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An overview of HAPEX-Sahel: a study in climate and desertification

THIERRY

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Abstract

HAPEX-Sahel was an international experiment designed to provide the field data needed to model the climate of the Sahel and its dependence on land surface conditions. The design of the experiment was based on the study of a 1° square experimental domain in which there were three observational supersites. At each of these supersites detailed hydro-meteorological studies were made at subsites for each of the three principal vegetation types: millet, fallow savannah and tiger bush. Remote sensing from satellite and aircraft was used to scale up from the local to the regional scale. Hydrological monitoring, from 1991 to 1993, was combined with an 8-week intensive observation period that covered the end of the wet season and the beginning of the dry season in 1992. The structure and content of the HAPEX-Sahel Special Issue are described and an introduction is given to the HAPEX-Sahel information system where the data are stored. © 1997 Elsevier Science B.V.

1. Introduction

During the past 25 years the Sahel has experienced a systematic decrease in annual rainfall. At the same time population growth has resulted in the natural savannah being replaced by agricultural crops or subject to greater pressure from grazing and fuelwood collection. Charney (1975) first demonstrated how a reduction in vegetation might feedback to produce a decrease in rainfall. Other large scale effects, such as changes in the surface temperature of the Atlantic, are correlated with fluctuations in Sahelian rainfall (Lamb, 1978; Folland et al., 1986; Fontaine and Bigot, 1993), but the relative importance of these external factors over more local causes (such as vegetation degradation) in changing Sahelian rainfall remains to be determined and understood. The geographic location of the Sahel (with the Sahara Desert to the north and the humid, equatorial coastal zone of West Africa to the south) makes the region particularly vulnerable to externally forced climate change. Predicting the likely consequences of global climate changes on such marginal areas is a priority application of climate modelling. A prerequisite to an improvement in predictive capability is an understanding of how the climate of the region is controlled under the current conditions. The Hydrologic-Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel) was an international experiment designed to provide the field data to develop this understanding of Sahelian climate.

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The interaction between the land surface and the atmosphere involves multiple processes and feedbacks, all of which may vary simultaneously. At present only atmospheric global circulation models (GCMs) and mesoscale models have the potential to reproduce the combined effects of all these interactions. They are the main tools for investigating the sensitivity of the climate to changes in surface conditions. The principal objective of HAPEX-Sahel was to improve the realism and accuracy of such sensitivity experiments by improving the models' representation of the Sahelian land surface. This was achieved by a combination of experimental and modelling work, with the first priority being to collect the necessary land surface, atmospheric and remotely sensed data. These experimental data could then be used for the development of models and algorithms at scales, ranging from 1 to several hundred kilometres, the grid length at which the meteorological models operate.

HAPEX-Sahel (see also Goutorbe et al., 1994) forms one of a series of large scale, land–surface–atmosphere experiments which have taken place within the framework of international programmes: HAPEX-MOBILHY (André et al., 1988) in South-West France, FIFE in Kansas, USA (Sellers et al., 1992) and European Field Experiment in Desertification threatened Area (EFEDA) in La Mancha, Spain (Bolle et al., 1993). HAPEX-Sahel is part of the World Climate Research Program (WCRP) through its Global Energy and Water Cycle Experiment (GEWEX), and the International Geosphere–Biosphere Programme (IGBP) through its core project Biospheric Aspects of the Hydrological Cycle (BAHC). The HAPEX-Sahel site is also one of the study areas of the French SALT (Savannes à Long Terme) programme, a part of the IGBP core project Global Change and Terrestrial Ecosystems (GCTE). SALT studies the way in which savannah ecosystems respond to climate change. The foci and objectives of this series of land–surface–atmosphere experiments have changed as the series proceeded: HAPEX-MOBILHY dealt with the parameterisation problem for GCMs and with the upscaling issue; while the primary objective of FIFE was to develop remote sensing methods for estimating land surface processes. Later, for EFEDA and then HAPEX-Sahel, attention changed to the description of marginal areas. The basic methodology however, is similar in each of these experiments: measurements are taken at a range of length scales from the leaf scale, through the plot scale up to the 100-km scale of the experimental domain as a whole. Ground measurements are then aggregated using atmospheric boundary layer measurements, aircraft measurements, remote sensing or hydrological and meteorological modelling.

This paper presents a brief introduction to the experiment and the contents of this Special Issue. It describes the experimental design, and measurement and modelling philosophy. General introductions to the HAPEX-Sahel experiment have been given by Goutorbe et al. (1994) and Prince et al. (1995). After an introduction to the sites some key elements of the experiment are described: the study of the effect of heterogeneity on energy, water and carbon exchange between the land surface and the atmosphere, and the use of remote sensing to map and classify this spatial heterogeneity. The paper ends with a description of the HAPEX-Sahel database.

2. Experimental design

2.1. Sampling strategy in space

The largest scale of observation is that of the experimental domain, which was an area of the Sahel, in the Republic of Niger, between 2 and 3° East and from 13 to 14° North (Fig. 1). The area of the experimental domain was equivalent to that of a GCM grid square—in this case a 1° × 1° square (approximately 110 × 110 km). An area of this size is large enough to allow observations of the exchanges within the planetary boundary layer, especially by aircraft, and to obtain frequent radiometric observations from space using high orbiting satellites. At this scale the strategy was to use a combination of satellite and aircraft-mounted remote sensing (Prince et al., 1995), radio sounding (Dolman et al., 1997a) and direct measurements of the average fluxes made from aircraft (Saïd et al., 1997), while on the surface climate was measured with a network of 12 automatic weather stations, as shown in Fig. 2 (Champeaux et al., 1993). Rainfall was measured with the EPSAT-Niger (Estimation des Pluies par Satellite) network of 107 recording raingauges (Lebel et al., 1995, 1997). Below the surface groundwater levels were monitored in 323 wells (Leduc et al., 1997).

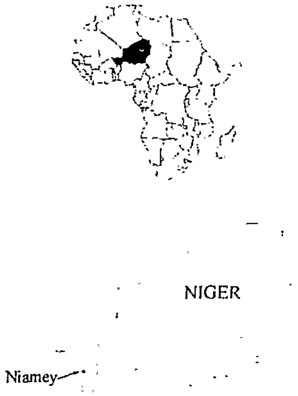

Fig. 1. The location of the HAPEX-Sahel experimental square in The Republic of Niger.

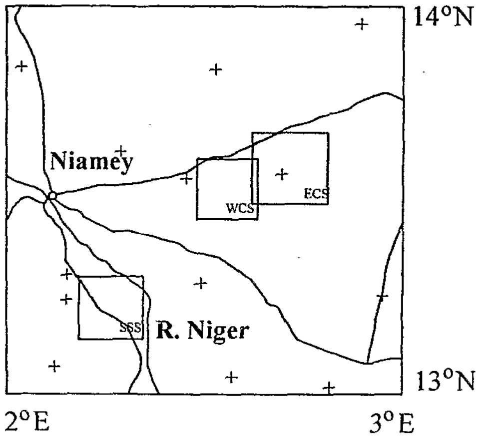

Fig. 2. The HAPEX-Sahel experimental domain showing the location of the Southern (SSS), West Central (WCS) and East Central (ECS) Supersites and the 12 automatic weather stations deployed during the IOP (+). The River Niger and the principal roads are also shown.

Across the Sahelian zone there is a long term south–north rainfall gradient of about 1 mm km^{-1}, so on average, a rainfall difference of 100 mm should be expected between the southern and northern boundaries of the square. In a semi-arid region, rainfall differences of this size produce differences in vegetation. However, superimposed on this gradient is the rain from each rainfall event. At the time scale of the convective systems, most of the spatial variability is associated with convective cells and clusters, over typical distances ranging from 1 to 30 km. This rainfall variability results in soil moisture fields which have a similar, short term variability. To try and sample these differences, three observational supersites were instrumented in the domain. At each supersite, measurements were made at subsites in each of the three principal vegetation types: millet agriculture and fallow savannah, on the sandy soils of the valley bottoms, and the open woodland known as tiger bush, on the laterite soil of the plateaux. The distribution of the supersites is shown in Fig. 2. The supersite scale is the scale at which the atmospheric boundary layer responds to the area average fluxes from the surface. It is the smallest scale at which aircraft mounted instruments can measure fluxes, and it can also be resolved by the advanced very high resolution radiometer (AVHRR) instrument on the National Oceanic and Atmospheric Administration (USA) (NOAA) meteorological satellite. For these reasons, but also because logistically it is a relatively easy scale at which to manage field operations, most of the surface measurements (the radiation components, fluxes of water and carbon dioxide, soil moisture and surface and subsurface water flows) were organised around the supersite structure.

Although the distinction in 1° square, supersite and local measurement scales is useful, it does not cover every measurement. For example, some hydrological measurements were made at scales imposed by the topography (Desconnets et al., 1997) and limited micrometeorological measurements were also made at a drier site (Danguey Gorou) in the north of the domain (see Gash et al., 1997). Radiosondes were also released from a site in the village of Hamdallaye (13°33′N, 2°24′E), from Niamey airport, and from a mobile system (Dolman et al., 1997a). Finally at a scale larger than the experimental domain some of the remotely sensed data and model outputs (GCM reanalyses) cover an area 500 × 500 km.

2.2. Sampling strategy in time

HAPEX-Sahel was designed around two time scales: a long term, hydrological, time scale with monitoring over several years and a short term, meteorological one limited to the intensive observation period (IOP) during which the fast changing responses of the vegetation and soil could be observed. If changes in land use and vegetation are to affect rainfall this will occur only during the wet season when the intertropical convergence zone (ITCZ) reaches the area during the northern hemisphere summer. Once the ITCZ has retreated southwards, in mid-September, there are dry north-easterly winds over the Sahel and the meteorological conditions for generating rainfall are absent. The timing of the IOP was therefore designed to include both a period of the wet season and the transition into the dry season. It took place between 15 August and 9 October 1992: a period which covered the last month of the wet season and the first month of the dry season. The data collected at the start of the dry season give the opportunity to derive those soil and vegetation parameters which characterise the response of the vegetation to soil moisture stress. The timing of the IOP relative to the rainfall for the 1992 wet season is shown in Fig. 3.

2.3. Implementation

HAPEX-Sahel was implemented as an integrated consortium of 67 individual studies. These are listed by Prince et al. (1995) and details of each are given in the experimental plan (Goutorbe et al., 1995). The scientific studies were organised into four groups: meteorology and mesoscale modelling, hydrology and soil moisture, surface fluxes and vegetation and remote sensing. For the field campaign, operations were organised by supersites, with aircraft operations being treated as an additional group.

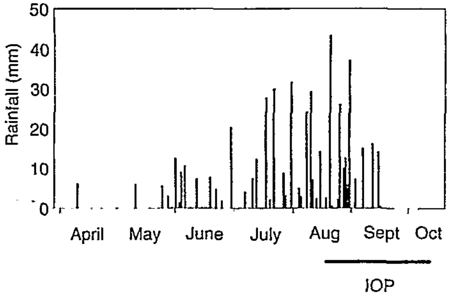

Fig. 3. Daily rainfall as measured by the EPSAT-Niger network for the HAPEX-Sahel experimental domain during the 1992 wet season (data from Lebel et al., 1995). The duration of the IOP is also shown.

Four aircraft were deployed in the IOP: the Merlin IV from Météo-France, for flux measurements; the French ARAT Fokker 27, used initially for remote sensing, but, in the second half of the IOP, for measuring flux; the NASA C-130 Hercules aircraft, deployed for remote sensing during the first half of the IOP and a Piper Saratoga, which was hired locally and used throughout the IOP collecting data in several visible and near-infra-red bands. Full details of the aircraft and satellite remote sensing are given by Prince et al. (1995).

3. Sites

3.1. The supersites

The location of the three supersites (Fig. 2) was a compromise between the scientific need to cover a range of different conditions and the practical necessities of operating field sites with large teams and complex equipment requiring frequent attention. The location of the subsites within each supersite is shown in Fig. 4. The Southern Supersite (Wallace et al., 1994) was centred on the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center near the village of Sadoré. Subsites covered the major

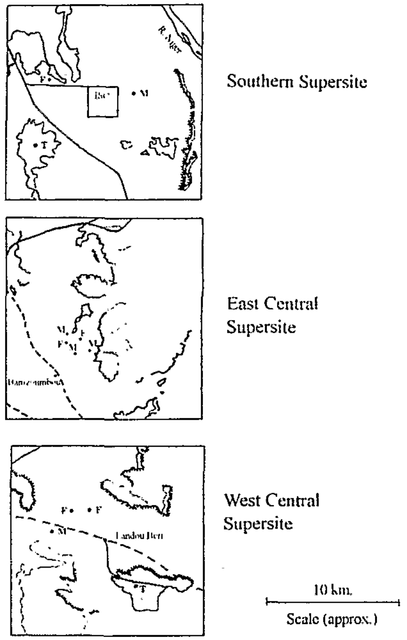

Fig. 4. The Southern, West Central and East Central Supersites, showing the main areas of tiger bush (hatched), and the location of the millet (M), fallow (F) and tiger bush (T) subsites. The ICRISAT Sahelian Center (ISC), the main villages and the principal access routes are also shown.

vegetation types: millet agriculture, fallow savannah and tiger bush. The West Central Supersite (Kabat et al., 1996) was centred on the village of Fandou Beri, with subsites in millet, fallow savannah and tiger bush, as well as a site in an area of degraded fallow bushland. The East Central Supersite (Monteny, 1993) was centred on the village of Banizoumbou, and had subsites in millet and fallow savannah, with soil and hydrological measurements, but not measurements of surface fluxes, as were being made elsewhere in the tiger bush. An overview of the deployment of micrometeorological equipment at all these sites is given by Gash et al. (1997) and of the soil measurements by Cuenca et al. (1997).

3.2. The millet sites

Millet (*Pennisetum glaucum* (L.) R Br.), the staple food crop of Niger, is widely grown in the sandy soil of the valley bottoms. The millet is sown in pockets about 1 m apart, at a density of some 5000 pockets ha^{-1}. After germination the seedlings are thinned to give 2–3 plants per pocket. Millet grows to a height of typically 2–3 m but, even when there is an adequate supply of soil moisture, the crop is nutrient-limited and is sparse, with a large percentage of exposed bare soil. The seed heads are harvested by hand some 100 days after sowing, while the residue is left as grazing for the coming dry season. Typically occasional trees (about 2–3 ha^{-1}) occur within the fields, and cowpea (*Vigna unguiculata* L.) is sometimes grown as a sparse intercrop. This was the case at the Southern Supersite.

3.3. The fallow sites

After some years of millet agriculture the land is left fallow and the natural vegetation is allowed to regenerate. Fallow periods of 6–10 years are typical but, as pressure on the land has increased, less land is being left fallow and rotation times are reduced. The vegetation regrows as a shrub savannah with a ground layer of annual herbs and grasses. The shrubs are mainly *Guiera senegalensis* (L.), which grows to a height of 2–3 m and covers some 10–15% of the area; the height of the herb layer is some 50 cm at the peak of the growing season. Bare soil occupies about 15% of the area. A survey of the southern fallow subsite (Wallace et al., 1994) revealed 30 different species of herbs, 15 of which were classified as either 'abundant' or 'less abundant'. Fallow is used primarily as grazing for cattle, sheep and goats, but the shrubs are also harvested for fuelwood.

3.4. The tiger bush sites

Tiger bush (*brousse tigrée*) is found on the laterite plateaux which comprise about a quarter of the experimental domain. It is an open woodland in which the vegetation is confined naturally to dense bands, 10–30 m wide and 100–300 m long, interspersed with strips of completely bare, crusted soil, about 30–100 m across. The form, structure, composition and causes of tiger bush are discussed by Thiéry et al. (1995), but in essence the bare soil acts as a natural rainfall harvesting system supplying water to the bands of vegetation, allowing it to be much denser than would be the case if the vegetation were distributed over the whole area. Tiger bush is used for grazing and fuelwood collection.

4. The scope and content of the Special Issue

4.1. Organisation

This introductory paper is followed by two papers which describe the vegetation and surface conditions (d'Herbès and Valentin, 1997) and the long term rainfall climatology (Le Barbé and Lebel, 1997). The collection of papers which follows brings together the results from most of the component studies listed by Goutorbe et al. (1995) and Prince et al. (1995). These papers are organised broadly according to scientific discipline: hydrology and soil science, fluxes and vegetation and meteorology. The distinction in scientific disciplines is one of convenience, and reflects the fact that this Special Issue presents the first results of a complex, multidisciplinary experiment. As such, the number of studies integrating the various measurements is still rather limited. Being the first Special Issue with HAPEX-Sahel results, it necessarily contains mostly papers related to individual datasets. To set the results of these papers in a somewhat wider perspective we now briefly describe some key elements of the experiments along the lines of two of the objectives of the experiment: the study of spatial heterogeneity in a semi-arid environment and the use of remote sensing techniques to quantify and understand this heterogeneity. A final paper (Dolman et al., 1997b) draws together the findings and looks at the research requirements of the future.

4.2. Heterogeneity

One prime objective of HAPEX-Sahel, which cuts across all disciplinary boundaries is investigating the effects of spatial heterogeneity. Descriptions and models of the variability of surface conditions have thus been considered in a number of papers. Spatial heterogeneity results from rainfall patterns generated by convective rainfall cells and from the heterogeneity in vegetation and soil. New information on rainfall distribution in time and space coming from the EPSAT-Niger raingauge network is presented by Lebel et al. (1997) and Lebel and Le Barbé (1997). The effects of redistribution of rainfall on the surface are presented by Desconnets et al. (1997), Gaze et al. (1997) and Peugeot et al. (1997). The variability of evaporation in time and space is addressed by Gash et al. (1997), Kabat et al. (1997), Lloyd et al. (1997) and Saïd et al. (1997). Brunel et al. (1997), Jacobs and Verhoef (1997), Tuzet et al. (1997) and Wallace and Holwill (1997) separate the fluxes from the component sources of complex vegetation communities: this is essential if models capable of reproducing the evaporation are to be developed and tested. Modelling fluxes for individual vegetation types is considered by Braud et al. (1997), Chehbouni et al. (1997), Lhomme et al. (1997) and Troufleau et al. (1997), while the problem of modelling fluxes at the larger scale is addressed by Blyth (1997). Taylor et al. (1997) used a mesoscale model to investigate the influence of vegetation distribution and rainfall patterns on surface fluxes and the boundary layer across the HAPEX-Sahel square.

GCM land surface models increasingly incorporate carbon fluxes in dynamic modelling experiments including interactive vegetation and variable ambient CO_2 concentration (e.g. Sellers et al., 1996). Flux measurements are needed to calibrate these land surface models: measuring the net ecosystem exchange of carbon is now fortunately straightforward using eddy co-variance systems, which employ closed path infra-red gas analysis. The system developed by Moncrieff et al. (1997a) was used routinely by five groups in HAPEX-Sahel and proved capable of working in the demanding conditions of the Sahel. The data have been analysed to investigate the overall variation (Moncrieff et al., 1997b; Monteny et al., 1997) and controls (Friborg et al., 1997; Levy et al., 1997) on carbon fluxes and their relation to the water use of semi-arid vegetation.

4.3. Remote sensing

The first objective of the remote sensing was to allow a characterisation of the 1° square at different scales and thus provide the investigators with complete fields of surface parameters. The second objective was to investigate and test the algorithms for the determination of surface parameters from remotely sensed data. This was especially necessary for new instruments or algorithms (such as Polarisation and directional reflectivity measurement (POLDER), PORTOS, LASER PROFILER and soil moisture retrievals). This Special Issue covers both the development of remote sensing techniques as well as application of remote sensing to specific problems.

PORTOS, and Push Broom microwave radiometer (PBMR), made measurements with resolutions ranging from 300 m to 2 km, and data at 25 and 50 km resolution were acquired through the special sensor microwave imager (SSM/I). To address the spatial variability over the 1° square, several flights were performed, observing strips across and along the whole experimental domain (Goutorbe et al., 1994). Access was sought to all the existing satellite data of relevance to the HAPEX-Sahel objectives (Prince et al., 1995).

d'Herbès and Valentin (1997) and Gond et al. (1997) characterised the HAPEX-Sahel area using optical sensors to extrapolate local results. Bidirectional reflectances, collected with ASAS or POLDER, were used to derive accurate assessments of the vegetation cover type. Barnsley et al. (1997) used ASAS data to validate bidirectionnal reflectance distribution function (BRDF) models and produce albedo maps. An attempt to reduce the influence of solar-view angles is presented by Ba et al. (1997), while the atmospheric contribution was addressed by classical corrections and compositing methods Kerr et al. (1993) and Gond et al. (1997).

Once inverse algorithms are established, it is important to test the results and HAPEX-Sahel offered good opportunities to do so. Andersen (1997) compares several algorithms to retrieve surface temperature from thermal infra-red data, while Chanzy et al. (1997) propose a method to estimate surface soil moisture from PORTOS. Magagi and Kerr (1997) show how the European Remote Sensing Satellite (ERS-1) wind scatterometer, with its high temporal sampling but coarse spatial resolution, can infer soil moisture and surface roughness as well as vegetation biomass. Teng et al. (1997) explored the influence of laterite on the brightness temperatures, while Xiang and Smith (1997) studied an algorithm to retrieve land surface temperature and emissivity with a view to using it for precipitation retrieval algorithms over land surfaces.

Finally, remotely sensed data were used to extract variables of interest in flux models. For example, Hanan et al. (1997) examine the errors induced when using remote sensing to infer intercepted photosynthetically active radiation (IPAR), Chehbouni et al. (1997) link classical measurements (aerodynamic temperature) and remote sensing retrievals (radiative temperature) through the use of the Normalised Difference Vegetation Index (NDVI) to estimate relevant variables from remotely sensed data. This is complemented by the in situ measurements and interpretative work of Troufleau et al. (1997) and Chehbouni et al. (1997) at the East Central Supersite.

5. HAPEX-Sahel information system (HSIS)

During the planning of HAPEX-Sahel, it became apparent that a database would have to be constructed to allow easy access to a standard set of measurements. This database would also serve as an archive ensuring availability of the data for future use. Building on the experience of previous mesoscale land surface experiments, particularly FIFE, it was decided to construct a database that was compatible with the FIFE Information System (FIS). This compatibility would greatly simplify the eventual task of using data coming from different ecosystems and environments to validate or run models and algorithms. To achieve this objective, Centre National d'Etudes Spatiales (France) (CNES), NASA and ORSTOM jointly developed a database compatible with FIS, but adapted to the specific needs of HAPEX-Sahel. This operation involved a diversity of investigators, in terms of discipline and country of origin, and a variety of scales and data types. The database is organised around the original file system and user interface developed by NASA, but has been adapted to run under a Unix working environment. The HAPEX-Sahel Information System (HSIS) contains over 8000 files with more than 10 GB of structured datasets. In October 1997, once thoroughly checked, the database will be made available in the public domain and maintained on a long term basis. Currently seven CD-ROMs have been produced and five are in press or in the final stages of production. In 1994 a World Wide Web (WWW) server was established (http://www.orstom.fr/hapex) so that the data could be obtained directly from the database. The goal is to produce a complete copy of the dataset on CD-ROMs before the database comes into the public domain. The WWW server will also be kept as long as possible, with the addition of a publication list giving all the papers, theses, and reports resulting from HAPEX-Sahel. Copies of the software developed by HSIS are also available for use in other large scale field experiments—the overall goal is to work towards the generation of a family of compatible databases.

6. Concluding remarks

This Special Issue publishes results from the primary investigators in HAPEX-Sahel: the front line field studies and analyses. Because understanding at the component level is often a prerequisite to understanding at the regional scale, a scaling up approach has been followed. It goes from multiple small scale measurements to more comprehensive 1° square studies. This inevitably produces a pyramid-like structure in terms of the number of studies and the results they produce. This structure is reflected in the content of the Special Issue: for every paper at the scale of the experimental domain there are ten describing the individual components that make up the heterogeneous land surface.

Publishing these papers together gives an integrated picture to those using the results and data in the future. HAPEX-Sahel has left us with a greatly improved appreciation of how the Sahelian land surface interacts with the atmosphere. It has taught us the limitations and uncertainties of our current measurement systems and, as the papers of this Special Issue show, has provided a wealth of data, waiting to be integrated into fully coupled models of the Earth system.

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