contains half-hourly averages of fluxes, profiles, and radiation measurements.

b. Surface temperatures

Surface temperatures were measured continuously by thermal-infrared radiometers from a 6 m height, along two 30 m cable systems, one in the savanna and one in the agricultural field (Fig. 5). Each cable system contained two radiometers with 4° and 15° fields of view (FOV). Surface temperature was also measured with the same instrument (15° FOV) mounted on a light aircraft. During six NOAA pass-overs, a 5 x 5 km² area was covered by 20 flight lines 250 m apart, also covering the thermal-infrared cable systems.

AGRICULTURAL FIELD

SAVANNA



T_d - DRY BULB TEMP
 T_w - WET BULB TEMP.

U - CUP ANEMOMETER
 CO_2 - CARBON DIOXIDE MEASUREMENT

Ly- α - LYMAN ALPHA
 S - SONIC ANEMOMETER

Fig. 4 Basic setup of meteorological instruments.

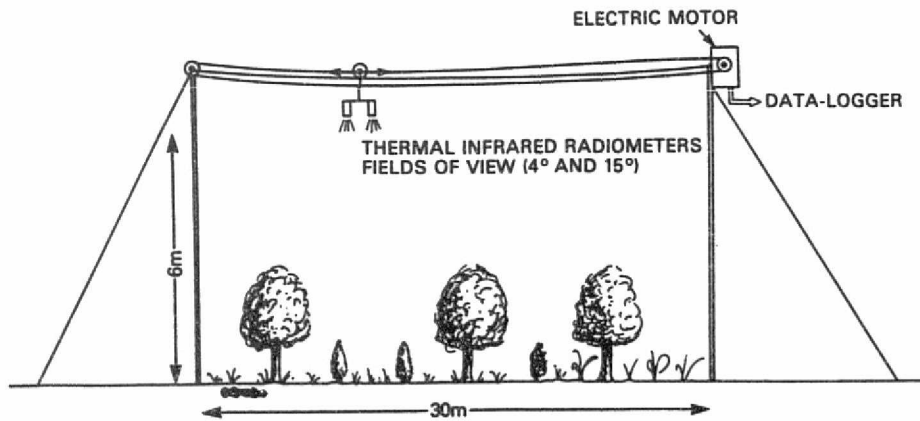


Fig. 5 Thermal infrared cable system for measuring radiative surface temperatures.

c. Soil temperatures

Soil temperatures were measured at eight vertical profiles (five depths) under the thermal-infrared cable systems (Fig. 6).

d. Soil moisture

Soil moisture was measured in three ways: volumetrically, by neutron probe, and by using gypsum blocks. About 60 neutron access tubes were spread over the experimental site and along the thermal-infrared cable systems and measured weekly. Ten-cm surface moisture was measured volumetrically twice weekly at all neutron tube locations and daily along the cable systems. The gypsum blocks were installed in four vertical profiles (five depths) along the cable systems and monitored every 15 minutes (Fig. 6).

e. Vegetation (LAI and biomass)

The intensive study site at Mmamashia was classified into "homogeneous" vegetation units using 1:50 000 panchromatic stereo aerial photographs, and field observations. Typical samples of the major units were described quantitatively in a vertical sequence of horizontal strata consisting of herbs, shrubs, and smaller and larger trees. Grass samples and individual shrubs and trees were harvested to determine leaf dry weight. Leaf area was measured in subsamples and used to calculate the relationship between leaf area and dry weight. From these observations, LAI was calculated for each vertical stratum of the vegetation units. The vertical and horizontal distribution of LAI and green leaf biomass was derived for the 5 x 5 km² study site from these data (Naber, 1991b).

f. Satellite data

During the field campaign the following satellite data were gathered:

- 1) NOAA/AVHRR (LAC-data): at 0220 and 1420 LTC (NOAA-11) and at 0720 and 1920 LTC (NOAA-10);
- 2) METEOSAT: every hour;
- 3) Landsat/TM: two images, at beginning and end of the field campaign; and
- 4) SPOT: two images, at beginning and end of field campaign.

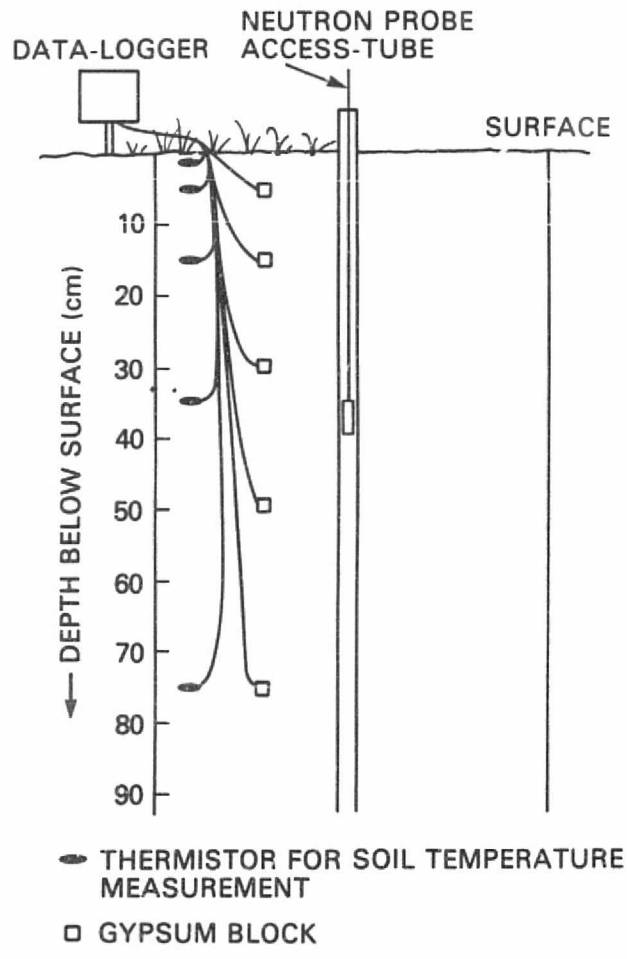


Fig. 6 Field instrumentation of thermistors, gypsum blocks, and neutron-probe access tubes for soil moisture studies.

g. Aircraft data

The reflection in the red and NIR bands was measured by an aircraft-mounted radiometer system. These measurements were made by an updated version of the Integrated Camera and Radiometer system (ICAR) described by Prince (1987). The ICAR consists of a computer operated optical camera and a red and NIR radiometer having exactly the same footprint as the camera. In addition, a thermal-infrared radiometer of the same type as used on the cable system was mounted on the ICAR, having a fixed footprint within the footprint of the optical camera. The radiometer system was mounted on a Cessna-206 aircraft.

The 5 x 5 km² intensive study area was traversed with twenty 5-km flight lines, spaced at intervals of 250 m. The photograph scale was 1:4300 on the film which could be projected to 1:400 with good resolution. Complete photographic coverage (1200 exposures) was obtained once, with a slight along-track overlap and 100 m between the lines. Individual FOV's were 100 x 150 m. Flights were made on five occasions to coincide with near-nadir NOAA-11 satellite overpasses. Complete radiometer and radiative surface temperature datasets were obtained on each flight.

h. Atmospheric soundings

Atmospheric soundings of air temperature and relative humidity were performed daily (in principle) from Gaborone International Airport, 7 km from the field site. Several days are missing, however, because of instrument malfunctioning or other reasons.

i. Stomatal resistance

The stomatal resistance was measured as an integral resistance for small samples of cover types different vegetation species.

j. Surface thermal emissivity

Surface thermal emissivity was measured frequently for different surface types (bare and vegetation covered) using a modified version of the emissivity box developed by Stoll and Becker (see e.g. Becker et al., 1986).

Surface	
1	bare soil (loamy sand)
2	sorghum, 10% coverage of bare soil
3	grass (partly covered)
4	dicotyledonous plants (Solanaceae), almost complete cover
5	grass, almost complete cover (Gramineae eragrostic)
6	open grass, partly covered (Gramineae eragrostic)
7	tall grass, complete cover (0.25 m high)
8	shrub, partly covered (Rygozum brevispinosum)
9	shrub, partly covered (Euclea undulata)
10	shrub complete cover (Euclea undulata)

Surface Type	Number of Measurements	Emissivity	
		Mean	Standard Deviation
1	10	0.914	0.011
2	10	0.940	0.006
3	12	0.956	0.013
4	3	0.985	0.005
5	3	0.958	0.006
6	3	0.949	0.008
7	3	0.958	0.003
8	5	0.952	0.009
9	5	0.976	0.008
10	5	0.986	0.006

Table 2 a) Description of surfaces for which the emissivity was measured by the Box Method;
b) Results of emissivity measurements for the different surfaces.

5. ITEMIZED ANALYSES OF DATA COLLECTED DURING THE FIELD CAMPAIGN

Due to some logistical delays (the first research associate left the project just after the field campaign) and the time spent to finish the "Passive Microwave Research Component" the "Energy Balance Modeling Component" could not be finished as anticipated. However, all of the raw data have been processed whereas several aspects have been studied of which some have already been described in the official literature. The follow-up project (BOTSWANA-2) is focused on the integration of the studied elements, and will address the scientific aspects described above. Itemized descriptions of research elements conducted within BOTSWANA-1 will be summarized below.

5.1 Measurement and Spatial Variability of Surface Thermal Emissivity

Knowledge of the surface thermal emissivity is necessary for the application of thermal infrared remote sensing, which forms the basis for water and surface energy balance monitoring from space. Thermal emissivity was measured for a series of representative surfaces within the bush-savanna environment, which was intermixed with cultivated fields (Table 2). The thermal infrared radiometers mounted on the cable system and those used in combination with the ICAR (mounted on the aircraft) measured in the wavelength band 8-14 μm (the only bandwidth commercially available). Emissivity therefore was measured for the same bandwidth.

The measurements were performed with an emissivity box, which was constructed at the workshop of the Faculty of Earth Sciences (Vrije Universiteit). The device is a modified version of the box described by Becker et al. (1986). The box was calibrated at the University of Strasbourg (Groupement Scientifique de Teledetection Spatiale) under supervision of Prof. Dr. M.Ph. Stoll.

The box turned out to be well-suited for bare soil, grass, and other types of soil and low-vegetation cover combinations. The measured emissivity varied between 0.914 for bare soil (loamy sand) and 0.986 for a surface completely covered with savanna shrub (Euclea undulata).

The emissivity calculations are based on the measurements of the radiative surface temperature of three different reflecting configurations of the box (Figs. 7 and 8). Repetitive estimates of the emissivity were found to be very reproducible for the same surface types and showed the large spatial variability of the surface emissivity within the study area (Table 2).

Background information on theory and the practical procedure can be found in Van de Griend et al., (1991). This paper describes the emissivity box together with other versions of the box concept found in the literature, and it describes the operation and calibration procedure as well as the results and consequences of the emissivity measurements for the application of thermal infrared remote sensing in the field and from space.

Fig. 7 Schematic representation of the emissivity box with sensor, blackbody heat source, top and bottom sliding plates, and interior reflecting surfaces.

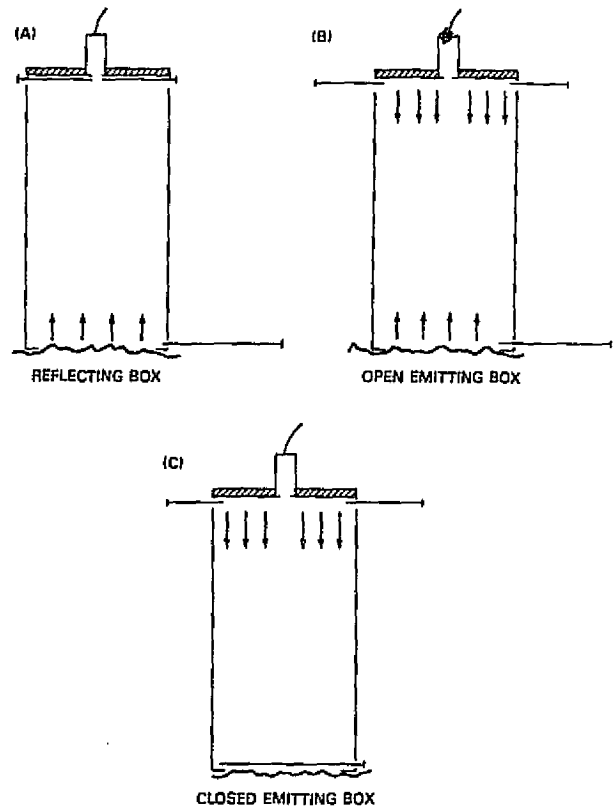
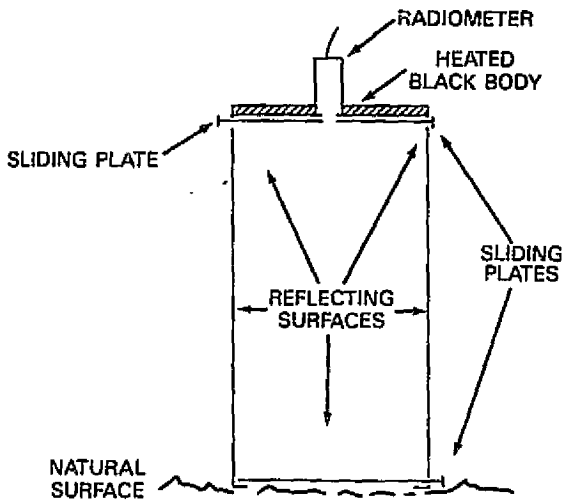


Fig. 8 (a) Reflecting box, configured with the top plates closed and the bottom open, exposing the surface to be measured. (b) The open emitting box, configured with both top and bottom plates in the open position. (c) The closed emitting box, with only the top plates open; it senses only the longwave radiation emitted from the blackbody.

5.2 The Normalized Difference Vegetation Index (NDVI) and Surface Thermal Emissivity

Spectral reflectance measurements in the red (0.58 - 0.68 μm) and near-infrared (0.73 - 1.1 μm) portions of the spectrum were made at the same spots where also emissivity measurements were performed. These measurements were made with a combined red and near-infrared radiometer, developed at the NASA/Goddard Space Flight Center. The bands correspond with the red and near-infrared bands of the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA satellites. The measured reflected NIR and red radiation levels were converted to reflectances using reference plates with known spectral reflectance characteristics. These values were used to derive the Normalized Difference Vegetation Index, defined as: $\text{NDVI} = (\rho_{\text{NIR}} - \rho_{\text{R}}) / (\rho_{\text{NIR}} + \rho_{\text{R}})$, where ρ_{NIR} and ρ_{R} are the reflectances in the near-infrared and red bands respectively.

The results of the measurements are presented in Table 3 in terms of the means and standard deviations of the replications for each surface type. It is shown that the standard deviations of both the emissivity measurements and the computed NDVI are quite small (in most cases less than 1%) for the individual surfaces, which indicates the high reproducibility of the measurements.

In Fig. 9, the mean emissivities are plotted against the mean values of NDVI for the different surface types. The relationship is best defined as logarithmic, and is of the form

$$\epsilon = a + b \cdot \ln(\text{NDVI})$$

giving a correlation coefficient of 0.941 ($R^2 = 0.886$), with $a = 1.0094$ and $b = 0.047$, at a 0.99 level of significance. This relationship might be of potential use for thermal infrared remote sensing because NDVI can be derived easily from spectral radiometer measurements which are on board many of the operational meteorological satellites. The measurement of emissivity in the field can only be done for small plots (say several square meters at most) and the estimation of the "effective" emissivity, therefore, forms a serious problem. The application of the relationship found, however, not only requires the definition of "effective emissivity" but also an "effective pixel-average NDVI". The meaning of pixel average entities, based on multiple measurements, however, depends on the within-pixel variability of the individual signatures and should be defined in terms of the heterogeneity as described by Becker et al. (1981) for temperature and emissivity.

A practical application for this relationship is to extend it to satellite data. Reflectances measured by satellite are integrated over an entire resolution cell, and hence are more areally representative of the corresponding surface than the average of a series of point measurements made on the ground. In a preliminary analysis we assumed the relationship between ϵ and NDVI to be scale-independent and derived thermal emissivity accordingly, using NDVI data from three different types of satellite imagery; Landsat/TM, AVHRR Local Area Coverage (LAC), and an AVHRR 10-day Global Area Coverage (GAC) composite. The GAC data were processed

Table 3 Results of NDVI and emissivity measurements performed for the different surfaces.

Surface Type	Number of Emissivity Measurements	Emissivity		NDVI (*)	
		Mean	σ	Mean	σ
1. Bare Soil (loamy sand)	10	0.914	0.011	0.157	0.002
2. Sorghum 10% coverage on bare soil	10	0.940	0.006	0.246	0.007
3. Graminea (partly covered)	12	0.956	0.013	0.280	0.002
4. Solanaceae (weed of cultivation), almost completely covered	3	0.985	0.005	0.506	0.009
5. Graminea (almost complete cover)	3	0.958	0.006	0.294	0.003
6. Open grass (Graminea), partly covered	3	0.949	0.008	0.278	0.005
7. Long grass (35 cm) complete cover	3	0.958	0.003	0.276	0.011
8. Shrub (Rhygozum brevispinosum), partly covered.	5	0.952	0.009	0.367	0.010
9. Shrub (Euclea undulata), partly covered	5	0.976	0.008	0.476	0.019
10. Shrub (Euclea undulata), completely covered	5	0.986	0.006	0.727	0.015

(*) The number of NDVI measurements is five for all surfaces.

THERMAL EMISSIVITY AND NDVI

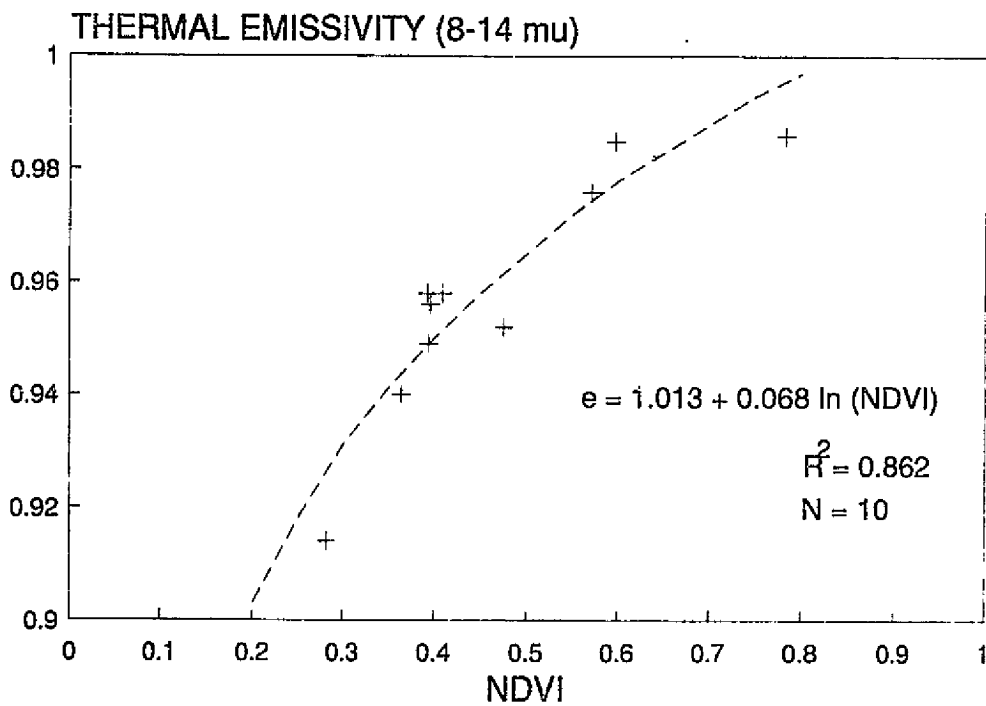


Fig. 9 Plot of the mean emissivity versus the mean NDVI for the ten plots described in Table 2.

according to Tucker et al., (1984, 1985). All images were acquired during the same several day period and are of the same ground area at the three different resolutions.

Results of these comparisons are contained in Table 4 and the relative differences in the spatial variability between scenes is illustrated vividly in Figure 10. It becomes clear that the potential for error when using point ground measurements as a basis for calculating spatial averages at any scale may be great. Satellite measurements of NDVI may therefore be helpful in making more representative areal estimates of thermal emissivity. The results of these analyses have been described in more detail in Van de Griend and Ow^ (1992).

Table 4 A comparison of thermal emissivities for three different image types of the same area, in terms of pixel size and spatial variability.

<u>Imagery</u>	<u>Pixel Size</u>	<u>Number Pixels</u>	<u>Mean</u>	<u>SD</u>	<u>Low</u>	<u>High</u>	<u>Range</u>
AVHRR GAC	7.5 km	4	0.93	.0082	.92	.94	.02
AVHRR LAC	1 km	224	0.92	.0153	.89	.95	.06
Landsat TM	30 m	262144	0.94	.0218	.89	.99	.10

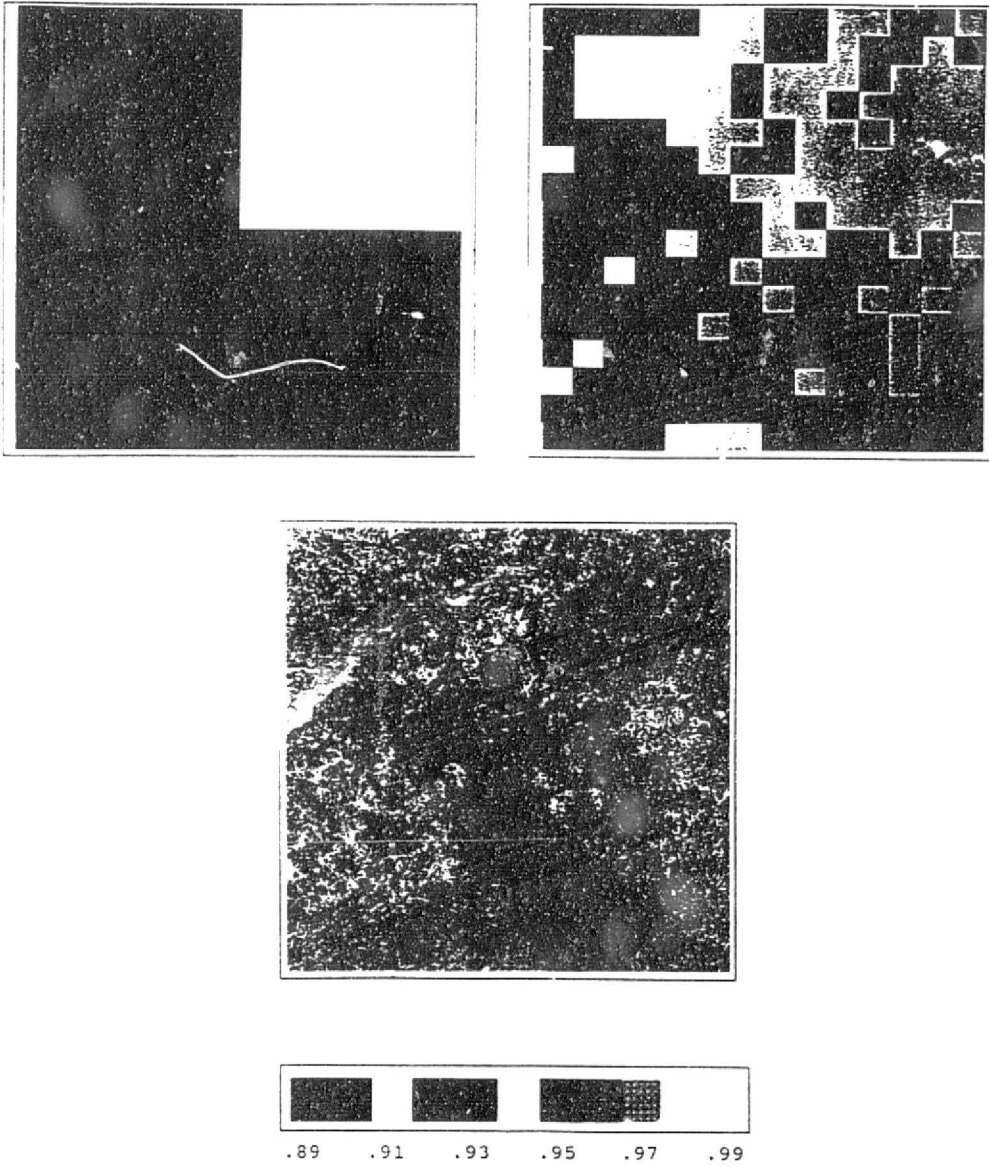


Fig. 10 One band grey-tone images representing derived thermal emissivity for three types of imagery; AVHRR GAC (top left), AVHRR LAC (top right), and Landsat-TM (bottom). Each area represents the same 15 x 15 km² area. Emissivities are indicated on the grey-tone bar.

5.3 Surface Temperature Measurements (Cable system, Aircraft and Satellite)

Surface temperatures were measured at various scales varying between small footprints of 40 cm by cable system and approximately 5 km by METEOSAT.

a. Small Scale Measurements by Cable Construction

Typical examples of the smallest scale surface temperature measurements in the agricultural field and in the savanna are shown in Fig. 11. The small scale variations in the "homogeneous" agricultural field (Fig. 11a), observed at the beginning of the field campaign when the fields were still bare, result from differences in angle of incidence across furrows, whereas the large differences up to 15 K in the "inhomogeneous" savanna (Fig. 11b) are due to small scale differences in surface conditions varying from bare spots (highest temperatures) to savanna bush (lowest temperatures).

b. Medium Scale Measurements by Low Flying Aircraft

Surface temperature was also measured with the same thermal infrared radiometer (15° FOV) mounted on a light aircraft. These measurements were performed to coincide with NOAA/AVHRR observations and consisted of twenty flight lines covering the 5 x 5 km² km study area. An example of the radiative surface temperatures measured along four flight lines is shown in Fig. 12. The range of surface temperatures within this area, measured with a footprint of approximately 30 m is 22 K, with a standard deviation of 3.6 K, and reflects the patchy structure of the "inhomogeneous" landscape consisting of vast areas of tree and bush savanna intermixed with agricultural fields.

c. Large Scale measurements by Satellite

During the field campaign satellite thermal data were gathered (a) from NOAA/AVHRR (LAC-data; NOAA-9 and NOAA-11) and (b) from METEOSAT (hourly data). Under cloud free conditions, the spatial standard deviation of radiative temperatures gathered by METEOSAT, computed for an area of 9 x 9 pixels, turned out to be less than 1 K. This criterium was used routinely to select clear sky satellite observations. This low external (between pixels) variability indicates the "homogeneity" of the savanna landscape at the scale of METEOSAT, notwithstanding the high internal (within-pixel) variability.

Fig. 13 shows an example of the daily course of the radiative surface temperatures measured by METEOSAT and those measured by the cable systems. After correction for atmospheric influences, the satellite derived physical surface temperatures fall well between the radiative temperature curves measured in the savanna and in the (bare) agricultural field. Atmospheric

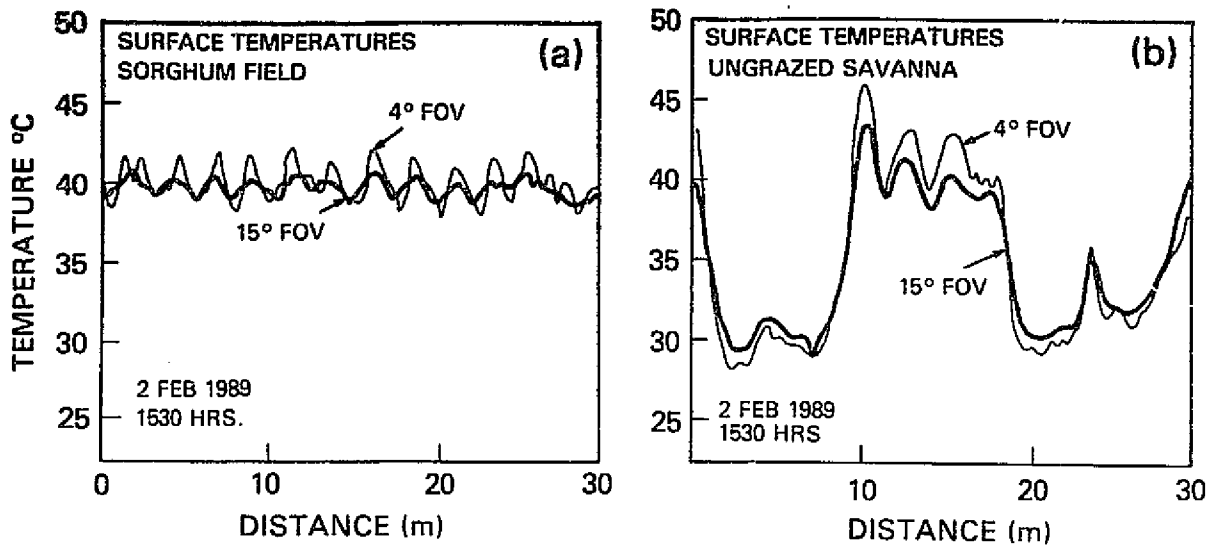


Fig. 11 Typical patterns of radiative surface temperatures measured in the agricultural field (a), and in the ungrazed savanna (b).

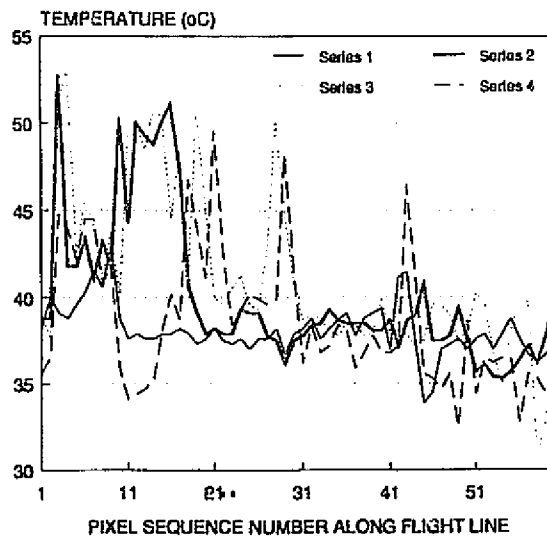


Fig. 12 Radiative surface temperatures measured by low flying aircraft (pixel dimensions 30 x 30 m²) along four flight lines (Date: 5 March, 1989; Time: 15 hrs LTC).

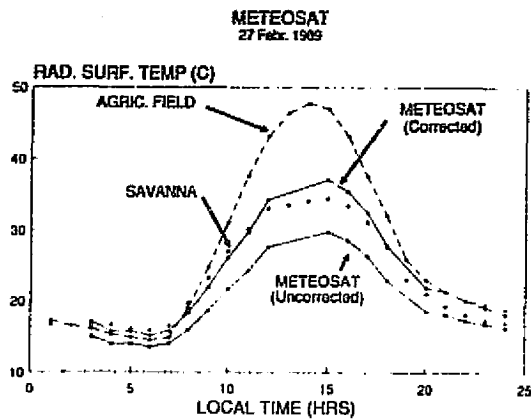


Fig. 13 Daily course of the radiative surface temperature measured by the cable systems in the savanna and agricultural field and by METEOSAT before and after atmospheric correction. Note that the METEOSAT pixel is over $5 \times 5 \text{ km}^2$.

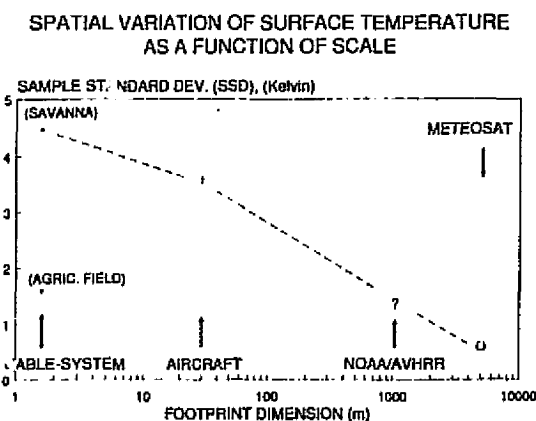


Fig. 14 The Sample Standard Deviation (SSD) versus pixel dimension for the different radiative surface temperature measurements.

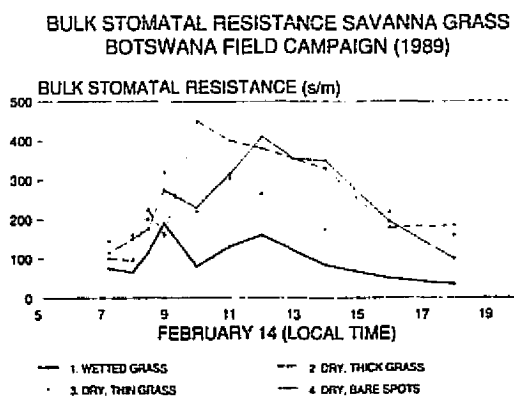


Fig. 15 The diurnal cycle of bulk stomatal resistance measured at four different sites.

corrections were performed at the KNMI (De Bilt, NL) using LOWTRAN-6 and the BANDMODEL developed at the KNMI.

d. Spatial Variability and Spatial Scales

On the basis of the above described radiative temperature measurements the spatial variability has been computed in terms of the Sample Standard Deviation (SSD) for the different data sets. The result is shown in Fig. 14. It shows the gradual decrease of the SSD from small footprints (42 cm) to large footprints (over 5 x 5 km² for METEOSAT).

5.4 Diurnal Characteristics of the Stomatal Resistance

The stomatal resistance was measured done by a bulk stomatal resistance chamber, which is a modified version of the chamber described by Kohsiek (1981). Measurements were done for small samples of cover types such as savanna grasses and small savanna shrubs. Special attention was given to the diurnal course of the bulk stomatal resistance at four different sites (Fig. 15). At all sites a characteristic diurnal cycle has been observed with high stomatal resistances around noon and lower resistances in early morning and late afternoon, showing the adaptation of the species to prevent extreme water losses due to evapotranspiration during the daytime.

5.5 Empirical Relationships between Energy Balance Components (Savanna and Agricultural Field)

The measured energy balance components of sensible heat (H), latent heat of evaporation (LE), net radiation (R_{net}) and the ground heat flux (G) form the basis for verification of energy balance models. They will also be used to stratify the fluxes from individual "homogeneous" surfaces to pixel average fluxes at different scales, i.e. from 1 to 5 km². For verification purposes it is almost a requirement to have a sufficiently large range of surface conditions in terms of soil moisture availability and evaporative conditions. The variation in micrometeorological conditions is demonstrated in Fig. 16. This figure shows the daily averaged energy balance terms throughout the measuring period (Julian day 25 till Julian day 70) for both the savanna and the agricultural field. The water balance terms such as precipitation (P) and top 10-cm soil moisture are given in Figs. 17 and 18. The general trend in changing conditions is clearly visualized. A dry first half of the field campaign was followed by a relatively wet period. The steady increase of crop biomass goes together with a gradual increase of the latent heat flux in the agricultural field.

For checks of consistency the daily latent heat fluxes were plotted against the daily R_{net} -values (Figure 19). The relationships are basically the same for both surfaces. The deviations are partly due to variations in soil moisture availability.

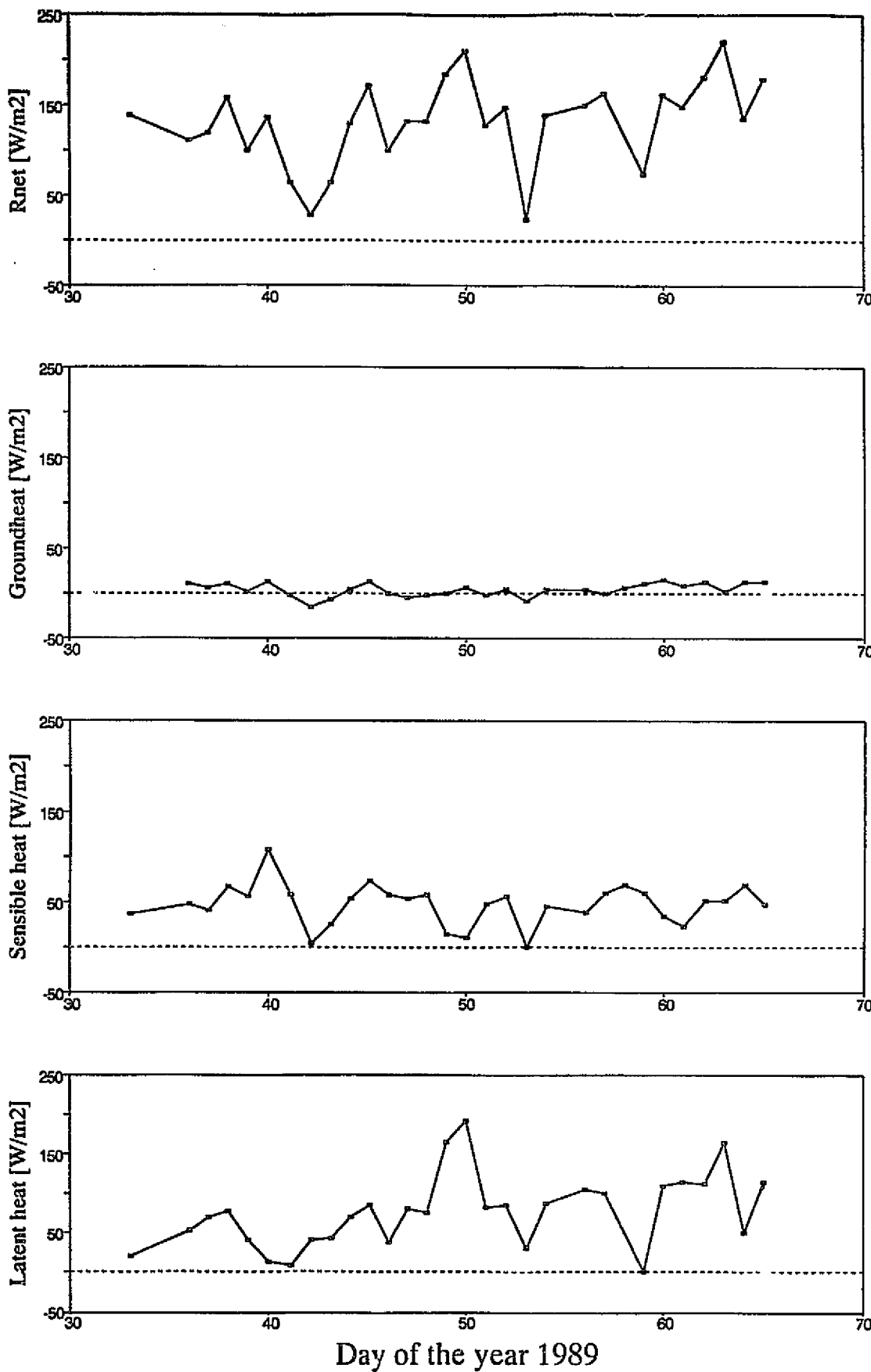
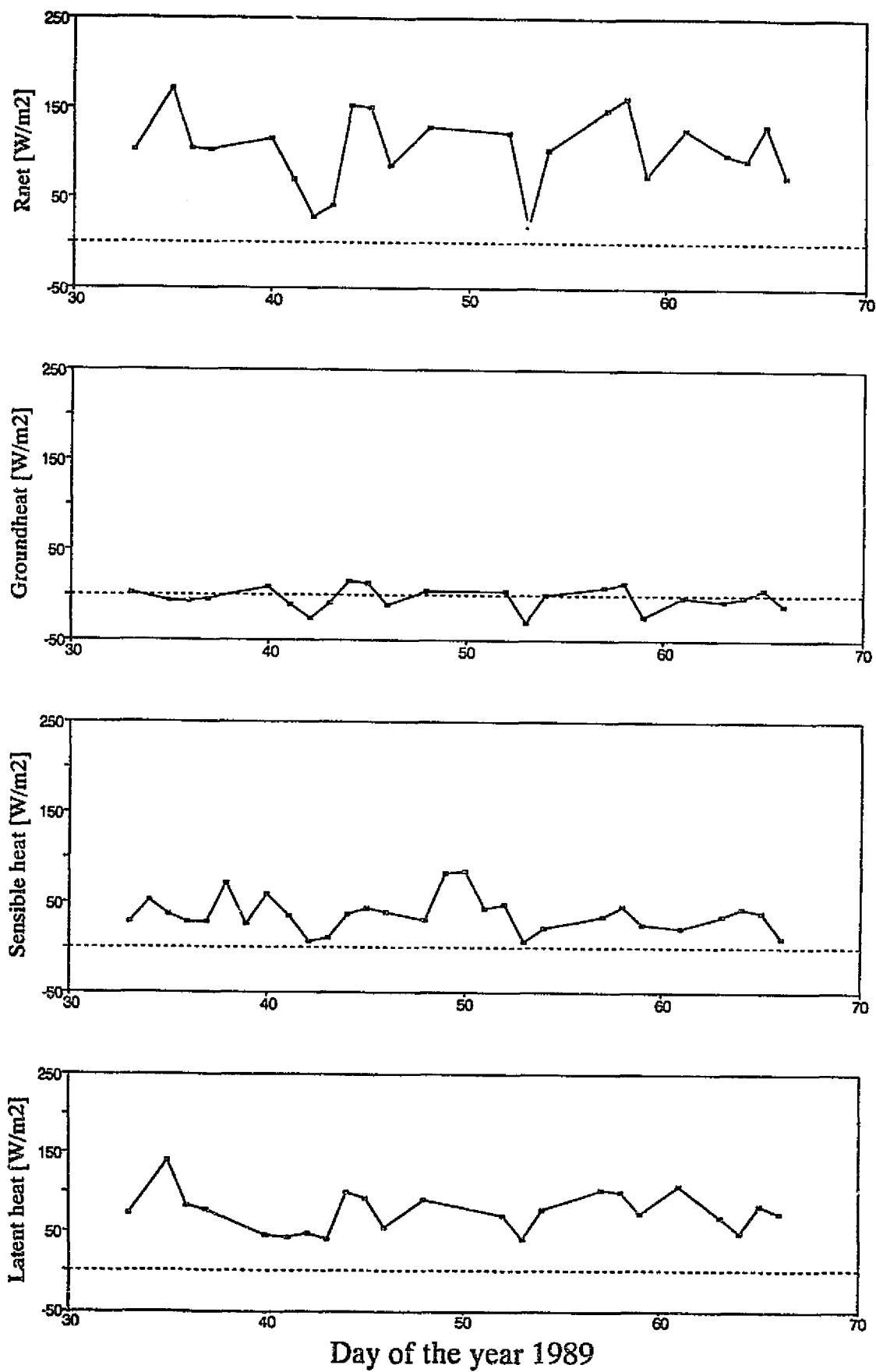


Fig. 16 The terms of the energy balance throughout the field campaign expressed as daily mean values for the savanna (a) and the agricultural field (b).

Agricultural field (sorghum)



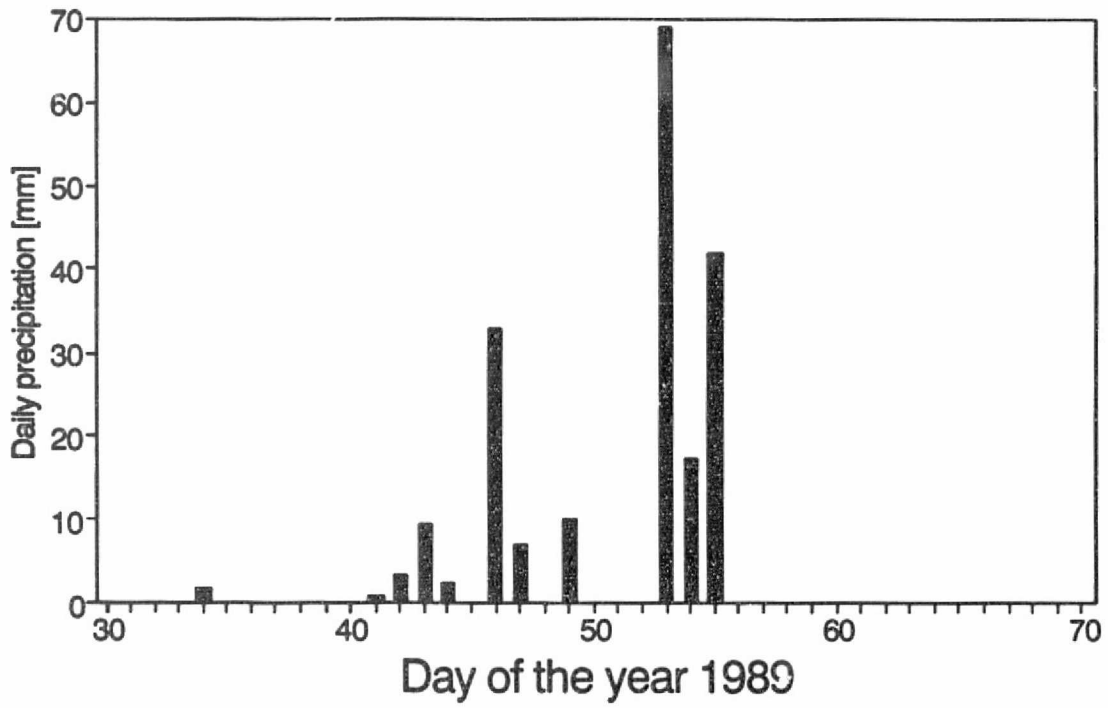


Fig. 17 The course of rainfall during the field campaign.

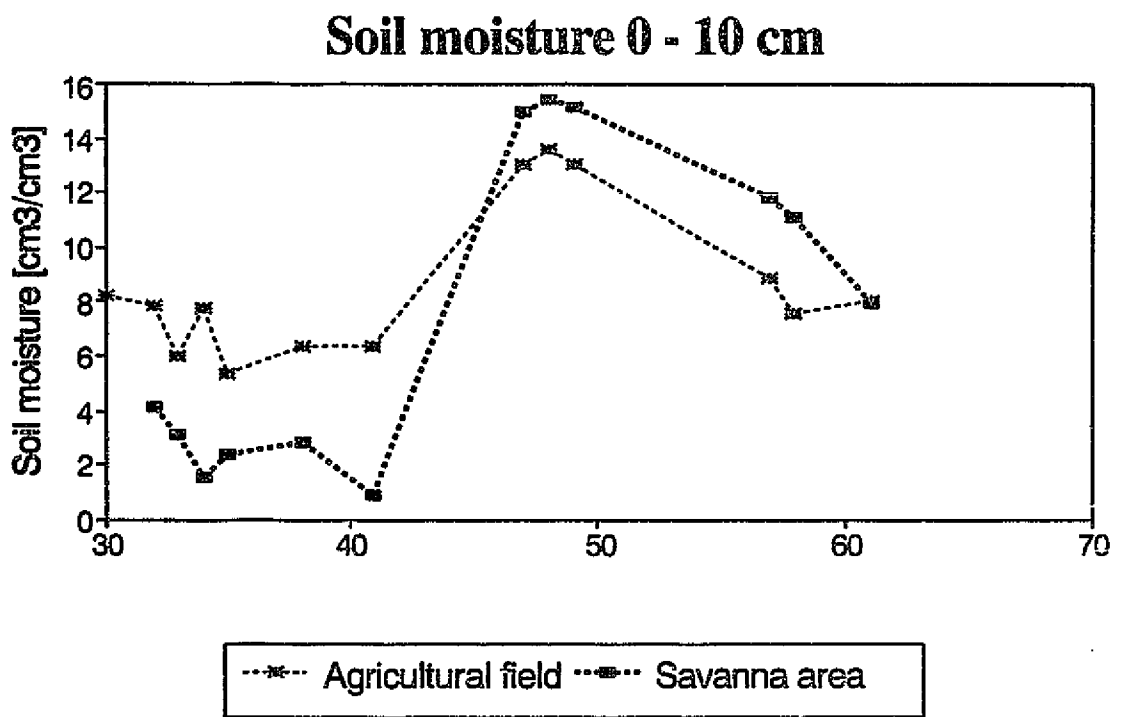


Fig. 18 The course of average soil moisture content in the top 10-cm during the field campaign.

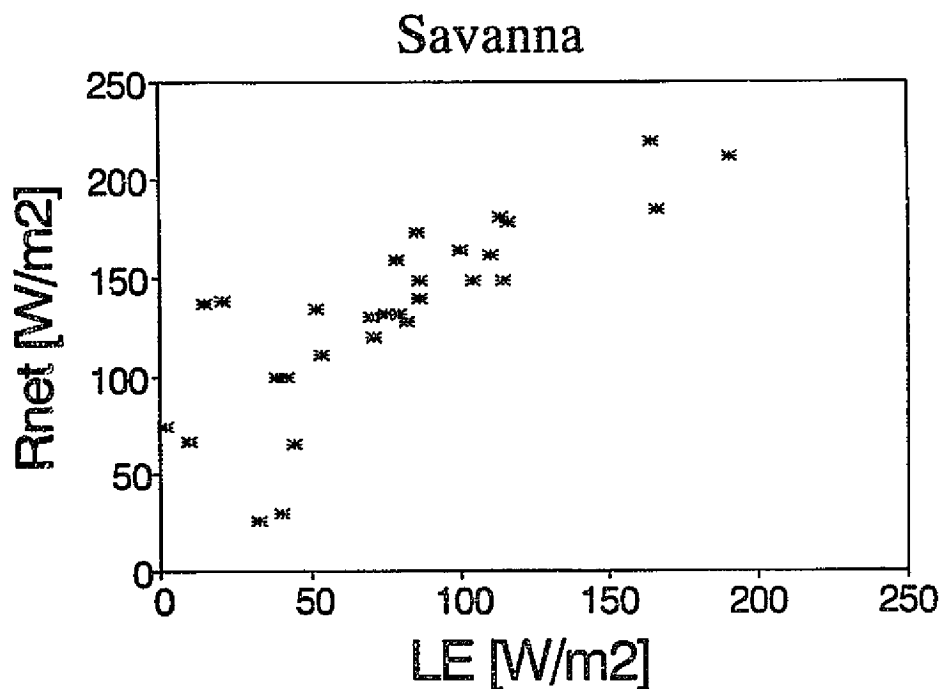
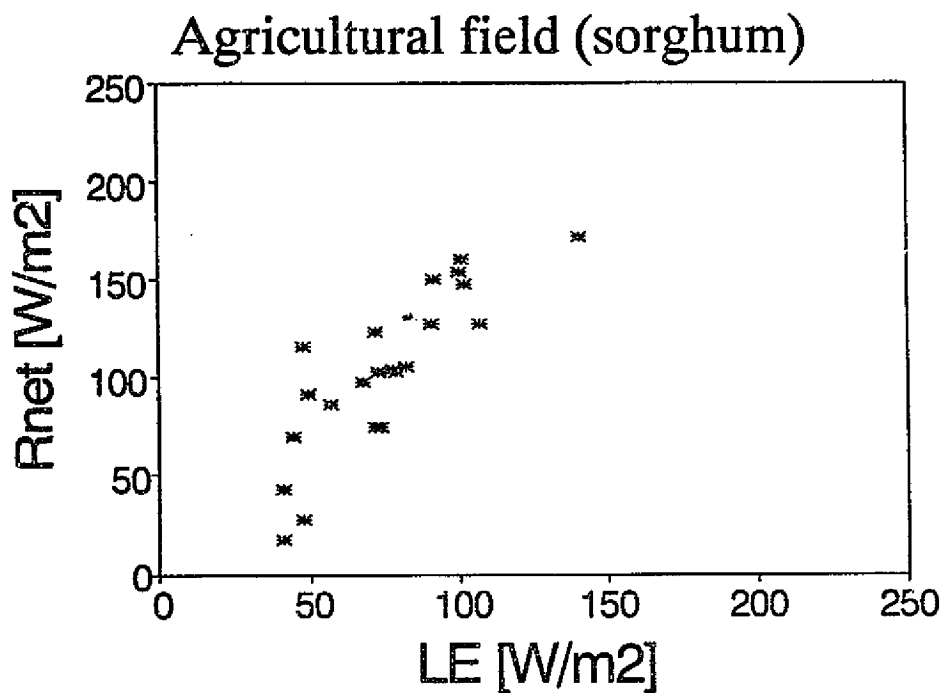


Fig. 19 Plot of the daily mean net radiation versus the daily mean latent heat flux in the savanna (a) and the agricultural field (b).

5.6 Diurnal course of CO₂ fluxes

In order to understand more about the CO₂ cycle, CO₂ profiles were measured in the savanna, using the differential method. Fig. 20 shows an example of the daily course of CO₂ concentration-difference, indicating the change in flux direction around 17.30 hrs. CO₂ fluxes will be derived from the observed concentration differences and aerodynamic resistances derived from observed wind profiles.

5.7 Regional Mapping of LAI, Vegetation Biomass and NDVI

An intensive regional mapping activity was conducted within the 5 x 5 km² study area to define the spatial distribution of vegetation types and vegetation characteristics such as LAI and wet and dry leaf biomass. This exercise consisted of an intensive field sampling campaign for ground data collection and several aircraft flights (aerial photography and red and near-infrared radiometry).

Aerial photography

A motor-driven automatic 50 mm camera (Nikon F3) was mounted in a sledge in the fuselage of a high-wing aeroplane (Cessna 206) and fitted with a radar altimeter. The pictures were obtained at a flying height of about 200 m and a speed of 160 km/hr using a 28 mm lens set to an aperture to ensure a shutter speed of at least 1/500 s. Ektachrome 200 colour transparency film was used.

The following coverages were made:

- two low altitude photographic coverages on 1 and 4 February;
- two partial low altitude coverages on 26 February and 2 March and two high altitude coverages at 26 february and 2 March.

The photographs were digitized to asses the coordinates of the radiometer readings which pointed at the same footprint.

Measurement of cover, biomass and leaf area of live herbaceous vegetation

After careful examination of aerial photographs of the area and ground reconnaissance, six plots were selected in order to represent the major variation in herbaceous vegetation present. In each plot fifty 0.5 x 0.5 m² quadrants were arranged in a line. Cover was estimated visually and biomass was measured by clipping, drying and weighing the live vegetation. For each type of coverage the average cover in percentages and dry green biomass in kg/ha were estimated.

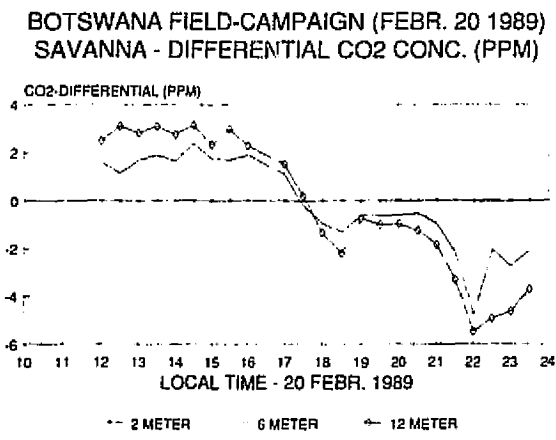


Fig. 20 Example of the daily course of CO₂ concentration-difference observed in the savanna.

Green leaf area was measured by clipping and scanning the green leaves and grasses of five quadrants per line. Before clipping, the normalized difference vegetation index (NDVI) was measured. Biomass was estimated by drying and weighing the leaves after scanning. The relationship between green leaf area, live biomass and NDVI was established by linear regression analysis. Good relationships were established between biomass and leaf area for all six types of herbaceous vegetation (Fig. 21).

Measurement of tree and shrub canopy diameter, biomass and leaf area

Crown diameter and height of the standing vegetation were measured. The biomass of the trees and shrubs was measured by clearing several members of the species Acacia spp., Combretum apiculatum, Terminalia sericea, Euclea undulata and Grewia flava. The leaves were dried and weighed in three separate horizontal strata of 0.1 m, 1-3 m and > 3 m. Also here, biomass and green leaf area were determined by clipping, scanning, drying and weighing the leaves. For all species one relationship between dry biomass and green leaf area was established by linear regression (Fig. 22).

Measurement of tree and shrub canopy cover

The crown diameters of trees and larger shrubs in the study site were measured using aerial photographs taken during the 1 february flight. The tree and shrub canopy was obtained using a dot-grid onto which the transparencies were projected at 10 times magnification. Different species were recognized by colour and shape as Acacia spp., Combretum apiculatum, Terminalia sericea, Euclea undulata and Grewia flava. Crown diameters were converted into live biomass using regression equations derived from the field measurements.

The measurements were integrated and used to create detailed maps of the spatial distribution of vegetation biomass, LAI and NDVI during the field campaign.

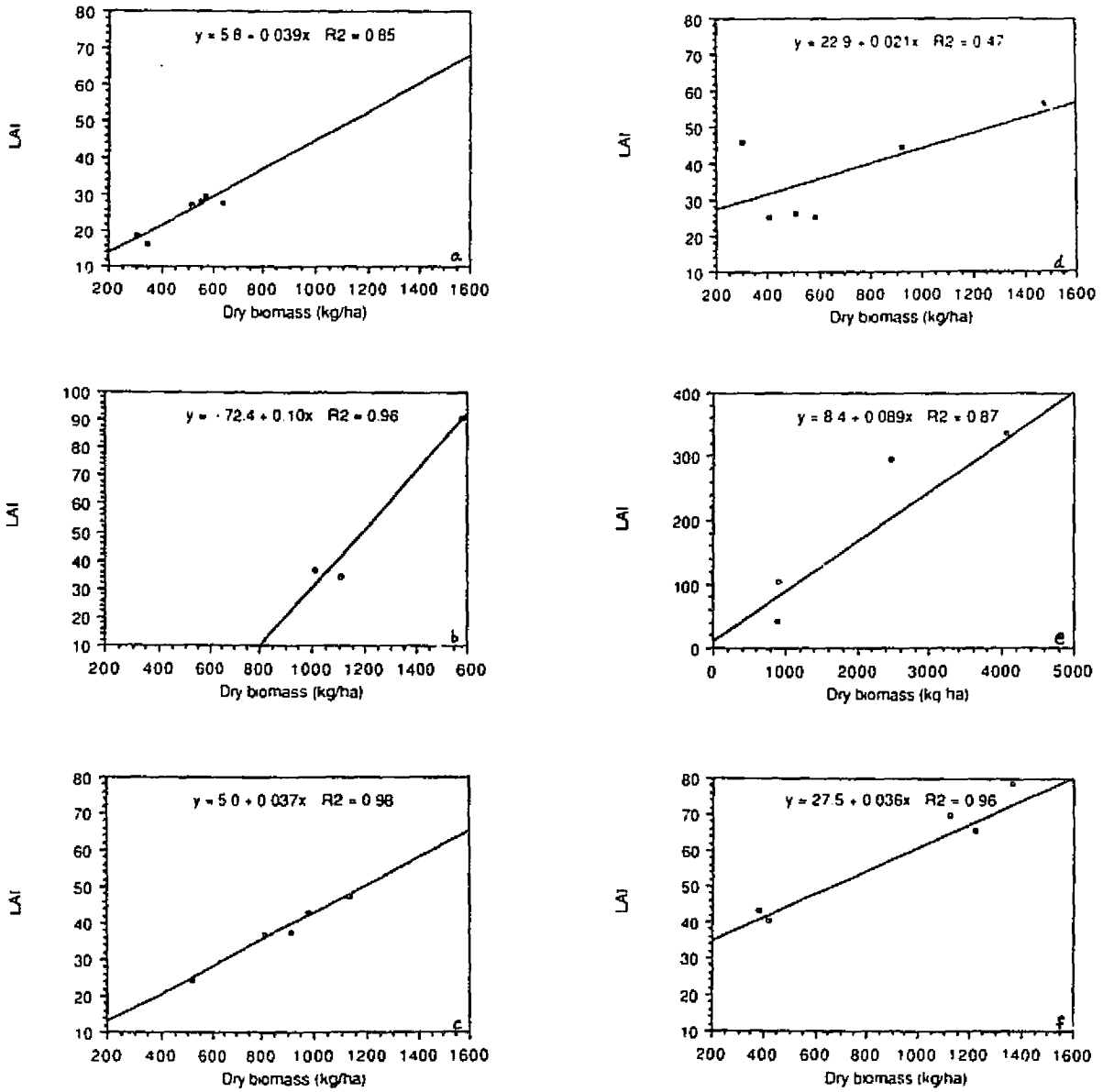


Fig. 21 The relationship between dry biomass and LAI for the herbaceous vegetation along 6 different flight lines (A-F).

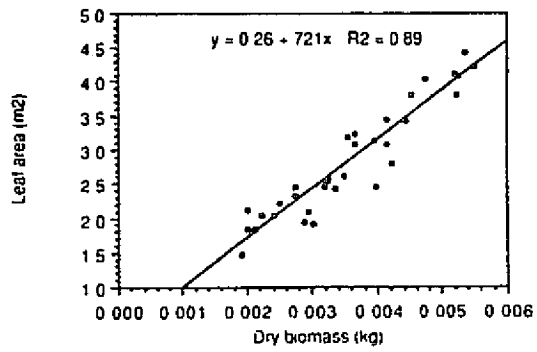


Fig. 22 The relationship between dry biomass and LAI for the standing vegetation.

6. SCIENTIFIC PAPERS ORIGINATED FROM BOTSWANA-1

Several scientific papers originated from the BOTSWANA-1 project. An overview is given below with reference to the two research components.

A. Energy Balance research Component

- [1] Van de Griend, A.A., Owe, M., Vugts, H.F. and Prince, S.D. (1989): Water and energy balance modelling in Botswana. *Bull. of the American Meteorological Society*, Vol. 70(11): 1404-1411.
- [2] Van de Griend, A.A., Owe, M., Vugts, H.F., Prince, S.D., Tesselaar, F.W. and De Bruin, H.A.R. (1990): Collection of ground data for pixel scale parameterization of energy balance models for remote sensing purposes. In: *Proc. Int. Symposium IGARSS'90 "Remote Sensing Science for the Nineties"*, Washington, D.C. (USA), May 20-24: 1251-1256.
- [3] Van de Griend, A.A., Owe, M., Groen, M. and Stoll, M.Ph. (1991): Measurement and spatial variation of thermal infrared surface emissivity in a savanna environment. *Water Resources Research*, Vol. 27 (3):371-379.
- [4] Van de Griend, A.A. and Owe, M. (1992): On the relationship between thermal emissivity and the Normalized Difference Vegetation Index for natural surfaces. *Int. Journal of Remote Sensing* (In Press).
- [5] Van de Griend, A.A. and Owe, M. (in review at NASA/GSFC): The estimation of atmospheric turbidity using NOAA/AVHRR: Theoretical approach and simulation results.

B. Microwave Research Component

- [6] Owe, M. and Van de Griend, A.A. (1990): Daily surface moisture model for large scale semi-arid land application with limited climate data. *Journal of Hydrology*, Vol. 121:119-132.
- [7] Owe, M., Van de Griend, A.A. and Chang, A.T.C. (1992): Surface moisture and satellite microwave observations in semi-arid southern Africa. *Water Resources Research* (in press).
- [8] Van de Griend, A.A. and Owe, M. (submitted): Determination of microwave vegetation optical depth and single scattering albedo from large scale soil moisture and Nimbus/SMMR satellite observations. Submitted to: *Int. Journal of Remote Sensing*.

- [9] Van de Griend, A.A. and Owe, M. (submitted): Microwave vegetation optical depth and inverse modeling of soil emissivity using Nimbus/SMMR satellite observations. Submitted to: Journal of Geophysical Research.
- [10] Owe, M., Van de Griend, A.A. and Carter, D.C. (submitted): Modelling of longterm surface soil moisture and monitoring of vegetation biomass response by satellite in semi-arid Botswana. Submitted to: Journal of Hydrological Processes.

7. SUMMARY

The Botswana Water and Surface Energy Balance Research program was originally conceived as a three year study of the moisture and energy exchanges in a semi-arid savanna environment. The study was to complement concurrent similar investigations being conducted in other ecosystems. The Botswana study was partitioned into two components:

1. A Surface Energy Balance Modelling Component, built around a extensive field campaign, and
2. A Passive Microwave Research Component, which consisted of a retrospective study of large scale soil moisture conditions and Nimbus/SMMR 6.6 GHz and 37 GHz microwave signatures.

The overall purpose of the study was to investigate the simultaneous integrated use of different portions of the electro-magnetic spectrum as gathered by satellites to determine and monitor the physical and hydrological status of the Earth's surface. The study established several specific objectives to help answer problems of scaling which occur when remotely sensed signatures of (by definition) heterogeneous pixels are to be analysed. These problems are related to:

1. The influence of pixel surface inhomogeneity on the satellite signal.
2. The parameterization of surface physical properties at satellite scales.
3. The influence of surface inhomogeneity on the performance of energy balance models.
4. The scaling of point measurements to pixel and regional scale processes.
5. The implications of these questions for the inverse problem, i.e., the extraction of information on the physical status of the Earth's surface from remote sensing measurements.

The acquisition of adequate ground data reflecting the spatial variability of surface physical and meteorological data was a necessity for the study. Therefore a field experiment was conducted from January to March 1989 in south-eastern Botswana. The key to the field campaign was a multi-level approach, whereby measurements by various similar sensors were made at several altitudes and resolutions. Data collection was performed at two adjacent sites of contrasting surface character. Instruments were located in an ungrazed natural savanna and a cultivated field in mixed agricultural and grazed areas. Together, these two locations were representative of the majority of land surfaces common to this type of ecosystem.

The following measurements were made at each site:

- Micrometeorological measurements
- Surface temperatures
- Soil temperatures
- Soil moisture
- Vegetation (LAI and biomass)
- Satellite data
- Aircraft data
- Atmospheric soundings
- Stomatal resistance
- Surface emissivity

All measurements have been checked for further analyses whereas several aspects have been studied in detail. The field campaign resulted in a database which forms the bases for the follow-up study (BOTSWANA-2) in which the measurements will be integrated and used to study the integrated approach described. This report summarizes the measurement results and some itemized analyses.

The retrospective study on large scale soil moisture monitoring using Nimbus/SMMR 6.6 and 37 GHz data has been finished within the framework of BOTSWANA-1. The results of the retrospective study have been put together in a separate BCRS-report which describes:

- (a) a model developed to simulate top soil moisture on a daily basis from 10-day interval soil moisture measurements and climate data;
- (b) a retrospective study of large scale soil moisture observations and normalized brightness temperatures derived from Nimbus/SMMR, with specific attention to the problem of vegetation optical depth;
- (c) a method to determine the vegetation single scattering albedo from horizontally and vertically polarized microwave signatures (at both 6.6 GHz and 37 GHz);
- (d) a synergetic approach to determine the top soil emissivity by inverse modeling.

The "Botswana Water and Surface Energy Balance Research Program" is a co-operative research activity of the Vrije Universiteit (Amsterdam, NL), the Hydrological Sciences Branch of NASA/GSFC (USA) and the Meteorological Services of Botswana. BOTSWANA-1 was funded by the Netherlands Remote Sensing Board (BCRS) under AO-4.4 and by NASA Headquarters Land processes Branch (Code SEL).

ACKNOWLEDGEMENTS

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