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An Overview of the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE)

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In the summer of 1983 a group of scientists working in the fields of meteorology, biology, and remote sensing met to discuss methods for modeling and observing land-surface–atmosphere interactions on regional and global scales. They concluded, first, that the existing climate models contained poor representations of the processes controlling the exchanges of energy, water, heat, and carbon between the land surface and the atmosphere and, second, that satellite remote sensing had been underutilized as a means of specifying global fields of the governing biophysical parameters. Accordingly, a multiscale, multidisciplinary experiment, FIFE, was initiated to address these two issues. The objectives of FIFE were specified as follows: (1) Upscale integration of models: The experiment was designed to test the soil-plant-atmosphere models developed by biometeorologists for small-scale applications (millimeters to meters) and to develop methods to apply them at the larger scales (kilometers) appropriate to atmospheric models and satellite remote sensing. (2) Application of satellite remote sensing: Even if the first goal were achieved to yield a "perfect" model of vegetation-atmosphere exchanges, it would have very limited applications without a global observing system for initialization and validation. As a result, the experiment was tasked with exploring methods for using satellite data to quantify important biophysical states and rates for model input. The experiment was centered on a 15 × 15 km grassland site near Manhattan, Kansas. This area became the focus for an extended monitoring program of satellite, meteorological, biophysical, and hydrological data acquisition from early 1987 through October 1989 and a series of 12- to 20-day intensive field campaigns (IFCs), four in 1987 and one in 1989. During the IFCs the fluxes of heat, moisture, carbon dioxide, and radiation were measured with surface and airborne equipment in coordination with measurements of surface and atmospheric parameters and satellite overpasses. The resulting data are held in a single integrated data base and continue to be analyzed by the participating scientists and others. The first two sections of this paper recount the history and scientific background leading up to FIFE; the third and fourth sections review the experiment design, the scientific teams and equipment involved, and the actual execution of the experiment; the fifth section provides an overview of the contents of this special issue; the sixth section summarizes the management and resources of the project; and the last section lists the acknowledgments.

1. INTRODUCTION

The First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) is an international, land-surface–atmosphere experiment centered on a 15 × 15 km test site near Manhattan, Kansas. The objectives of FIFE are to better understand the role of biology in controlling the interactions between the atmosphere and the vegetated land surface and to investigate the use of satellite observations for inferring climatologically significant land surface parameters. FIFE was and is by necessity an interdisciplinary, coordinated effort as progress toward these objectives requires that researchers working in the fields of meteorology, biology, and remote sensing cooperate with each other in carrying out a wide variety of measurements over an extended range of spatial scales; see Figure 1.

FIFE was conceived a little over eight years ago in 1983, progressed rapidly through two large experimental phases in 1987 and 1989, and has now moved on to the most rewarding part of any endeavor of this kind: the analysis of results and the testing of new theories and models. This volume contains a comprehensive set of papers which describe the experimental results from FIFE, but more importantly, many lessons learned from the scientific analyses are presented here for the first time. This first paper is intended to introduce the reader to FIFE and to provide an overview; specifically, it covers the scientific history leading up to the initiation of FIFE, the scientific background, and the FIFE objectives (section 2); the design and organization of the experiment (section 3); the field operations of 1987 and 1989 (section 4); and an overview of the contents of this special issue (section 5). A summary of the results and analyses published in this volume is given in the closing paper of this special issue.

As far as possible, all the contributors to this issue have adhered to a common nomenclature and set of acronyms, reproduced in the notation section of this paper. Additionally, the site location and identification scheme, which evolved through several versions during the project, has been standardized and is reproduced in this paper in Figure 4 and Table 1. While this journal issue is intended to be a comprehensive summary of the results and analyses of FIFE, the reader should be aware that there are two other significant sources of information about the project. First, there have already been many papers which have appeared in the scientific literature that utilized FIFE results; a list is available from the FIFE project office (Attn: FIFE/BOREAS, 923 NASA/GSFC, Greenbelt, MD 20771, USA). Second, considerable effort went into documenting the detailed planning, execution, and preliminary results of the experiment in a series of internal reports. A few of these reports are referred to many times in this issue and are briefly reviewed below.

The experiment plan for the 1987 field phase, FIFE 87, provides the details of the experiment design, lists the

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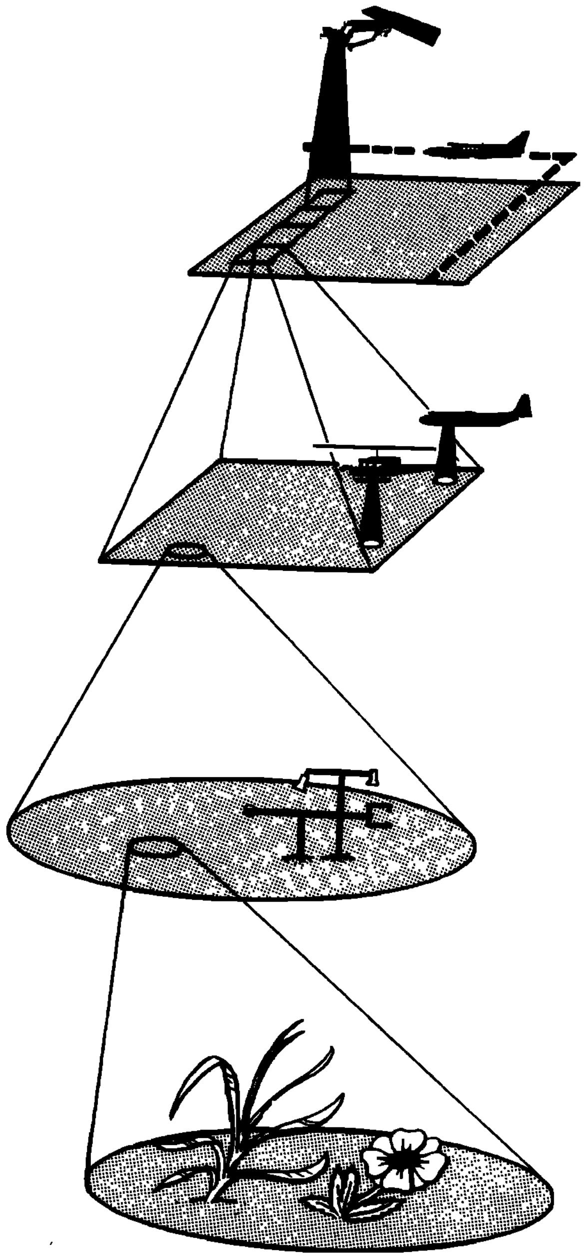

Fig. 1. Range of spatial scales addressed by FIFE.

investigators and equipment used, and reviews the organization of the project (flight plans, research priorities, etc.). This document [*Sellers and Hall*, 1987] is referred to as EXPLAN 87 in this issue. A similar document [*Sellers and Hall*, 1989] covers the FIFE 89 field phase and is referred to as EXPLAN 89. The FIFE interim report [*Sellers et al.*, 1990*a*] documents the execution of FIFE 87 (weather conditions, measurements completed, airborne missions performed, etc.) and also presents some of the preliminary results. These reports and descriptions of the FIFE information system by *Strebel et al.* [1990*a*, *b*] are available from the FIFE project office. Lastly, many results were presented at the American Meteorological Society Symposium on FIFE in Anaheim, California, in 1990. Forty-six papers were combined into a single proceedings volume, edited by *Hall and Sellers* [1990].

The interdisciplinary nature of FIFE and the range of scientific expertise involved in the analyses is reflected in the support provided to the project by national and international bodies. ISLSCP is sponsored by the World Meteorological Organization (WMO), the International Commission of Scientific Unions (ICSU), the United Nations Environmental Program (UNEP), and the International Geosphere-Biosphere Project (IGBP). For FIFE itself the National Aeronautics and Space Administration (NASA) is the "lead" agency, but important contributions were made and continue to be made by the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Department of Interior, the Nature Conservancy, the National Research Council of Canada, and many universities and research institutes in the United States and abroad.

2. The History and Objectives of FIFE

2.1. *The Formation of the International Satellite Land Surface Climatology Project (ISLSCP) and the Initiation of FIFE*

In the summer of 1983 a group of approximately 100 scientists working in the fields of meteorology, biology, and remote sensing assembled for a workshop in Boulder, Colorado, to discuss the role of satellite remote sensing in studies of the interactions between the land surface and the atmosphere. During the workshop it became clear that the represented scientific communities had made little practical use of the existing satellite data; in particular, the data had seldom been exploited for the initialization and validation of the land surface component of general circulation models (GCMs) used for numerical weather prediction and climate studies. As a result of this and a parallel workshop in Europe, the ISLSCP was conceived with the aim of matching the apparent potential of satellite data to the needs of the Earth Science community. The scientific framework for the project was published in the work of *Rasool and Bolle* [1983] and reformulated by *Sellers et al.* [1988, p. 22] as follows:

> In any study of the Earth's climate system, including investigations into the causes and effects of climatic change, it is essential to consider the forcing of the atmosphere by the land surface and oceans. Little is known about the global distribution of energy, moisture, carbon dioxide and momentum sinks and sources over the land, how these vary seasonally, the intrinsic interannual variability associated with them, and the effect they have on the atmospheric component of the climatic system. By contrast, there is considerable knowledge of how these sinks and sources are related on the small scale; for example, observations and theory strongly suggest that leaves and individual plants have tightly interconnected evapotranspiration and photosynthetic rates that ensure efficient photosynthesis for minimal water loss. There is also strong evidence that these mass fluxes are linked to chlorophyll density which should be quantifiable from remote sensing. However, there is a huge gap between our understanding of these processes on small scales and their integrated effects on the atmosphere, as detected by satellites, on larger scales. Currently, very sketchy assumptions about the vegetated land surface are used to explore the sensitivity of the climate system to surface processes, but even these efforts are of limited value unless relevant global-scale data sets are available for initialization and validation. It is clear that in most cases such data sets can only be gathered in a consistent, timely, and economical fashion through the use of satellite remote sensing.

TABLE 1. Site Identifiers (IDs), Locations and Treatments for the Flux Measurement Stations, and Automatic Meteorological Stations (AMS) in FIFE 87 and FIFE 89

Grid ID	Station ID	Northing UTM	Easting UTM	Latitude North	Longitude West	Elevation m	Treatment
Surface Flux Site and AMS Positions for 1987							
Bowen Ratio							
1246-BRL	40	4331666	714212	39 06 35	96 31 21	365	BMs
1445-BRL	42	4331160	714090	39 06 19	96 31 27	400	BSn
1478-BRS	38	4331216	720603	39 06 15	96 26 56	350	BT
1916-BRS	2	4330296	708270	39 05 56	96 35 30	340	UB
2043-BRL	44	4330003	713536	39 05 42	96 31 51	415	?UT
2132-BRK	6	4329774	711336	39 05 36	96 33 23	405	USn
2133-BRK	60	4329720	711521	39 05 34	96 33 15	405	UT
2516-BRK	14	4328956	708102	39 05 12	96 35 38	405	UMe
2655-BRL	36	4328787	716070	39 05 00	96 30 07	367	BMne
2915-BRK	12	4328167	708028	39 04 47	96 35 42	415	USn
3129-BRK	8	4327702	710711	39 04 30	96 33 51	430	BMne
3414-BRK	10	4327286	707854	39 04 19	96 35 51	410	BBw
3479-BRL	34	4327134	720890	39 04 02	96 26 49	420	?USse
4268-BRK	32	4325626	718579	39 03 15	96 28 27	445	BTw
4439-BRV	18	4325218	712792	39 03 07	96 32 28	445	BT
6340-BRL	20	4321484	713000	39 01 06	96 32 23	410	UMsw
6912-BRW	24	4320111	707336	39 00 26	96 36 20	397	UT
Eddy Correlation							
2731-ECA	4	4328678	711110	39 05 01	96 33 34	446	BT
4268-ECG	30	4325626	718574	39 03 15	96 28 27	445	BTw
4439-ECV	16	4325215	712794	39 03 07	96 32 28	445	BT
4609-ECW	22	4324890	706705	39 03 02	96 36 41	390	UMse
6943-ECW	28	4320147	713500	39 00 22	96 32 04	415	?UMse
8739-ECB	26	4316699	712845	38 58 31	96 32 35	442	?UT
AMS							
1563-PAM	27	4331067	717658	39 06 12	96 28 59	350	BSw
2139-PAM	31	4329843	712789	39 05 37	96 32 23	385	UMsw
2428-PAM	3	4329265	710635	39 05 20	96 33 53	415	UMne
3221-PAM	7	4327682	709112	39 04 30	96 34 58	410	USnw
4439-PAM	11	4325219	712795	39 03 07	96 32 27	445	BT
4609-PAM	17	4324766	706700	39 02 58	96 36 41	398	UMse
6469-PAM	23	4321189	718752	39 00 51	96 28 25	440	BMne
6912-PAM	19	4320178	707307	39 00 29	96 36 21	385	UT
Super-AMS							
0847-SAM	52	4332377	714419	39 06 58	96 31 12	415	?UT
2123-SAM	5	4329866	709506	39 05 41	96 34 39	405	UT
4168-SAM	51	4325783	718675	39 03 20	96 28 22	445	BTw
8639-SAM	21	4316771	712827	38 58 33	96 32 36	440	?UT
Surface Flux Site and AMS Positions for 1989							
Bowen Ratio							
1478-BRS	938	4331223	720664	39 06 15	96 26 53	375	Un
1916-BRK	902	4330282	708259	39 05 55	96 35 30	351	Bn
1942-BRL	944	4330133	713414	39 05 46	96 31 56	422	UT
2133-BRL	904	4329704	711576	39 05 34	96 33 13	443	BT
2330-BRK	908	4329314	711066	39 05 22	96 33 35	424	Be
2655-BRL	936	4328787	716070	39 05 00	96 30 07	367	Ue
3129-BRK	912	4327822	710820	39 04 33	96 33 47	431	Be
3317-BRK	910	4327395	708485	39 04 22	96 35 24	427	Uw
4268-BRL	932	4325633	718582	39 03 16	96 28 26	420	UT
6735-BRL	913	4320652	712073	39 00 40	96 33 03	385	UB
6912-BRL	924	4320111	707336	39 00 26	96 36 20	397	Un
Eddy Correlation							
1942-ECL	946	4330121	713402	39 05 46	96 31 57	420	UT
2133-ECA	906	4329726	711604	39 05 34	96 33 12	443	BT
4439-ECV	916	4325193	712773	39 03 06	96 32 28	443	Bn
8639-ECU	954	4316770	712828	38 58 33	96 32 36	440	UT
8739-ECB	926	4316699	712845	38 58 31	96 32 35	442	UT

Accordingly, the ISLSCP was initiated to address the research problems associated with interpretation and exploitation of satellite data over the Earth's land surface. As the project developed, it was recognized that these objectives could not be attained unless there was also a clearer understanding of the biophysical controls acting on land-surface–atmosphere fluxes. If scientific connections could be made among surface biophysical parameters, surface-atmosphere fluxes, and remote sensing, then the science community would be in a position to (1) monitor global scale changes of the land surface caused by climatic fluctuations or by human activities; (2) further develop mathematical models designed to predict or simulate climate on various time scales; and (3) permit inclusion of land surface

TABLE 1. (continued)

Grid ID	Station ID	Northing UTM	Easting UTM	Latitude North	Longitude West	Elevation m	Treatment
Surface Flux Site and AMS Positions for 1989 (continued)							
AMS							
2133-PAM	931	4329706	711577	39 05 34	96 33 13	443	BT
4439-PAM	911	4325219	712795	39 03 07	96 32 27	445	Bn
6469-PAM	923	4321189	718752	39 00 51	96 28 25	440	Une
6912-PAM	919	4320178	707307	39 00 29	96 36 21	385	Un
Super-AMS							
0847-SAM	929	4332344	714439	39 06 57	96 31 11	418	UT
2123-SAM	905	4329866	709506	39 05 41	96 34 39	405	BT
4168-SAM	925	4325704	718646	39 03 18	96 28 24	438	UT
8639-SAM	921	4316771	712827	38 58 33	96 32 36	440	UT

The locations of "roving" (intercomparison) Bowen ratio flux stations have been omitted. Grid ID: First two digits refer to northing, second two digits to easting on site grid scheme; see Figure 4. (The site was divided up into 10^4 grid areas; 100 × 100.) The three letters refer to station type. BR_, Bowen ratio flux station; EC_, eddy correlation station; PAM, automatic meterorological station (AMS); SAM, super-AMS. For the BR and EC stations the third letter refers to the measurement team, e.g., BRL, ECV. A, Wesely (Argonne Laboratory), SF-7; B, Stewart (Britain), SF-5; G, Gurney/Field, SF-3; K, Kanemasu (KSU), SF-1; L, Fritschen, SF-2; S, Smith, SF-4; U, Soviet (USSR), SF-SU1; V, Verma, SF-6; W, Weaver, USGS. Station ID: site reference number used in operations, also used in EXPLAN 87 and 89. In FIFE 89, many of the sites were reassigned the same or matching equipment as in FIFE 87. In these cases the site ID numbers were preceded by a "9", for example, site 16 (4439-ECV) in FIFE 87 became site 916 (4439-ECV) in FIFE 89. Northing/easting: universal transverse mercator (zone 14 coordinates). Latitude/longitude: degrees, minutes, seconds. Elevation: meters above mean sea level. Type: treatment of site. B/U/A, first letter, burned/unburned/agriculture; T/B/M/S, second letter, top/bottom/moderate/steep; n/s/e/w, third letter, aspect direction. "Moderate" is 3°–8°. "Steep" is > 8°.

climatological variables in diagnostic and empirical studies of climatic variations.

ISLSCP sponsored a number of activities related to the above objectives. These included a retrospective analysis program, see *Asrar* [1990*a*, *b*], which focused on the use of the satellite data record in detecting changes in the land surface, and an assessment of existing satellite data algorithms, see *Sellers et al.* [1990*b*]. However, it was recognized that some novel experimental work was required to obtain a clearer understanding of the links among surface states (biomass, cover type, temperature, etc.), surface processes (transpiration, photosynthesis, etc.), and their signatures, as observed by satellite sensors. To be successful, the experimental work would have to assemble data that included satellite observations along with contemporaneous measurements of heat, radiation, and mass fluxes at the surface and the associated biophysical variables. During the formation of ISLSCP in 1983 it was recognized that such experiments were urgently necessary and the First ISLSCP Field Experiment, FIFE, was proposed as a pioneer effort. The first planning meetings for FIFE referred to the contemporary and anticipated needs of climate modelers, among others, to frame a preliminary experiment design.

2.2. *Scientific Background*

The study of the Earth's climate system is an important central focus for the new discipline of Earth System Science. Simulation models, particularly GCMs of the atmosphere, are essential tools for global change research as they allow detailed investigation of the roles of different processes within the Earth system and offer some promise for predicting its response to perturbation.

The development of GCMs over the last 20 years has paralleled improvements in computer power to the point where the most glaring shortfalls in model performance can no longer be blamed solely on the coarseness of model resolution. *Anthes* [1985] reported that more than half of the errors in a series of trial short-range numerical forecasts were associated with poor initialization, that is, the inaccurate specification of the initial state of the system, and with the inadequacy of the physical parameterizations used in the models. These parameterizations describe the essentially one-dimensional processes of surface-atmosphere interaction, convection, cloud-radiation feedback, etc., within GCMs and so are responsible for describing the transfer of energy from solar radiation to the atmospheric system via radiative, sensible, and latent heating.

Simple sensitivity studies conducted within the last 15 years have shown that land-surface–atmosphere interactions can exert important influences on the climatic fields of temperature, humidity, and precipitation, particularly over the continental interiors; see *Charney et al.* [1977], *Sud and Smith* [1985], and *Shukla and Mintz* [1982]. As a result, efforts have been made to improve the realism of the land surface parameterizations (LSPs) used in GCMs (see, for example, *Dickinson* [1984] and *Sellers et al.* [1986]), with encouraging results; the study of *Sato et al.* [1989] showed that the inclusion of a simple model of the Earth's vegetation in a GCM improved the description of radiation, heat, water, and momentum exchange over land surfaces which in turn led to improvements in the simulation of continental rainfall fields.

The study of *Sato et al.* [1989] and other research efforts have shown that land-surface–atmosphere interactions have a strong biophysical component; the Earth's vegetation affects the interception of radiation (albedo), the exchange of momentum and gaseous species between the lower atmosphere and the surface (turbulent transfer), and the partitioning of intercepted energy into sensible and latent heat fluxes (biophysical control of evapotranspiration). The first GCM-biosphere models incorporated very crude descriptions of these processes based on plant or even leaf scale models which had their origins in small-scale biological and micrometeorological studies.

Prior to the work of *Dickinson* [1984], almost all GCMs parameterized the exchange of radiation and momentum between the land and the atmosphere by independently specifying fields of surface albedo and roughness length over the Earth's surface. The net radiation at the surface could then be simply calculated by

$$R_n = K\downarrow(1-\alpha) + L\downarrow - \varepsilon\sigma T_s^4 \qquad (1)$$

where

R_n = net radiation, W m^{-2};
$K\downarrow$ total solar radiation incident on the surface, W m^{-2};
α broadband surface albedo;
$L\downarrow$ downwelling longwave radiation, W m^{-2};
T_s surface temperature, K;
ε surface emissivity;
σ Stefan-Boltzman constant, J m^{-2} K^{-4}.

Shear stress exerted on the atmosphere by the surface was calculated as

$$\tau = \rho u_r / r_{am} \qquad (2)$$

where

τ = shear stress, kg m^{-1} s^{-2};
ρ density of air, kg m^{-3};
u_r wind speed at a reference height above the surface, m s^{-1};
r_{am} aerodynamic resistance for momentum transfer, s m^{-1}.

The value of τ results in a transfer of momentum from the atmosphere to the surface by decelerating a parcel of air moving horizontally over the surface; τ is proportional to the difference between the unperturbed wind speed, u_r, and the wind speed, u_0, at the surface, assumed in (2) to be zero, and inversely proportional to an aerodynamic resistance, r_{am}, which regulates the momentum flux; r_{am} is conventionally calculated using an eddy diffusion concept, whereby a "conductance" to momentum transfer is inverted and integrated between the surface and the reference height. Under neutral conditions, r_{am} is given as

$$r_{am} = \frac{1}{u_r}\left[\frac{1}{k}\ln\left[\frac{z_r}{z_0}\right]\right]^2 \qquad (3)$$

where k is von Karman's constant, 0.41; z_0 is roughness length, m; and z_r is reference height, m.

The roughness length z_0 in (3) is a function of the height and density of the surface vegetation. This means that rough surfaces, such as forests and shrub lands, are more strongly coupled to the atmosphere via turbulent transfer than are smooth surfaces, such as deserts and grasslands. In most models, (3) is modified with empirically based formulations to take account of the effects of atmospheric nonneutrality.

The net radiation R_n, as given by (1), is partitioned into four components at the Earth's surface:

$$R_n = H + \lambda E + G + P_s \qquad (4)$$

where

H = sensible heat flux (conduction to the air), W m^{-2};
λE latent heat flux (release to the air by evaporation), W m^{-2};
λ heat of vaporization, J kg^{-1};
E moisture flux into the air, kg m^{-2} s^{-1};
G heat flux into the ground, W m^{-2};
P_s energy used for photosynthesis, W m^{-2}.

On land surfaces the magnitude of each component is determined by the community composition and structure of the surface vegetation, its reflective properties, its rate of photosynthesis and transpiration (water loss), and the water storage and loss characteristics of the underlying terrain and soils.

The energy used for photosynthesis P_s is effectively negligible in the context of the surface energy budget, and over a day or longer the ground heat flux G averages out to be a relatively small term, seldom more than about 10% of R_n. H and λE are much larger and it is the ratio of sensible to latent heat release into the atmosphere (the Bowen ratio) that can be an important determinant of the local and regional climate: sensible heat flux heats the air above the surface locally in both space and time (its major effect is to provide a forcing for the development of the planetary boundary layer (PBL) in the daytime hours); by contrast, the latent heat flux may have a small local heating effect, but generally the released water vapor is transported into the free atmosphere, moved downstream by the winds, and condenses to form clouds and precipitation some distance in time and space from its point of release. Since these two modes of heat release have such different effects on the internal heating and radiative properties of the atmosphere (condensing water vapor releases heat energy and forms clouds), the accurate calculation of the terms in the surface energy budget is of real importance to the realistic simulation of the atmospheric circulation.

A key component for the calculation of the surface energy budget is a correct description of the biology and mechanics of moisture storage and release by vegetation and soils. Prior to the mid-1980s the Budyko bucket model was used in almost all GCMs to calculate the storage and release of moisture (see the reviews of *Carson* [1981] and *Mintz* [1984]). Generally, the bucket model specifies a maximum water-holding capacity (usually taken to be 15 cm) for each grid area within the GCM. The actual volume of water in the bucket is determined by the time series of precipitation (addition) and evaporation (subtraction). The surface energy balance is then calculated by

$$G = f(dT_s/dt) \qquad (5)$$

$$H = (T_s - T_r)\rho c_p / r_a \qquad (6)$$

$$\lambda E = \beta\rho c_p/(\gamma r_a)[e(T_s) - e_r] \qquad (7)$$

where

T_r, e_r = air temperature and vapor pressure, K, Pa;
$e(T_s)$ saturated vapor pressure at surface temperature, Pa;
c_p specific heat of air, J kg^{-1} K^{-1};

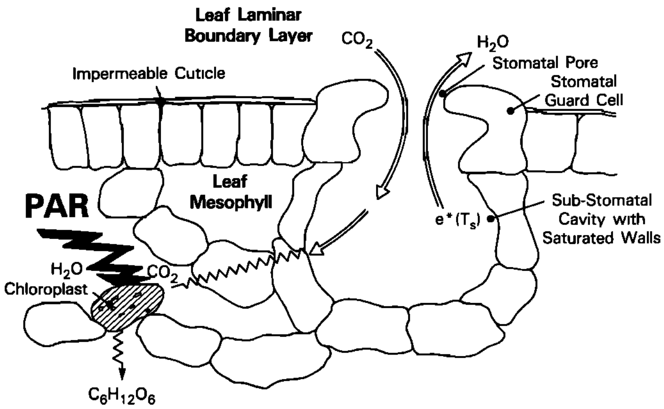

Fig. 2. Schematic of a leaf cross section showing links between stomatal gas exchange (CO_2, H_2O) and photosynthesis. The stomatal conductance is related to the area-averaged value of the stomatal pore width which is of the order of 10 μm. The stomatal pores are under active physiological control and appear to act so as to maximize the influx of CO_2 for photosynthesis for a minimum loss of leaf water. Thus photosynthesis and transpiration are dependent on PAR flux, atmospheric CO_2 concentration, humidity, temperature, and soil moisture; see *Collatz et al.* [1991].

γ psychrometric constant, Pa K^{-1};
β moisture availability function;
r_a aerodynamic resistance for heat and water vapor, s m^{-1}.

In (5), G is calculated using models of soil conduction; see, for example, *Deardorff* [1977]. In (6) and (7) the aerodynamic resistance, r_a, is calculated in much the same way as r_{am} in (2), with a similar dependence on z_0 and atmospheric stability. The most important determinant of the energy budget in this formulation is β, the moisture availability function. In most GCMs this is taken as a simple monotonic function of the level of water in the "bucket," that is,

$$\beta = f(S/S_{\max}), \; 0 < \beta < 1 \tag{8}$$

where, for example, β is 4/3 ($S/S_{\max}$); S is bucket water level, mm; and $S_{\max}$ is maximum value of S, usually 15 cm.

From an inspection of the equation set, we see that the important land surface parameters are the albedo, the roughness length, and the surface wetness or moisture availability function which together influence the fluxes of energy, momentum, heat, and moisture between the land surface and the atmosphere.

The example given above is used in a number of GCMs, including the U.S. National Meteorological Center model for medium-range forecasts and a number of climate simulation models; see *Miyakoda and Sirutis* [1986]. These simple models of land-surface–atmosphere interactions have been used extensively in studies which have investigated the sensitivity of the atmospheric motion, precipitation, temperature, and humidity fields to changes in the bulk land surface parameters of albedo, roughness length, and surface wetness; see, for example, *Charney et al.* [1977], *Sud and Smith*, [1985], and the review of *Mintz* [1984]. It was first pointed out by *Dickinson* [1984] that these experiments, though illustrative, were unrealistic, particularly with regard to the description of the land surface evapotranspiration process, as conventionally specified by the bucket model in the GCMs. He proposed that more realistic descriptions of land surface processes be incorporated within GCMs and designed such a model which attempts to account for the effects of vegetation explicitly.

The particular problem with the commonly used bucket hydrology formulation in (7) is that it is a poor representation of the evapotranspiration process as it occurs in nature, where the plant canopy stomatal resistance exerts a powerful role in regulating the transfer of water from soil to atmosphere. A more realistic description of the evapotranspiration rate was proposed by *Monteith* [1973]:

$$\lambda E = (\rho C_p/\gamma)[e(T_s) - e_a]/[r_a + r_{\text{surf}}] \tag{9}$$

where r_{surf} is bulk surface (soil and canopy) resistance, s m^{-1}.

Here, as opposed to (8), the role of vegetation is explicitly acknowledged in the r_{surf} term which parameterizes the resistance of vegetation and soil to the release of soil moisture for evaporation. The surface resistance is often dominated by the vegetation stomatal resistance; see Figure 2.

The model of *Dickinson* [1984] and the simple biosphere model (SiB) of *Sellers et al.* [1986] use different versions of (9) in their evapotranspiration formulation. Preliminary results from the models of *Dickinson* [1984] and *Sellers et al.* [1986] indicate that the "realistic" vegetation models with realistically large values of surface resistance over the vegetated land give rise to far less evaporation over the continents than the conventional abiotic bucket models; this result has the further effect of reducing the simulated continental precipitation rates (particularly in the northern hemisphere summer), increasing the daytime atmospheric boundary layer (ABL) heights and increasing the diurnal amplitude of the near-surface air temperature wave. All of these effects have brought GCM simulations into closer agreement with observations, which indicates that the realistic modeling of vegetation should yield practical dividends in improved weather forecasts as well as better climate simulations for scientific research. More recent work has shown how the stomatal conductance of vegetation is closely linked to the photosynthetic process: essentially, plants open their stomates to take in atmospheric CO_2 for photosynthesis when radiation, soil moisture, and atmospheric conditions permit; at the same time, water vapor is lost from the saturated leaf interiors over the same route; see Figure 2 and *Collatz et al.* [1991]. Research continues into methods to link the observed spectral properties of vegetation to the coupled biophysical processes of photosynthesis and transpiration and thus provide quantitative estimates of the large-scale fluxes of sensible heat, latent heat, and carbon dioxide.

2.3. *The Role of Remote Sensing in the Study and Modeling of Vegetation-Atmosphere Interactions*

The vegetation-atmosphere models of *Dickinson* [1984] and *Sellers et al.* [1986] are based on our current understanding of biological processes on the scales of individual plants and small plots. Remote sensing could play a central role in integrating our descriptions of small-scale processes up to the larger (regional) scales appropriate to the modeling of exchanges between the terrestrial landscape and the atmosphere. It is essential that we learn how to do this correctly if we wish to specify the parameters (albedo, roughness length, surface resistance) of the vegetation-atmosphere interaction models and initialize their prognostic variables (e.g., soil moisture or initial evapotranspiration rate) on continental or global spatial scales. Theory and experiment have indicated that it is possible to estimate some of these quantities from remotely sensed data, specifically, some components of the radiation budget, roughness length, surface resistance, and soil moisture.

Radiation budget. Satellite sensors have been used for some time to estimate components of the shortwave radiation budget: cloudiness, surface insolation, $K\downarrow$, incident photosynthetically active radiation (PAR), and albedo, α, have been calculated using GOES and Meteosat observations. Thermal and microwave instruments have also been used to calculate the atmospheric profiles of temperature and humidity and the surface radiative temperature. These parameters may be used to calculate the net surface longwave flux ($L\downarrow - \varepsilon\sigma T_s^4$) and combined with the information on net shortwave fluxes $K\downarrow(1-\alpha)$ to yield time series of net radiation in (1). It should be noted that the extraction of these parameters from the satellite-observed radiances (at the top of the atmosphere) is not straightforward, given the problems of viewing geometry, sensor calibration, narrowband to broadband interpolation, cloud screening, and atmospheric corrections. However, a number of algorithms exist to compensate for these effects, and research continues to improve them. Summaries of the algorithms are given in the review by *Sellers et al.* [1990*b*].

Surface roughness. A sensitivity study by *Sud and Smith* [1985] indicated that the climate system is relatively insensitive to the realistic range of uncertainties in the surface roughness field. Remotely sensed data can be used to classify the Earth's surface into vegetation categories, which combined with morphological data for each category could provide adequate fields of the surface roughness length (z_0). The effect of surface roughness on the backscatter of coherent and incoherent microwave radiation (measurable with radar and passive microwave instruments) has been investigated both experimentally and through the development of theoretical models [*Fung and Eom*, 1981; *Tsang et al.*, 1982; *Mo et al.*, 1984; *Pitts et al.*, 1987]. These models relate the morphological characteristics of vegetated canopies to the strength of the scattered microwave signal. By using these models and inversion techniques, it may be possible to utilize radar data to extract vegetation canopy morphological properties (e.g., canopy height and density) for use in (2) and (5).

Surface resistance and soil moisture. Surface resistance and soil moisture determination are bound up with our understanding of how vegetation controls the energy budget. A number of different (though related) methods for extracting these parameters have been proposed; these include analyses of surface temperature, visible and near-infrared reflectances (spectral vegetation indices), and the microwave emission and scattering from the surface.

With regard to surface temperature, satellite observations of the radiometric surface temperature may be used directly or may be converted to the "aerodynamic" surface temperature T_r in (6). Meteorological data can be used to estimate r_a and T_a over the site and the sensible heat flux H may be calculated from (6); λE may then be obtained as a residual from (4), provided observations or estimates of R_n and G are available.

Spectral vegetation indices (SVI) have been used extensively to study the vigor and temporal dynamics of vegetation on large scales; see, for example, *Tucker et al.* [1986]. A number of theoretical analyses have shown that (1) canopy and leaf photosynthesis are closely related to the transpiration rate through the control of leaf stomata; see Figure 2 and the work of *Collatz et al.* [1991]; (2) the fraction of photosynthetically active radiation (FPAR) absorbed by the vegetation canopy is a nearlinear indicator of canopy photosynthetic capacity and unstressed canopy conductance, see *Sellers* [1987], *Sellers et al.* [1992], and *Hope* [1987]; and (3) some spectral vegetation indices are near linearly related to FPAR, see *Sellers* [1987] and *Hall et al.* [1990]. Thus the SVIs have the potential of providing direct information on vegetation canopy photosynthetic rates, stomatal conductances (inverse of resistance, see (9)), and hence transpiration rates.

With regard to soil moisture some vegetation-atmosphere models calculate the canopy resistance as a function of plant physiological terms and soil moisture. Solution of the energy balance relations (4) through (9) using remotely sensed data may allow an inference of soil moisture content in the root zone. In addition, microwave remote sensing has shown some promise for measuring soil moisture content in the upper few centimeters of the soil (see, for example, *Schmugge* [1983], *Dobson and Ulaby* [1986], and *Wang et al.* [this issue]). These data also have potential when used in conjunction with water and energy balance models to infer root zone soil moisture.

In summary, it was proposed that realistic biophysical models should improve our representation of land-surface–atmosphere interactions and that such improvements should enhance the realism and accuracy of climate models. It was also apparent that such models would be of limited use without a capability for obtaining critical input parameters on a global scale. Satellite remote sensing represents the most feasible means for obtaining such data.

While this line of thought looked promising, prior to the Boulder workshop of 1983 there had been no serious attempt to take simultaneous land surface observations of meteorological and biophysical parameters at sufficient temporal and spatial resolution (to allow for the effects of surface heterogeneity) and over a large enough area (to be observable from orbit) to permit proper comparison of satellite-derived quantities with actual surface conditions. In fact, very little work had been done on the role of biology in controlling the exchanges of mass, heat, and momentum between the surface and the atmosphere at length scales larger than a few hundred meters. To obtain a complete understanding of how the important biological scale processes governing energy-water-carbon exchange scale up to the "atmospheric" and remote sensing length scales of a few kilometers, it was essential to design a multiscale, multidisciplinary experiment.

2.4. *FIFE Objectives*

The GCM-biosphere models currently in use or under development incorporate very crude descriptions of the biophysical processes described above (most current land surface parameterizations have their origins in small-scale biological studies). Additionally, these models are initialized, with respect to vegetation type, cover fraction, phenological stage, and soil moisture, with climatologies based on geographic survey work or extrapolation. In short, existing land surface parameterizations suffer from (1) the "scale gap" between the biological and the meteorological disciplines and (2) from the lack of a global observing system to initialize and validate them.

FIFE was designed to address these issues. Specifically, the goals of the experiment and associated research were as follows:

1. Upscale integration of models: The experiment was designed to test the soil-plant-atmosphere models developed by biometeorologists for small-scale applications (millimeters to meters) and to develop methods to apply them at the larger scales (kilometers) appropriate to atmospheric models and satellite remote sensing.

2. Application of satellite remote sensing: Even if the first goal were achieved to yield a "perfect" model of vegetation-atmosphere exchanges, it would have very limited applications without a global observing system for initialization and validation. Accordingly, the experiment was tasked with exploring methods for using satellite data to quantify important biophysical states and rates for model input.

Given the broad goals of the project, upscale integration of models and the application of satellite remote sensing, the experiment team dedicated itself to designing a feasible experiment that would provide the necessary data for testing models and satellite data algorithms. The specific objectives of the field phase of the experiment followed directly from the goals.

1. The simultaneous acquisition of satellite, atmospheric, and surface data: At the most basic level, FIFE provides a data set which allows direct comparison between satellite observations and surface parameters and processes associated with surface-atmosphere exchanges of energy and mass. These observations include satellite data, airborne radiometric data, and measurements of surface and near-surface states, such as vegetation characteristics and soil moisture.

2. Understanding the processes controlling surface energy and mass exchange and how these are manifested in satellite-resolution radiometric data: To achieve this objective, an active effort was made to acquire data over a range of spatial and temporal scales. These data were used to test various methods of integrating our understanding of small-scale processes (e.g., photosynthesis, transpiration, light scattering by leaves) up to the scale of satellite pixels and atmospheric turbulent transport, that is, several kilometers. In this sense, FIFE was directed at resolving the problem of studying processes and states over a range of scales, from individual plant leaves up to fluxes over large landscape units. To achieve this objective, radiometric data, measurements of the fluxes of heat, water vapor, CO_2, and momentum, and biophysical data were collected at scales ranging from the leaf $(10^{-2}\ m)^2$, through the canopy $(1\ m)^2$, flux station $(10–100\ m)^2$ up to the dimensions of the entire site (several kilometers); see Figure 1. A stratified sampling design was implemented with the aim of spatially aggregating the results from the relatively small scale surface measurements (surface flux stations, biophysical studies, direct soil moisture samples) to provide equivalent information on the scale of the entire FIFE area.

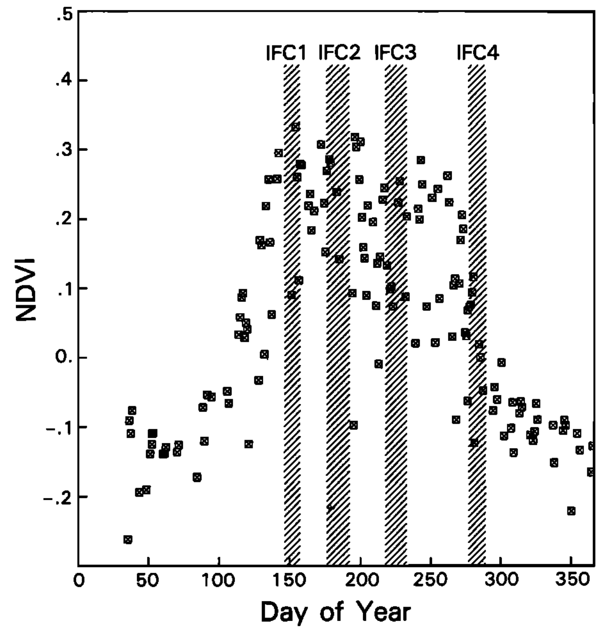

Fig. 3. Timing of the intensive field campaigns (IFCs) of FIFE 87, superimposed on clear-day NOAA 9 NDVI data (uncorrected) collected during FIFE 87.

3. Experiment Design

3.1. *Size, Duration, and Scope*

Given the objectives, three central issues framed the experiment design: the size of the site, the duration of the field phase, and the location of the site. First, the size of site was determined by constraints arising from the practicality of meshing surface observations with satellite data and airborne eddy correlation measurements, that is, the site had to be small enough to conserve the maximum density of the available surface instrumentation but large enough so that the turbulent structure of the planetary boundary layer could be adequately sampled by aircraft and a reasonable number of satellite pixels could be placed within the site boundary. The resulting compromise was a 15×15 km site in which the surface instrumentation was distributed using a stratified sampling allocation based on land management treatment and topography; see the paper by *Davis et al.* [this issue].

The duration of FIFE was determined by the need for data covering a range of surface conditions in terms of soil moisture, vegetative phenology, incoming radiation, and the constraints on the available measurement resources. Clearly, an annual cycle is the minimum interval required to observe the range of surface conditions that would allow an adequate evaluation of interpretive and predictive algorithms. Therefore a monitoring program of continuous data acquisition (satellite, automatic meteorological station, hydrological, and biometric data) was initiated in early 1987 and extended through October 1989. This effort provided the data necessary to force the simulation models and a record of the slowly varying processes associated with vegetation phenology and hydrology. In 1987 the monitoring program was punctuated by four intensive field campaigns (IFCs); see Figure 3. During the IFCs, teams of experimenters with their specialized equipment and research aircraft were committed to the field for periods of 12 to 20 days at a time. Each IFC was scheduled to cover a different phenological

Plate 1. SPOT image of FIFE experimental area and environs acquired on March 20, 1987; 60 × 60 km, view angle 2·3° from nadir. The FIFE experiment area is the 15 × 15 km area slightly right of center in the image. Manhattan, the Kansas River, and the Tuttle Creek reservoir are just to the north.

stage of the vegetation. The objective of the IFCs was to gather those data necessary for the rigorous testing of models and algorithms relating observed radiances to surface states (vegetation cover, health, soil moisture, etc.) and surface fluxes (heat, water vapor, CO_2, momentum). In 1989 an additional 20-day IFC was executed.

The location of the experiment was mainly decided by practical considerations. The site selection criteria included a requirement for a grassland of moderate topography (measuring fluxes over forests or steep slopes is relatively difficult), strong seasonal climatic forcing (that is, a midcontinental climate), proximity to a research organization for logistical support, and airfields for basing the research aircraft. The Konza Prairie Research National Area, owned by the Nature Conservancy and managed by Kansas State University (KSU) with the support of NSF, was selected as the focus of the study because of its relative homogeneity and logistical advantages. The entire FIFE study area thus consists of this prairie reserve area, which is an NSF long-term ecological reserve (LTER), and the surrounding privately owned pastures, all located a few kilometers southeast of Manhattan, Kansas; see Plate 1.

3.2. *Stratification of the FIFE Area*

One of the goals of FIFE was to provide a description of the near-surface climatology and fluxes over the entire 15 ×

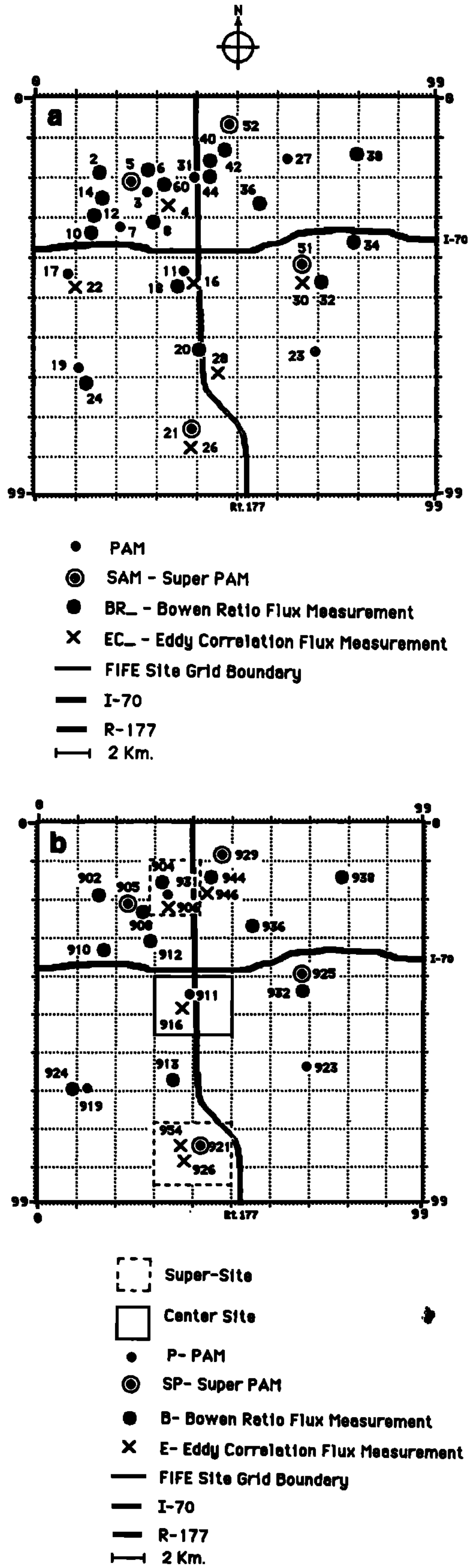

Fig. 4. Location of automatic meteorological stations and surface flux measurement stations in (*a*) FIFE 87 and (*b*) FIFE 89; see also Table 1. The site reference grid numbers in Table 1 can be read off the easting (first two digits) and northing (second two digits), respectively. For example, the full reference "ID" for site 16 in FIFE 87 is 4439-ECV, which interprets into: 44 is northing grid number, 39 is easting grid number, EC is eddy correlation, and V is Verma.

15 km area using surface instrumentation (automatic weather stations and flux measurement equipment) to compare with the relatively large-scale estimates provided by radiosounding, airborne flux equipment, and models forced with satellite data. Accordingly, the site was stratified on the basis of topography (valley bottoms, slopes of different aspect and grade, and plateau tops) and management treatment (burned or unburned); see EXPLAN 87. The automatic weather stations and the flux measurement stations were distributed among the strata to provide an area-weighted and strata-weighted sampling scheme; see Figure 4 and Table 1.

In the spring of 1987 the automatic meteorological stations (AMS) were set out as shown in Figure 4*a*. These were the portable automatic mesonet (PAM) stations built and fielded by the National Center for Atmospheric Research (NCAR). In addition to a conventional suite of meteorological measurements, four super-AMS (SAMS) were equipped with several extra sensors for measuring components of the radiation balance. These SAMS were distributed one to each quadrant of the site; see Figure 4.

Fourteen Bowen ratio and six eddy correlation flux stations were put in position prior to the first IFC of 1987. The surface flux equipment, described in more detail in the Surface Flux (SF) section of this issue, was typically mounted on small towers standing 1 to 2 m above the surface. At this height, most of the measured flux is thought to be influenced by the land surface extending from a few tens to a few hundred meters upwind of the instrument. The devices were therefore assumed to be taking data representative of their assigned strata. Some of the stations operated more or less continuously from the beginning of IFC 1 through to the end of IFC 4, but most were running only during the IFCs. In 1989 the site was equipped with a smaller complement of flux sensors, see Figure 4*b* and Table 1*b*, which operated for the 20 days of the FIFE 89 IFC.

3.3. *Organization and Planning*

In the fall of 1986 the project was organized into two interlocking components. The staff science group, which was made up of NASA scientists and contractors and Kansas State University scientists, technicians, and students, was charged with managing the execution of the experiment and ensuring the collection of the monitoring-type data sets or data sets that required highly specialized equipment. Specifically, the staff science group had responsibility for the overall coordination of the experiment, management of the airborne remote sensing program, the FIFE information system (FIS), and a range of ancillary measurement and logistic support activities; see Table 2.

In 1986, 29 investigator teams were selected to participate in the experiment through a standard NASA peer review process. At the first meeting of all the FIFE participants the teams were divided into six groups, more or less on the basis of disciplinary interest and instrumentation. The team principal investigators and their reference numbers are listed in Table 2. A brief description of the aims, composition, and equipment of each group is given below; more details may be found in EXPLAN 87.

The ABL group consisted of three teams equipped with flux aircraft (the NCAR King Air, the University of Wyoming King Air, and the Canadian National Aeronautical Establishment Twin Otter), a radiosounding team, two lidars and some sodar equipment. The group had the aim of

TABLE 2. Staff and Principal Investigator Science Teams in FIFE

Staff	Responsibility
Goddard Space Flight Center (GSFC)	Experiment coordination, FIFE information system, radiometric calibration, helicopter instrument package, airborne remote sensing data processing, sunphotometry.
Kansas State University (KSU)	Surface monitoring program: soil moisture, biophysics, hydrology and photometry. Intensive field campaign activities: intensified monitoring program, logistic support, cloud monitoring (Henderson-Sellers).

Reference Number	Principal Investigator	Equipment
	Atmospheric Boundary Layer (ABL)	
ABL-1	Brutsaert	Radiosondes
ABL-2	Eloranta	Near-Infrared LIDAR
ABL-3	Gal-Chen	Thermal Doppler LIDAR
ABL-4	Grossman	Flux aircraft (NCAR King Air)
ABL-5	Kelly	Flux aircraft (University of Wyoming, King Air)
ABL-6	McPherson	Flux aircraft* (NAE Twin Otter)
	Surface Fluxes (SF)	
SF-1	Kanemasu	Bowen ratio (6, 4)
SF-2	Fritschen	Bowen ratio (6, 7)
SF-3	Gurney	Bowen ratio (2, 0)
SF-4	Smith	Bowen ratio (2, 2)
SF-5	Stewart	Eddy correlation (1, 1*)
SF-6	Verma	Bowen ratio (1, 0)
SF-7	Wesely	Eddy correlation (1,* 1*)
SF-G	Weaver	Eddy correlation (3, 0)
SF-SU1	Panin	Eddy correlation (0, 1)
	Correction/Calibration (CC)	
CC-1	Bruegge	Photometer
CC-2	Gautier	Calibration work
CC-3	Palluconi	TIMS, emission spectrometer
CC-4	Wrigley	C-130 airborne photometer
CC-SU1	Kozoderov	Sun spectrophotometry
	Surface Radiances and Biology (SRB)	
SRB-1	Asrar	CO_2, H_2O enclosure
SRB-2	Blad	Surface radiometer
SRB-3	Deering	Surface radiometer (PARABOLA, SE-590)
SRB-4	Irons	Airborne pointable scanner (ASAS)
SRB-5	Schimel	Biophysical measurements
SRB-6	Seastedt	Grazing experiments
SRB-7	Groffman	Trace gas fluxes
SRB-SU1, 2	Beliav, Pliuta	Helicopter spectrometers
SRB-SU3	Migalin	Helicopter infrared radiometer
SRB-SU4	Mihalenko	Biophysics
	Soil Moisture (SM)	
SM-1	Milly/Wood	Catchment water balance
SM-2	Peck	NOAA airborne γ ray sensor
SM-3	Ungar	Impedance probe
SM-4	Van Zyl	NASA airborne SAR
SM-5	Wang	NASA C-130 radiometer (PBMR)
SM-6	Moore/Gogenini	Airborne, helicopter radar/scatterometer
SM-SU1	Grin	Surface validation
	Integrative Science (IS)	
IS-1	Dozier	Remote sensing, geographic analyses
IS-2	Goward	Remote sensing, energy balance
IS-3	Sellers	Remote sensing, energy balance
IS-4	Wetzel	Remote sensing, energy balance

For SF teams, numbers in parenthesis refer to number of devices deployed in FIFE 87 and 89 respectively. Asterisks denote CO_2 flux measurement.

obtaining area-averaged flux profiles of momentum, heat, moisture, and CO_2 over the FIFE area with an emphasis on characterizing diurnal variability. There was a specific objective directed at comparing the flux estimates provided by different techniques from within the group and with those provided by the SF group and modelers. The SF group consisted of seven teams in 1987 and nine teams in 1989, fielding 20 and 16 flux measurement rigs, respectively. In 1987 the rigs were distributed around the site with due reference to the stratification scheme and the need for approximately uniform coverage.

In 1987, only one rig measured CO_2 flux in addition to latent and sensible heat fluxes. In 1989 the experiment was redesigned and many of the flux rigs were concentrated at or

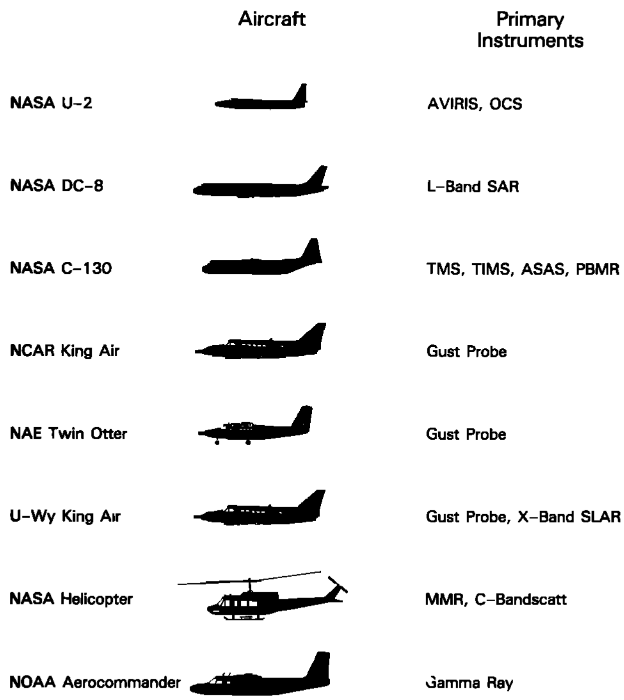

Fig. 5. Aircraft and airborne instruments used in FIFE.

near three supersites, see Figure 4*b*, which became the foci of integrated flux measurement and remote sensing validation studies. Each supersite was assigned at least one CO_2 flux measurement rig in 1989. The SF group measured radiation, heat and moisture fluxes at all the sites, and momentum and CO_2 fluxes at some sites with a view to providing data that could be used to generate large-scale (15 × 15 km) estimates of the surface fluxes at half hourly or better time resolution.

The correction and calibration (CC) group used surface and airborne sunphotometers to provide information for the atmospheric correction of the satellite and airborne remote sensing data. Additionally, laboratory and field equipment were used by this group and some staff scientists to calibrate all the airborne and field radiometers used in the study.

The surface radiances and biology (SRB) group was directed at establishing links between remote sensing signatures and surface states. Three teams used a variety of surface equipment and a tiltable airborne scanner to characterize the radiance and emittance fields associated with vegetated surfaces. A staff science team used a helicopter equipped with a tiltable radiometer to address the same issues and was effectively an integral part of the group's activities. The remaining teams, four in 1987 and five in 1989, worked on a range of biophysical problems concerned with the small-scale validation of surface flux and radiance measurements. These studies included measurements of photosynthesis, soil respiration, vegetation response to different management treatments, and some ecophysiological work.

The soil moisture (SM) group consisted of three teams working with airborne sensors (a microwave radiometer on the NASA C-130, a gamma ray sensor on the NOAA Aerocommander, and a scatterometer on the NASA helicopter) and two teams who took surface measurements to support hydrological and soil moisture studies. The overall goal of the group was to characterize the spatial and temporal patterns of soil moisture within the FIFE area and to validate and calibrate the different methods of soil moisture measurement.

The integrative science (IS) group contained four teams who had proposed modeling or analytical studies with no measurement component. The IS group participated in the specification of the sampling strategy described earlier and worked to maintain the interdisciplinary links between the groups.

The division of the science teams into this group structure was intended to facilitate the coordination of similar activities, to iron out calibration problems, and to specify common data quality standards for FIS. In practice, interactions among the groups and with staff scientists proceeded continuously and were a regular feature of operational planning meetings, workshops, and symposia.

3.4. *The FIFE Aircraft*

During the IFCs, several research aircraft were committed to the site to gather remote sensing and turbulent flux data in coordination with surface team observations and satellite overpasses. A total of eight aircraft worked over the FIFE area in FIFE 87 and 89, see Figure 5, but only six had major roles in the day-to-day execution of the experiment.

1. The NASA C-130: This aircraft comes equipped with two scanners (thematic mapper simulator (TMS) and thermal infrared multispectral scanner (TIMS)) that collect visible, near-infrared, and thermal infrared data in a total of 14 wavelength bands. From its operating height of 16,000 ft (4840 m) above ground level (agl) the aircraft could "cover" the entire site twice with about 30% overlap using six flight lines. This series of observations routinely provided multiple-view-angle measurements of surface radiances. The aircraft was also equipped with a tracking sunphotometer for atmospheric corrections (ATSP), a pointable, linear array high spectral resolution radiometer (advanced solid state array spectroradiometer (ASAS)) designed for bidirectional reflectance studies, and a push broom microwave radiometer (PBMR) for soil moisture mapping. When conducting a soil moisture mission with the PBMR, the aircraft would fly a series of parallel lines at 1000 to 3000 ft (303 to 901 m) agl and roughly the same distance apart. Coverage of two thirds of the site in this manner required 12 flight lines.

2. Three "flux" (measurement) aircraft: The NCAR King Air and the University of Wyoming King Air measured turbulent fluxes of momentum, sensible heat, and latent heat using eddy correlation equipment. The National Aeronautical Establishment (NAE) of Canada contributed its similarly equipped Twin Otter to FIFE for three IFCs in 1987 and also to FIFE 89. The Twin Otter had the unique capability of measuring CO_2 fluxes (area-averaged photosynthesis minus respiration) in addition to the other fluxes. Usually, two flux aircraft were available per IFC, which allowed for full coverage of daytime conditions and intercomparison between instruments. The flux aircraft employed a variety of flight patterns to collect their data. Often, when two aircraft were available, one would fly a low-level grid over the area to measure the spatial arrangement of surface fluxes while the other flew a "double-stack" pattern to characterize the three-dimensional flux field; see papers in the Atmospheric Boundary Layer section of the issue.

3. The NASA H-1 (Huey) helicopter: The H-1 was

TABLE 3. Aircraft Missions for FIFE 87

Aircraft	Mission Code	Instrumentation
C-130	C-1N	Night thermal survey (TIMS, TMS).
	C-1D	Daytime survey (TIMS, TMS, ASAS, ATSP).
	C-3	Soil moisture survey (PBMR); 1–15 lines in FIFE 87. Lines reoriented north-south in FIFE 89.
	C-3*	Partial C-3.
	C-1S	Reduced set of low-level soil moisture survey (PBMR) flight lines used in FIFE 89.
Flux aircraft (3)	F-1	Airborne flux pattern (gust probe).
	F-3	Soil moisture survey (University of Wyoming SLAR).
	F-E	Regional survey.
Helicopter	H-1A	Nadir radiometric data collection (MMR).
	H-1B	Multiangle radiometric data collection (MMR).
	H-3	Soil moisture survey (C-band scatterometer).
Aerocommander	N-3	Soil moisture survey (γ ray).

See Figure 5 for aircraft information. Mission codes are used in the IFC summaries shown in Table 5. Asterisk denotes partial mission.

equipped with a pointable radiometer (MMR) that recorded visible, near-infrared, and thermal infrared radiation reflected or emitted from the surface. A C-band scatterometer was used for soil moisture surveys. The H-1 hovering capability provided precisely located nadir and multiangle radiometric data on a nearly simultaneous basis over large areas.

4. The NOAA Aerocommander: This aircraft was equipped with a gamma ray instrument and was used to conduct low-level soil moisture surveys over the FIFE area in IFCs 1 and 2 in FIFE 87, and during the FIFE 89 IFC.

The aircraft participating in FIFE were assigned sets of flight plans which were each directed at specific data acquisition goals while minimizing interference with the other FIFE aircraft and civil and military air traffic operating in the area; see Table 3. (Up to five FIFE aircraft were working within the limited FIFE area simultaneously.) The flight plans were coordinated with each other, with the appropriate surface measurements, and with satellite overpasses to provide the meaningful combination of data sets specified in the project goals. To do this, three broad plans, subject to wide operational interpretation, were proposed and executed as conditions permitted.

Coordinated mission plan 1 (CMP 1), diurnal cycle: During CMP 1 all the surface teams gathered data at as high a time resolution as possible throughout a complete diurnal cycle. Aircraft missions were timed to coincide with satellite overpasses and provided remote sensing data (imagery and point radiometric measurements) and flux data over the entire site. These data are being used in those simulation models that rely on the temporal variations in surface heating and fluxes for the calculation of surface states. Figure 6*a* shows the aircraft missions associated with a CMP 1.

Coordinated mission plan 2 (CMP 2), satellite overpass: CMP 2 corresponds to a segment of CMP 1, so that aircraft and surface radiometric observations are coordinated with each other and a single satellite overpass; see Figure 6*b*.

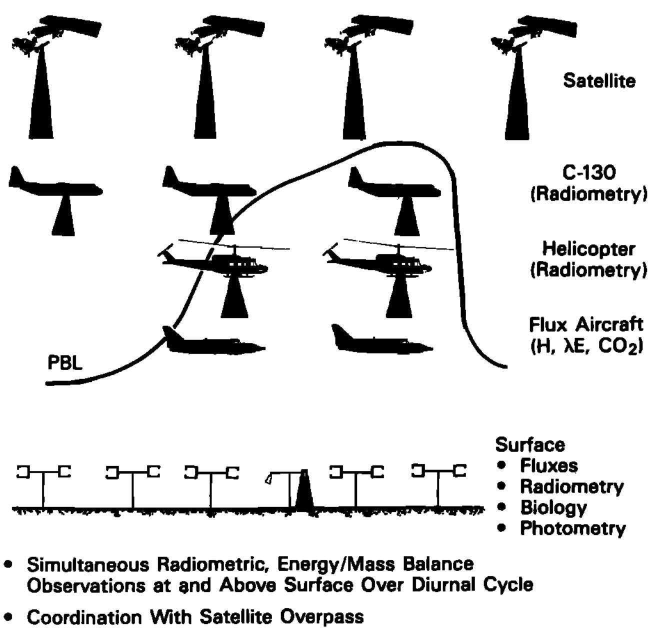

Fig. 6*a*. Scheme of coordinated mission plan 1 (CMP 1): aircraft underflights were scheduled for all satellite overpasses during a 24-hour period.

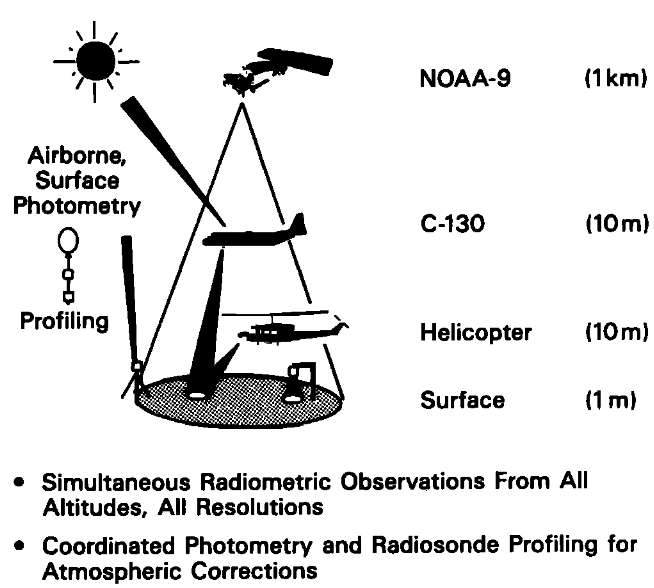

Fig. 6*b*. Scheme of coordinated mission plan 2 (CMP 2): aircraft support a single satellite overpass.

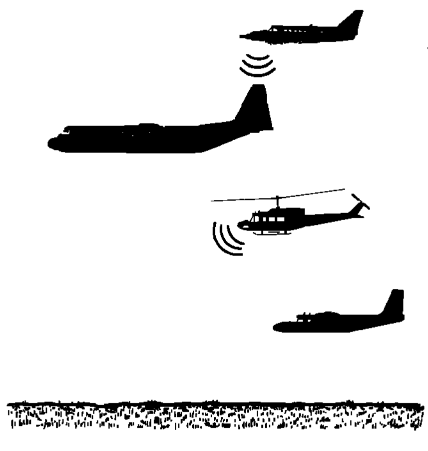

Fig. 6*c*. Scheme of coordinated mission plan 3 (CMP 3): aircraft support a soil moisture experiment, in many cases on overcast days when satellite data could not be acquired.

These data are being used for the testing of radiometric algorithms.

Coordinated mission plan 3 (CMP 3), soil moisture survey: In CMP 3, surface teams and a variety of airborne instruments were used to provide estimates of soil moisture content on scales ranging from surface gravimetric sampling up to complete coverage of the site; see Figure 6*c*. Validation and calibration of indirect measurement techniques, e.g., microwave radiometry, was an important goal.

Flight plans contributing to CMP 1 or CMP 2 were assigned a "1" after the aircraft-type identifier; those contributing to CMP 3 were assigned a "3"; see Table 3. Full details of the flight plans used by all of the FIFE aircraft and descriptions of their instrument complements are given in EXPLAN 87 and EXPLAN 89.

3.5. *Satellite Data Acquisition*

Satellite data acquired over the FIFE site from the spring of 1987 through to the end of October 1989 were routinely processed and entered into the FIFE information system (FIS). During the IFCs, attempts were made to capture all the available data provided by the GOES, NOAA series, Landsat, and SPOT satellites. In 1989 a few images were also obtained from the Russian satellite Kosmos 1939.

The characteristics of the satellites used in FIFE are listed in Table 4. Briefly, the GOES satellite provides half hourly, coarse spatial resolution, visible, and thermal data that are useful for surface and atmospheric radiation studies. The NOAA polar orbiter satellites (NOAA 9, 10, and 11) each passed over the site twice a day and provided visible, near-infrared, and thermal data at 1- to 2-km resolution depending on view angle. The visible and near-infrared data can be combined to give estimates of surface albedo or compared to yield vegetation indexes (vegetation is typically dark in the visible wavelength region and reflective in the near-infrared, while bare soil normally shows little change in reflectance with wavelength). The thermal infrared data can be used in thermodynamic energy balance models. The NOAA series of satellites acquire data over the entire globe every day. It is hoped that the algorithms and models developed as a result of FIFE will permit a quantitative use of these data in future global scale studies of the land surface.

The Landsat, SPOT, and Kosmos 1939 sensors collect their most useful high spatial resolution data, of the order of a few tens of meters, within the visible and near-infrared regions. Opportunities for acquiring these data at a specified site are limited: two or three days out of six for SPOT and one day in sixteen for Landsat. However, these data are provided at a sufficiently high spatial resolution to permit direct comparison with aircraft remote sensing data and surface flux station measurements.

3.6. *The FIFE Information System (FIS)*

An integral part of the first FIFE science plan [*Schmugge and Sellers*, 1986] was a data system that could serve the FIFE investigators as a tool for designing the experiment as well as for organizing and manipulating the complex data set during and after the data collection effort. A dedicated, remotely accessible data system was developed at NASA's Goddard Space Flight Center (GSFC) to meet this requirement. For a full description of the evolution and operation of FIS, see *Strebel et al.* [1990*a*, *b*].

An experiment like FIFE can be described as having four phases: planning, execution, analysis, and publication of results. The supporting information system had to take on different tasks in each phase and move smoothly from one to another.

Planning activities. The FIS, although still in an early development stage at the time, contributed to many of the initial experiment planning activities. As early as December 1986 a rudimentary geographic information system (GIS) capability was used to provide site background information for the first planning meeting of all of the investigators. A data base of satellite overpass times and viewing geometries was also developed to assist preexperiment mission planning. The same data base was later used on a daily basis in the field during the IFCs in the summer of 1987 to schedule aircraft and ground operations.

In planning the additional 1989 field campaign, the information system played an even more active role. In order to target areas which required further study, mission planners relied on the now fully functional GIS and data distilled from the 1987 IFCs. The data review encompassed satellite and aircraft images, photographs, maps, charts, plots, documents, and personal communications with the investigators. As priorities for the 1989 data collection effort were established, FIS staff initiated supporting activities, including assigning consistent site and instrument identification numbers and planning site survey efforts (including the use of GPS technology) to enhance the usefulness of the GIS.

Execution. It was discovered during the FIFE 87 IFCs that a field presence by the information system was invaluable for operations management. A full coordinated mission plan involving a 24-hour cycle of multiple aircraft missions and ground observations could represent an expenditure of many tens of thousands of dollars. Real-time information (especially on weather and field conditions) was critical to informed decision making by the duty mission manager and the science steering group.

In addition to providing mission support, FIS personnel were deployed at the experiment site to facilitate the following functions: (1) design and implementation of software and procedures for data quality control; (2) documentation of site locations and characteristics, collection of descriptions of

TABLE 4. Satellites and Associated Sensors Used in FIFE

Satellite	Instrument/Band	Band Pass	Nidar Resolution	Repeat/Time
NOAA 9/11	AVHRR-1	0.570–0.699	1.1 km	2/day
	AVHRR-2	0.714–0.983		
	AVHRR-3	3.525–3.931		~0400–0600
	AVHRR-4	10.334–11.252		~1500–1700
	AVHRR-5	11.395–12.342		
NOAA 10	AVHRR-1	0.571–0.684	1.1 km	2/day
	AVHRR-2	0.784–0.984		~0900
	AVHRR-3	3.554–3.3930		~2100
	AVHRR-4	10.601–11.445		
SPOT	XS1	0.500–0.588	20 m	2–3 days
(HRV-1)	XS2	0.615–0.658	20 m	in 6 days
	XS3	0.773–0.865	20 m	1200–1300
	PAN	0.516–0.715	10 m	
(HRV-2)	Similar to HRV-1			
Landsat 5	MSS-1	0.497–0.607	60 m	1/16 days
	MSS-2	0.603–0.615	60 m	~0945
	MSS-3	0.704–0.814	60 m	
	MSS-4	0.809–1.036	60 m	
	TM-1	0.451–0.521	30 m	
	TM-2	0.526–0.615	30 m	
	TM-3	0.622–0.699	30 m	
	TM-4	0.771–0.905	30 m	
	TM-5	1.564–1.790	31 m	
	TM-6	10.45–12.46	120 m	
	TM-7	2.083–2.351	31 m	
GOES	VAS/VISSR	0.55–0.75	1 km	48/day
		10.00–12.00	4 km	48/day
	TOVS (sounder)	22 infrared	17 km	48/day
		4 microwave	109 km	48/day
Kosmos 1939	S-band radiometer	visible	150 m	irregular
	(410 conical scan)	NIR	150 m	
		2 MIR	500 m	
		TIR	500 m	
	High-resolution	0.5–0.6	45 m	
	radiometer	0.7–0.8	45 m	

instruments, and experimental procedures; (3) assistance to investigators in performing preliminary analyses of their data (software and hardware); (4) entering initial data sets into the on-line data base as they became available in the field to resolve potential formatting problems and expedite future availability; (5) operation, in conjunction with NCAR, of a field analysis system to provide real-time evaluation of data received from the NCAR AMS; and (6) installation and maintenance of a PC-McIdas station to provide a real-time monitoring and weather forecasting capability for mission management.

Analysis. Active distribution of data by FIS began during the preliminary experiment design phase of the experiment. Soon after the October 1987 field campaign, user log-ins climbed rapidly to a level of 100–200 queries per month. During this period the primary use of the on-line portion of FIS was to obtain supporting data sets interactively and to obtain information about processed image data, which were then distributed by mail on magnetic tape. As the analysis phase unfolded, interactive usage intensified, and there was more frequent use of the analog data sets and paper documentation located in the archive at GSFC.

Data publication activities. The FIS is now engaged in the fourth stage of its evolution, archiving and publishing the data for long-term use by the scientific community. The volume of digital data in FIS exceeds 120 Gbytes. Most of these data are the "raw" (level 0) digital imagery from aircraft platforms and satellite sensors such as advanced very high resolution radiometer (AVHRR), SPOT, and Landsat TM. A reduction factor of about 20 is achieved as the digital imagery is screened for suitability for further analysis during processing to level 1 (reformatted data, with location information added) or level 2 (geometrically and/or radiometrically corrected data). In addition, there are over 110 on-line data sets (organized as tables in a relational data base management system), occupying approximately 50 Mbytes of disk storage, which contain a complete inventory, reference information, and all of the nonimage digital data. An archive of analog data, primarily maps, photography, and video tapes, is also part of the data system. For the near future the entire tape archive, and on-line data base, is being incorporated into NASA's pilot land data system (PLDS). Eventually, resource constraints will prohibit maintaining these data on-line and so, as a long-term solution, a comprehensive collection of the reduced data sets is being published on a series of compact disk-read-only memories (CD-ROMs). The prototype volume, containing basic data from the 1987 field campaigns, was distributed in the fall of 1991 [*Strebel et al.*, 1991; *Landis et al.*, 1992].

The FIFE CD-ROMs are being published as simple ASCII files for as much of the data as possible, instead of employing a commercial CD-ROM data base package which would have encoded the data in special formats. This allows the data to be read on any computer, regardless of the operating

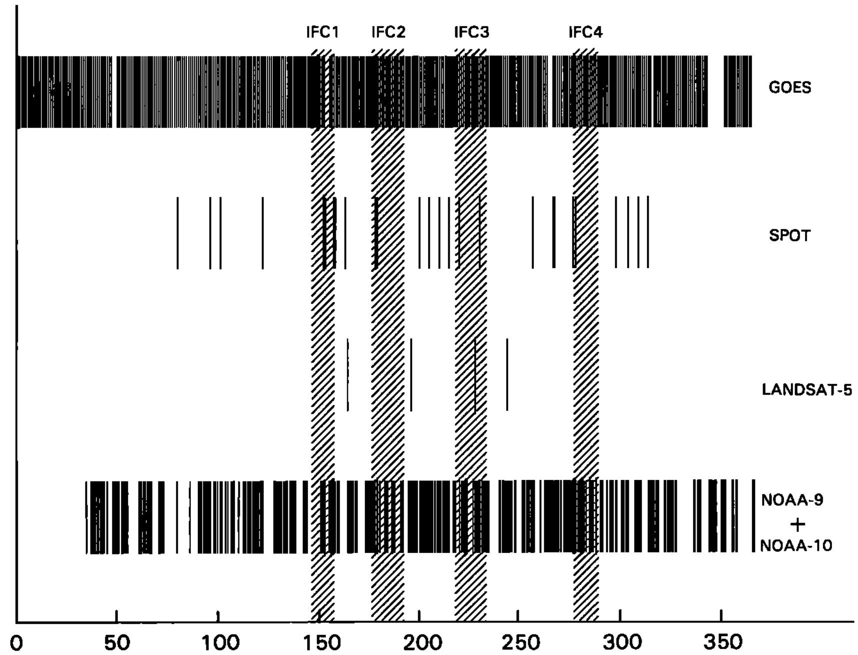

Fig. 7. Inventory of satellite data acquired in FIFE 87.

system. The data file structure allows the data to be linked by data type, location, and date. Detailed documentation accompanies each data set.

A custom PC-based (MS-DOS and MacIntosh) user-friendly interface has also been created. This interface gives simplified access to the data. Keywords can be used to find data, so that users need not known table names and structures to find what they need. Users can also browse through the data along any data type, location, or date axis, due to the links within the data files.

There is also a large volume of digital imagery contained in the FIFE CD-ROM set. All of the images have been compressed using an efficient encoding scheme developed by the FIS. On average this compresses the image and ancillary data files to 15 to 50% of their original size with no loss of information. The encoding scheme is fully documented and decoding source code and executables for a variety of machines (PCs, MacIntoshes, workstations, minicomputers) are provided with the CD-ROM.

The full series of CD-ROMS planned for issue during 1992 includes volume 1, all "point" data, indexes, documentation, and interface software; volume 2, all AVHRR level 1 data and Landsat and SPOT "browse" products; volume 3, selected C-130 airborne scanner (TMS) acquisitions covering all IFCs; volume 4, selected ASAS acquisitions; and volume 5, all AVHRR, Landsat, and SPOT level 2 data (NDVI, greenness, etc.). This CD-ROM series will make the entire FIFE data collection available to investigators on their desktop. Productive analyses using the data will therefore be possible throughout the rest of the decade and possibly well into the next century.

4. Field Operations

4.1. *Field Operations in 1987*

Starting in early 1987, the FIFE monitoring program provided a continuous record of satellite (GOES, NOAA series, Landsat, and SPOT) data, mesometeorological data from National Weather Service stations located within a 250-km radius of the site, micrometeorological data from the 12 AMS located on site, and a wide variety of soil (moisture content, physical properties, etc.), vegetation (leaf area index, species composition, biomass, etc.), and hydrological (rainfall, runoff, etc.) measurements. Figure 7 shows the satellite data inventory for 1987; this probably represents the most complete data set for a single study site ever assembled. Note, however, that only one usable Landsat scene was acquired during a FIFE 87 IFC (August 15, 1987) although five other scenes were obtained during 1987. The IFCs of 1987 saw the commitment of the six science groups to the site for a total of 57 days, supported by six research aircraft. During the IFCs, approximately 150 people were working at, around, or above the FIFE site; see Figure 8. The surface component of the monitoring program was intensified during the field campaigns: soil moisture samples were taken daily at all of the AMS locations and the frequency and scope of the biometric survey work were upgraded. The experiment operations were coordinated by a small staff working from a ranch house located within the site, supported by ground-to-ground and ground-to-air radio networks and a weather forecast operation.

Overall, the FIFE team succeeded in assembling the data sets called for in EXPLAN 87; in particular, at least one CMP 1 and two or more CMP 3s were executed in each IFC; see Table 5. Bad weather, storms and persistent cloudiness, hampered many operations in IFCs 1, 3, and particularly in IFC 2; see Figure 9. A complete record of FIFE 87 operations is published in the work of *Sellers et al.* [1990*a*], so only a brief synopsis will be presented here.

Table 5 summarizes the weather conditions, the SPOT and Landsat data acquisitions, and the aircraft missions executed during FIFE 87; explanations of the aircraft mission codes are given in Table 3. The last column on the right of

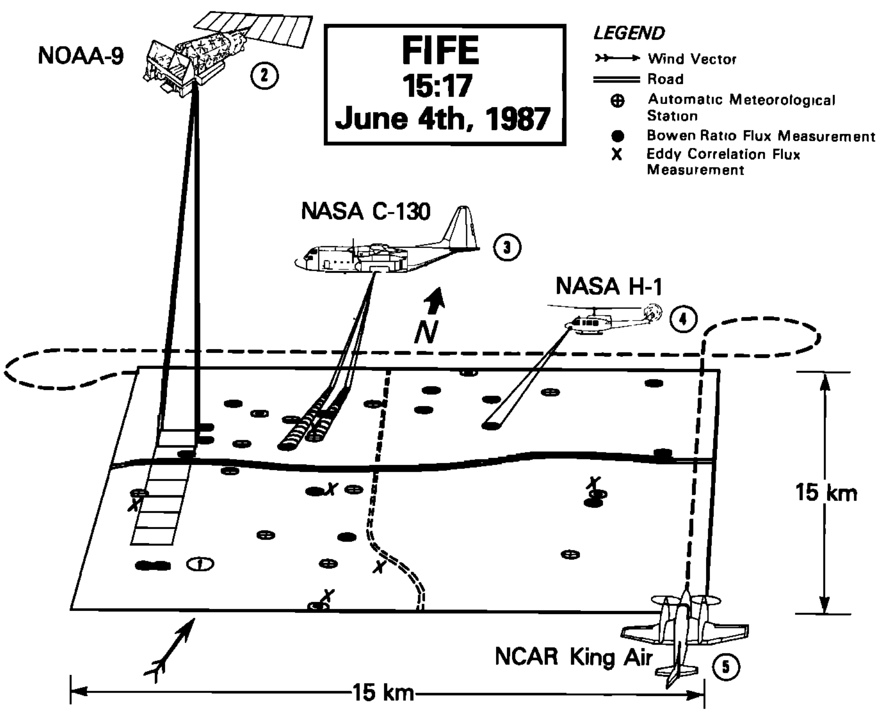

Fig. 8. Situation at the FIFE site at 1517, June 4, 1987, time of the NOAA overpass. (1) Surface flux stations and automatic meteorological stations monitor surface flux and near-surface meteorological conditions. (2) NOAA 9 satellite scans the site at 1-km resolution. (3) NASA C-130 traverses the site at 5000 m agl, taking scanner and sunphotometer data. (4) NASA helicopter hovers above preselected site at 250 m agl, acquiring radiometric data. (5) NCAR King Air collects eddy correlation data at 160 m agl.

Table 5 shows which, if any, coordinated mission plans were completed on a given day. At the end of FIFE 87 the participating scientists reviewed the preliminary data sets and mission logs and identified the best day in each IFC as the highest priority for data processing and submission (these days are specified as the "golden days" in Table 5). Other days which are known to have good data sets were assigned a slightly lower priority for data preparation and are identified as "silver days." Most days on which no aircraft missions were flown had bad weather.

The following are summaries of the four IFCs.

IFC 1, May 26 to June 6 (days 146–157). This IFC was targeted at capturing the vegetation "green-up" phase of late spring. The first few days were marked by clouds and rain followed by three clear days at the end of the IFC, during which almost all of the optical/thermal missions were flown. The golden day is June 6 (157), silver days are June 4 and 5.

IFC 2, June 25 to July 11 (days 176–192). This IFC was targeted at the "peak-greenness" stage of the vegetation phenology. The IFC was cloudy and rainy most of the time. As a result, little useful optical/thermal remote sensing was carried out. The TMS instrument on the C-130 failed on July 10 and this, combined with a poor weather prognosis for the last few days of the IFC, led to a decision to stop operations on the evening of July 11. The golden day is July 11 (192), silver days are July 7 and 10.

IFC 3, August 6–21 (days 218–233). This IFC was intended to capture soil moisture "dry-down" conditions in the late summer. There were two days of continuous rain in the middle of the IFC and conditions of variable cloudiness throughout most of the rest. The "best" CMP 1 was executed on August 15 (227) when Landsat 5 was underflown. The golden day is August 15 (227), silver days are August 16 and 17.

IFC 4, October 5–16 (day 278–289). This IFC was scheduled to characterize the fully senescent phase of the vegetation. There were scattered rain showers and cloudiness throughout most of the IFC. The IFC was preceded by a Landsat acquisition (October 4, day 277). There were a number of flux missions and helicopter missions conducted without the C-130 in the first part of the IFC (C-130 technical problems). The golden day is October 11 (day 284) although no predawn thermal mission was flown due to cloud cover. The rest of the day was exceptionally clear. The silver days are October 7 and 8.

Following the field phase of FIFE 87, data sets were processed by the staff science and team science groups and submitted to FIS. While complete or almost complete data sets were obtained by the monitoring program and many of the surface teams, see Figures 10 and 11, it was clear that the unusually wet summer of 1987 had substantially reduced the range of conditions observed by the science teams during the IFCs. Figure 9 shows the precipitation and soil moisture record during FIFE 87; the wet conditions during the first three IFCs impacted the surface energy balance regime so that the partitioning of energy was very similar (high evaporation rates, low sensible heat fluxes) during those periods; see Figure 12*a*. However, it appears that much of the high evaporation rate observed during IFC 3 was contributed by soil evaporation following the intense storms of August 12–13, 1987, as the net CO_2 flux in IFC 3 was considerably lower than that observed in IFCs 1 and 2; see Figure 12*b*.

The preliminary results and analyses carried out on the FIFE 87 data set are summarized in the FIFE interim report,

TABLE 5. Mission Summaries for FIFE IFCs

Date	Day of Year	Satellite	Aircraft Mission: Optical/Thermal	Aircraft Mission: Soil Moisture	Aircraft Mission: Flux	Cloud/Rain oktas/mm	CMP/Priority
				1987 IFC 1			
May 26	146					8/37.86	
May 27	147					8/0.00	
May 28	148			C-3		7/0.00	
May 29	149			C-3*		7/0.00	Incomplete C-3
May 30	150		C-1D, H-1B	C-3	F-1	3/0.00	
May 31	151	SPOT	C-1D			4/1.00	
			H-1B, H-1B				
June 1	152	SPOT	C-1N		F-1	2/0.00	
			H-1B		F-1		
June 2	153			N-3		7/0.00	
June 3	154		H-1B	N-3	F-E	3/0.00	
June 4	155		C-1N, C-1D, C-1D	C-3, N-3		*/0.00	Silver day
			H-1A, H-1B, H-1B				Partial CMP 1
June 5	156	SPOT	C-1N, C-1D, C-1D			*/0.00	Silver day
			H-1A, H-1B, H-1B				Partial CMP 1
June 6	157	SPOT	C-1N, C-1D		F-1	0/0.00	Golden day
			H-1A, H-1B		F-1		Partial CMP 1
				1987 IFC 2			
June 25	176			C-3		1/0.00	
June 26	177	SPOT	C-1N, C-1D, C-1D*		F-1B	1/0.00	*Partial CMP 1
			H-1A, H-1B*, H-1B*		F-1B		
June 27	178	SPOT				1/0.00	
June 28	179		C-1D, H-1B		F-1, F-1	2/17.64	
June 29	180					7/1.09	Weather down
June 30	181					8/3.36	
July 1	182		C-1D*, H-1A*			2/0.00	
July 2	183			C-3, H-3		4/0.00	
July 3	184					5/0.00	Weather down
July 4	185					6/0.00	Weather down
July 5	186				F-1	5/8.45	
July 6	187		C-1N, C-1D*	N-3	F-1	2/0.00	*Partial CMP 1
			H-1B, H-1B*				
July 7	188			C-3, H-3 N-3, N-3		7/1.32	
July 8	189	SPOT		N-3	F-1	6/0.00	
July 9	190			C-3, N-3	F-1	5/0.00	Silver day
July 10	191		C-1D, H-1B	N-3	F-1	4/0.00	TMS intermittent
July 11	192		C-1N, C-1D, C-1D		F-1, F-1	1/0.00	golden day, CMP 1*
			C-1N, H-1B, H-1B				TMS failed
				1987 IFC 3			
August 6	218		C-1N			?/6.50	Rain
August 7	219	SPOT	C-1D, C-1D		F-1, F-1	?/0.00	SPOT
			H-1, H-1				
August 8	220					?/0.95	Weather down
August 9	221			C-3, F-3	F-1,	?/0.00	
August 10	222		C-1D, C-1D, C-1D		F-1, F-1	1/0.00	CMP 1
			H-1, H-1				
August 11	223		C-1N, C-1D, 2H-1		F-1, F-1	*/0.00	
August 12	224					7/83.27	Weather down
August 13	225					7/0.86	Weather down
August 14	226			C-3, H-3, F-3	F-1	4/0.00	CMP 3
August 15	227	Landsat	C-1N, C-1D, C-1D		F-1, F-1	*/0.00	Golden day
			H-1, H-1		F-1		Landsat, CMP 1
August 16	228		H-1, H-1A	C-3*	F-1	*/0.00	Silver day
August 17	229	SPOT	C-1N, C-1D		F-1, F-1	*/0.00	Silver day
			H-1, H-1		F-1		SPOT
August 18	230					3/6.11	Weather down
August 19	231				F-1	2/0.00	C-130 to Iowa
August 20	232		C-1N, C-1D, C-1D		F-1	1/0.00	CMP 1
			C-1N, 2H-1, H-1		F-1, F-1		
August 21	233			C-3*, H-3, F-3		*/0.00	CMP 3*
				1987 IFC 4			
October 5	278					3/0.00	
October 6	279		H-1,	C-3, H-3	F-1	0/0.00	
					F-1, F-1		
October 7	280		H-1N, H-1		F-1, F-1	*/0.00	Silver day
					F-1, F-1		
October 8	281				F-1, F-1	*/0.00	Silver day
October 9	282		C-1D			1/0.00	

TABLE 5. (continued)

Date	Day of Year	Satellite	Aircraft Mission: Optical/Thermal	Aircraft Mission: Soil Moisture	Aircraft Mission: Flux	Cloud/Rain oktas/mm	CMP/Priority
				1987 IFC 4			
October 10	283					8/0.50	
October 11	284		C-1D, C-1D H-1, H-1		F-1 F-1, F-1	1/0.00	Golden day, CMP 1 CMP 1
October 12	285		C-1N, C-1D C-1D, H-1		F-1, F-1	1/0.00	Partial, CMP 1
October 13	286		C-1N, C-1D H-1, H-1		F-1	4/0.00	
October 14	287					5/2.32	Hard down
October 15	288			C-3, H-3	F-3	8/8.73	
October 16	289					5/17.09	
				1989 IFC 5			
July 24	205					?/0.00	
July 25	206					?/0.00	
July 26	207		H-1, H-1		F-1, F-1	?/0.00	
July 27	208		H-1		F-1, F-1 F-D, F-1	?/0.00	
July 28	209		H-1, H-1		F-D F-D, F-1, F-1	?/0.00	
July 29	210					?/0.00	Hard down
July 30	211	SPOT				?/2.50	
July 31	212			C-1S, H-3		?/17.15	
August 1	213			C-3, N-3, H-3		?/1.33	CMP 3
August 2	214			N-3	F-1 F-1, F-1	?/0.00	
August 3	215			D-J	F-1	?/2.64	
August 4	216	Landsat SPOT	C-1N, C-1D H-1, H-1	N-3 C-1S	F-1 F-1, F-1	0/0.00	Golden day, CMP 1
August 5	217			N-3		7/3.30	
August 6	218		C-1N, C-1D, C-1D H-1, H-1	N-3	F-1 F-1, F-1	0/0.00	CMP 1
August 7	219		C-1D, H-1	H-3, C-3, N-3	F-1, F-1 F-1, F-1	2/0.00	CMP 3+
August 8	220		C-1N, C-1D, C-1D H-1, H-1	N-3, N-3	F-1, F-1 F-D, F-D	4/0.00	CMP 1
August 9	221	SPOT Kosmos				1/0.00	Hard down
August 10	222			C-1S, H-3, N-3	F-1 F-1, F- 1N	6/0.00	CMP 3*
August 11	223		C-1D, H-1		F-1	3/0.00	CMP 2
August 12	224			H-3, C-3	F-1, F-1 F-1, F-1	6/0.00	CMP 3

Note that only successful SPOT and Landsat acquisitions are shown in the satellite columns. Explanations of the aircraft mission codes are given in Table 3. "Golden" and "silver" days are specified in the last column. Data collected on these days were given the highest priority for processing and analysis. Note that asterisk in aircraft mission column denotes a partial mission; asterisk in cloud or rain column denotes "trace"; "weather down" means all missions cancelled due to bad weather; "hard down" means scheduled stand down of all crews. CMP, coordinated mission plan.

edited by *Sellers et al.* [1990*a*]; it was the consensus of the FIFE scientists that the FIFE 87 data set had a few serious shortcomings, summarized below.

1. Dry down: The first three IFCs were marked by an unusually large number of storms and wet soil conditions, see Figures 9 and 12, while the last IFC was dry with dead vegetation. No extended soil moisture dry-down period was tracked by the science team which would have allowed the rigorous testing of the more sophisticated biophysical models.

2. CO_2 split: Insufficient data were collected to allow the partitioning of the total CO_2 flux into photosynthetic and respiration components. Some promising hypotheses relate gross photosynthesis to remotely sensed variables; these could not be satisfactorily tested with the FIFE 87 data alone.

3. Evapotranspiration components: Again, insufficient data were collected to allow the partitioning of the total evapotranspiration rate into vegetation (transpiration) and soil (evaporation) components.

4. Concentration/coordination: The experimental techniques used in FIFE 87 were subjected to criticism and reformulated. In particular, a more detailed strategy for correlating surface and airborne radiometry with surface flux

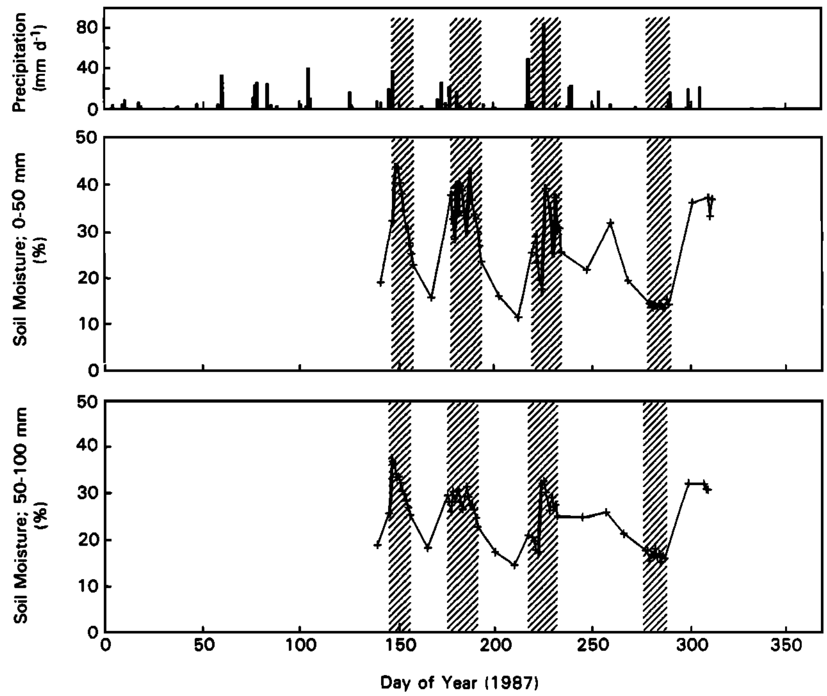

Fig. 9. Precipitation record and soil moisture conditions (gravimetric method) at the FIFE site during 1987. Time series of (top) total daily precipitation (millimeters); (middle) percentage soil moisture in 0- to 50-mm layer; (bottom) percentage soil moisture in 50- to 100-mm layer. Saturated soil moisture content is about 43%. Note wet conditions in IFCs 1, 2, and 3 and dry downs in between. Data from staff/Kansas State University (KSU) and staff/Goddard Space Flight Center (GSFC).

station measurements was developed. A decision was made to concentrate these more difficult coordinated measurements at only a few sites in future work. These findings militated for a return to the FIFE site in 1989.

4.2. *Field Operations in 1989*

The monitoring program, as organized for 1987, was continued with minor changes through 1988 and 1989. The single FIFE 89 IFC involved many of the same science teams and aircraft as in FIFE 87 but with some notable differences in experiment design.

1. Timing: The timing and length of the IFC were aimed specifically at "capturing" a soil moisture dry-down event; accordingly, the IFC was scheduled for 20 contiguous days in the late summer of 1989 (July 24 to August 12, days 205–224).

2. Alternating missions: Soil moisture missions (CMP 3) and optical/thermal surveys (CMP 1) were alternated to obtain a detailed picture of changing soil moisture conditions during a dry down.

3. Supersites: Most of the experimental resources were concentrated at three "supersites" located in the FIFE area; see Figure 4*b*. This allowed for better coordination between measurements and a more realistic attempt at splitting the total CO_2 flux. The soil moisture flight lines for the C-130 and the NOAA Aerocommander were also oriented north-south to cover the three supersites.

At each supersite the area upwind of the flux measurement equipment became the target for the remote sensing and field validation work. The "wind-aligned blob" or WAB, see Figure 13, was the term given to this area which was calculated to be the main source of the measured surface fluxes. The WABs were also the intersections of the flight lines for the remote sensing aircraft.

The record of field operations for FIFE 89 and a few preliminary results are documented in the "FIFE 89 experiment operations" document, edited by *Sellers and Hall* [1992]. Figure 14 shows the meteorological conditions for the FIFE 89 IFC. The IFC started with rain and the first clear day was July 28 (day 209) which was followed by cloudy

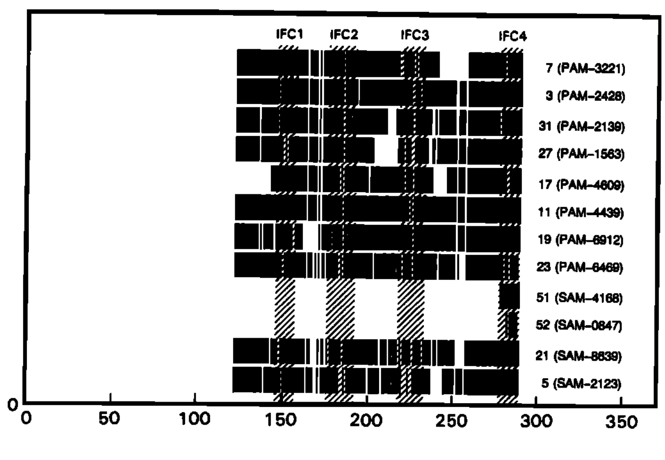

Fig. 10. Inventory of automatic meteorological station (AMS) data acquired by the National Center for Atmospheric Research for FIFE 87 and archived in FIS. Note that two super-AMSs were not operating until the last IFC. Data from staff/GSFC.

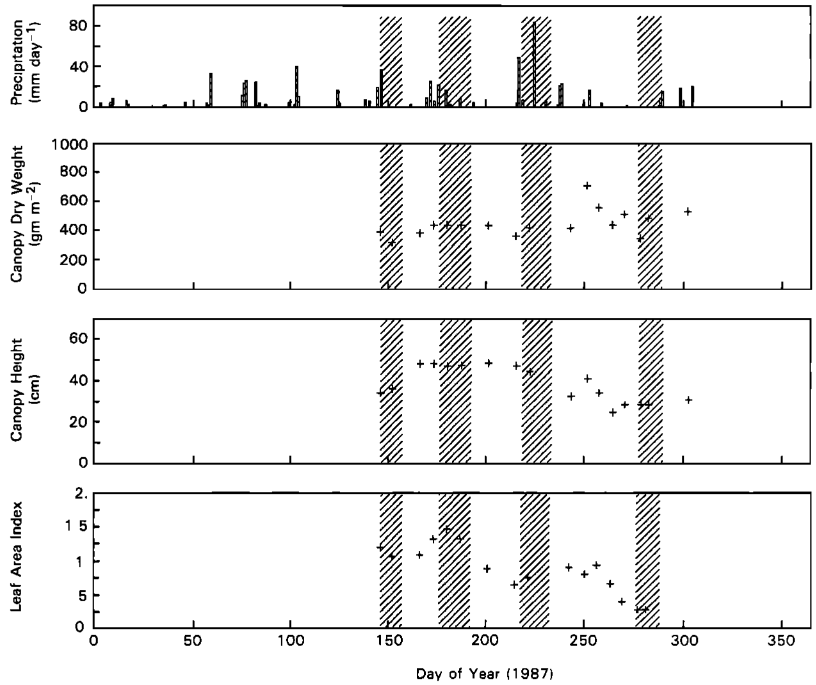

Fig. 11. Time series of biophysical parameters as measured at the FIFE site during and between IFCs in FIFE 87. Values were calculated by taking means of all station values within sequences of 5-day intervals. Data are from staff/KSU.

weather and heavy rains on July 31 (212). An extended drying period started on August 4 (216) and lasted through August 11 (223). During this time there were some localized rain showers, but August 4 (213), August 8 (220), and August 11 (223) were marked by clear conditions.

The soil moisture trace reflects the precipitation record. Two dry-down periods are apparent: one starting at the beginning of the IFC and ending on July 31 (212), the second starting on August 4 (216) and extending through the end of the IFC. Aircraft operations, satellite overpasses, and golden and silver days are identified in Table 5. The days with the best satellite optical data were 209, 216, 218, 220, and 223. The period of August 4–8, 1989 (216–220) was marked by numerous aircraft missions of different types; airborne soil moisture surveys were carried out throughout the entire IFC.

The day of August 4 (216) stands out as a particularly good one for FIFE 89; see Figure 15. The sky condition was exceptionally clear and good SPOT and Landsat images were acquired within an hour of each other. FIFE 89 was successful in that a wide range of soil moisture conditions were observed within the site and over the period of the IFC; in one sense, three experiments were executed as the supersites had very different soil moisture and vegetation cover characteristics; see Figure 16.

The northern supersite (906) had exceptionally dry soil moisture conditions throughout the IFC, the southern supersite (926) moderately dry, and the center site (916) moist conditions. This was in part due to a single thunderstorm cell passing through the center of the site on July 28 (209).

5. The Contents of This Special Issue

Many of the preliminary results from FIFE 87 have been presented in the FIFE interim report [*Sellers et al.*, 1990*a*], in the proceedings of the FIFE American Meteorological Society Symposium [*Hall and Sellers*, 1990], and elsewhere as individual publications in the refereed literature. However, this journal issue represents the first complete publication of results and analyses and also includes some findings from FIFE 89.

The contents of this issue are organized loosely along the lines of the project itself. Five sections cover the results obtained by the five measurement science groups: atmospheric boundary layer (ABL); surface fluxes (SF); correction and calibration (CC); surface radiances and biology (SRB); and soil moisture (SM). It should be noted, however, that far more than just the observations are reported in the papers in these sections; a full range of disciplinary analyses are presented, some of which refer to results and analyses obtained from other science groups. Each section is headed by an overview paper that summarizes the activities of the group during the experiment and briefly describes the contents of each paper.

Following these five sections, several interdisciplinary papers are presented together in the Integrative Science section. These papers are the result of either modeling and analysis work or describe studies that make extensive use of data from two or more science groups.

The closing section consists of one paper which attempts to summarize the main findings of FIFE and to explore the implications of the experiment for future research.

6. Management and Resources of the Project

NASA was the lead agency for the management of FIFE. The Land Processes Branch within the Space Science and Applications Division of NASA headquarters oversaw the initial science planning and worked with the scientific com-

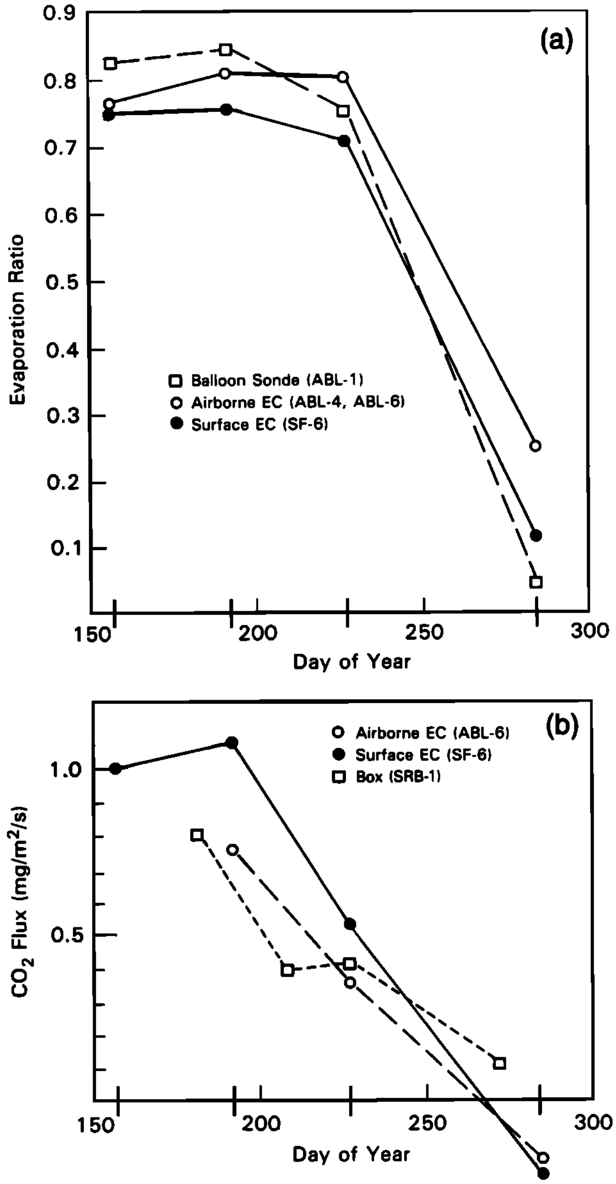

Fig. 12. Synopsis of surface flux variations over the FIFE site in FIFE 87. (*a*) Evaporation ratio, $\lambda E/(H + \lambda E)$, as estimated using surface (SF-6) and airborne (ABL-4 and -6) eddy correlation data and radiosonde data (ABL-1). The estimate from the radiosonde (ABL-1) data was obtained from the gradients of temperature and humidity over the lowest 150 m of sonde flight. Data points are for 1200 LT on the golden days within each IFC. (*b*) Net CO_2 flux at and over site 16 (4439-ECV) as measured by surface enclosure (SRB-1), surface eddy correlation (SF-6), and airborne eddy correlation (ABL-6) equipment. Data are for golden days within each IFC.

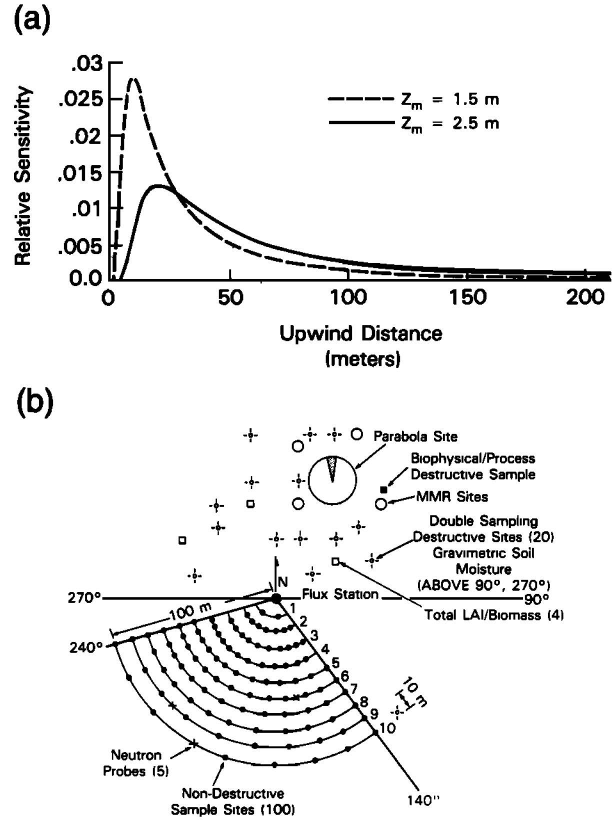

Fig. 13. Supersite configurations for FIFE 89. (*a*) Relative sensitivity of flux measurements to a line source located at a specific distance upwind as a function of mast height. The function is normalized to integrate to unity over the distance zero to infinity; from P. H. Schuepp (personal communication, 1989). The area close to the mast with the most influence was referred to as the wind-aligned blob (WAB) in FIFE 89. (*b*) Plan view of supersite in FIFE 89. The WAB zone is heavily instrumented with soil moisture sample tubes and nondestructive vegetation sample sites and was the target for airborne remote sensing. Destructive samples and disruptive measurements were made outside the WAB. The dominant wind direction was assumed to be 140° through 240°, based on FIFE 87 records.

munity to set the overall science goals of FIFE and to define the science plan. The Land Processes Branch then managed the proposal solicitation and selection process, releasing the FIFE science plan as part of a "dear colleague" letter in 1986. In addition, the Land Processes Branch managed the interagency contacts to obtain critical additional FIFE resources and equipment. In late 1985 the Land Processes Branch management placed the day-to-day management of FIFE within the Biospheric Sciences Branch of NASA GSFC. An informal, unofficial project office was established in the branch to manage the experiment design, resource requirements definition, procurement activity, the experiment implementation, day-to-day operations, and the FIFE information system.

The proposal solicitation and selection process resulted in the selection of the 29 investigator teams from 92 proposals received in the autumn of 1986. Two experiment design workshops were then held with the teams in December 1986 and March 1987. The first intensive field campaign began in May 1987. Thus less than 6 months elapsed between the selection of investigators and the beginning of experiment operations.

The FIFE project office was staffed with a science coordinator, a staff scientist, and a FIFE information scientist, who comanaged the project, supported by a group of civil servants (approximately two full-time equivalents), and on-site contractors (approximately 10 full-time equivalents at the peak) to manage the FIFE information system, procurement, and to execute the staff science activities defined by the experiment plan.

The FIFE project office was also supported by a science steering group, consisting of the chairpersons of the six FIFE science subgroups. Each group chair was elected by

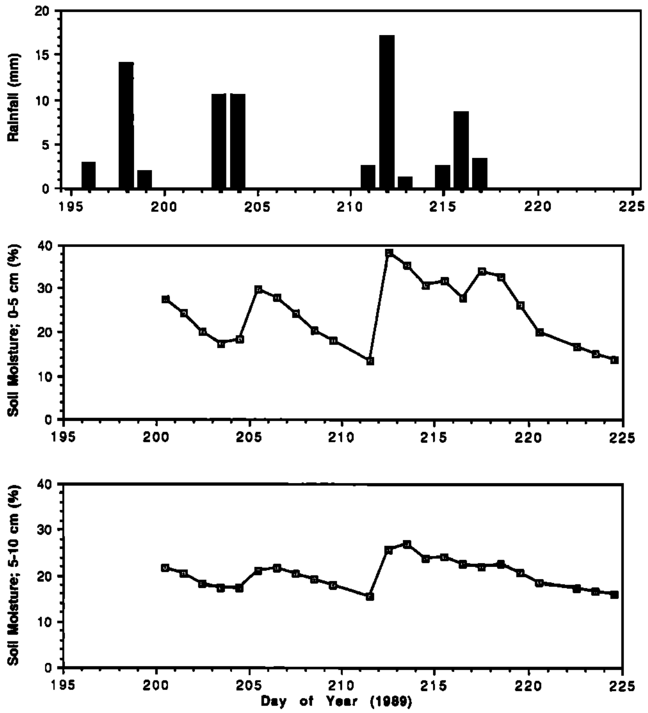

Fig. 14. Soil moisture and precipitation record for the FIFE 89 IFC.

science investigators within that group. During each phase of FIFE the major science decisions were made after discussions between the FIFE project office and the science steering group. To accomplish this, twice yearly workshops

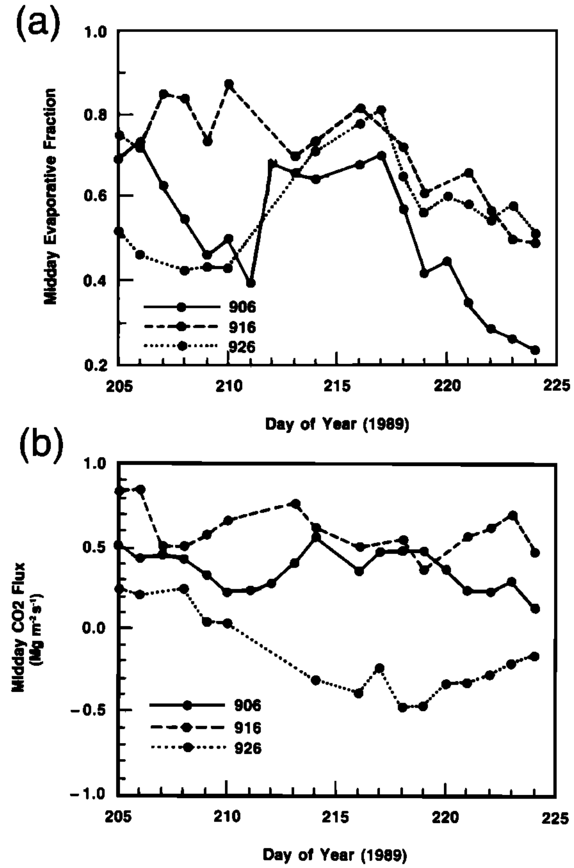

Fig. 16. (*a*) Time series of evaporative fraction measurements at the three supersites in FIFE 89. (*b*) Time series of net CO_2 fluxes at the three supersites in FIFE 89.

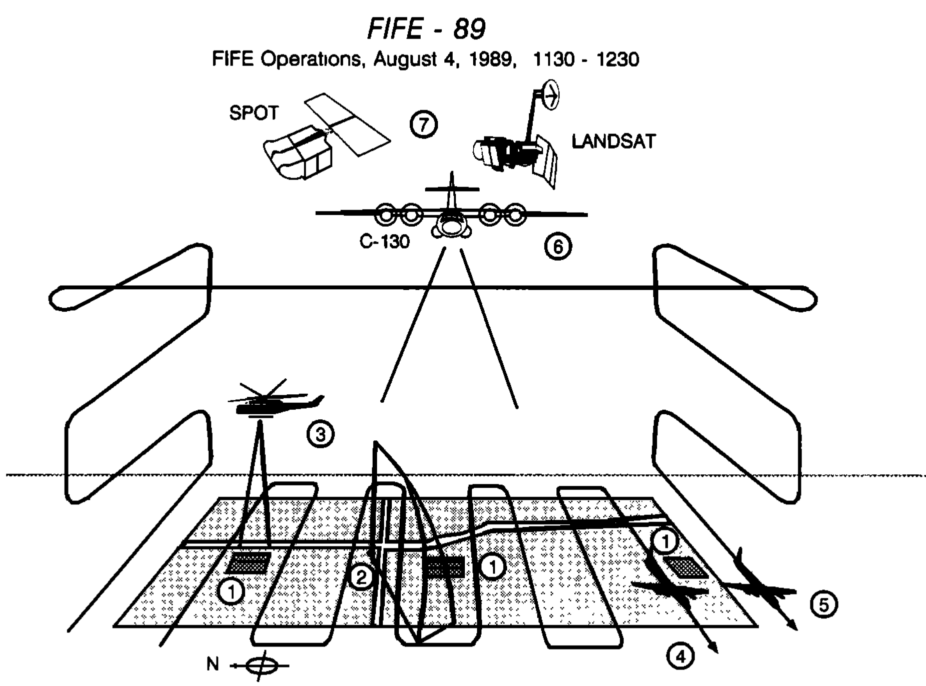

Fig. 15. "Snapshot" of FIFE 89 operations on the golden day of August 4, 1989 (216). (1) Flux measurements and surface radiation studies are being conducted at the three supersites. (2) A lidar is being used to investigate turbulent structures in the PBL. (3) The helicopter is taking radiometric data over a supersite. (4) One flux aircraft is taking low-level data to study the spatial distribution of surface fluxes. (5) A second flux aircraft takes data to measure the divergence and advective contributions to fluxes over the FIFE site. (6) The NASA C-130 collects multiangle scanner data over the site, with intersecting flight lines over the supersites. (7) The SPOT and Landsat satellites acquire data over the site and surrounding area.

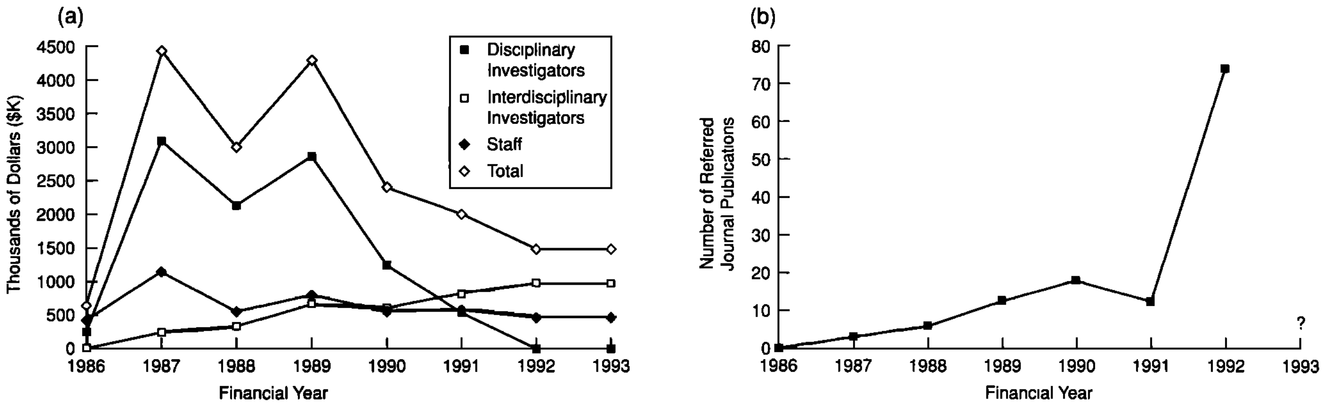

Fig. 17. (*a*) Cost of the FIFE project by year, by category. (*b*) Number of referred journal publications produced by FIFE by year (proceedings articles omitted).

were held with all the FIFE investigation teams as well as frequent telephone, E-mail, and fax communications between scientists and project management.

Figure 17*a* gives a sense of the overall FIFE project resources expended each year. The resource dollars shown are the large majority of the actual dollars spent for FIFE; however, they do not include many of the "contributions-in-kind" that FIFE received in the way of people, labor, and equipment from the several agencies participating in FIFE. Perhaps the largest contribution of this nature was in the form of aircraft hours contributed by other programs within NASA, such as the NASA C-130, DC-8, and ER-2, and the Canadian Twin Otter. In addition, civil service salaries and facilities support are not included in the resource values of Figure 17*a*. A very rough dollar estimate of all contributions other than those shown in Figure 17*a* is $500,000 per year in 1987 and 1989 and about $200,000 in other years.

The financial resources expended by FIFE are plotted by category in Figure 17*a*: (1) total; (2) disciplinary investigations, which include the data acquisition costs and the peer-reviewed investigations in the ABL, SF, SRB, CC, and SM groups; (3) the interdisciplinary investigations of the IS group; and (4) the staff support for FIS and staff science activities. In 1986, FIFE spent $625,000 to hire start-up staff, lay out site infrastructure, begin implementation of the information system, purchase equipment, and fund selected scientists for preliminary experiment design studies. In 1987 the peak field year of FIFE with four IFCs conducted, as shown in Figure 18*b*, the resources ramped up by a factor of 7 from 1986. As discussed earlier, in 1988 some monitoring activities as well as a few field measurements were conducted. Then in 1989, FIFE staff and investigators returned to the field for another full-up 3-week-long IFC. After 1989 the disciplinary science and staff funding fell sharply as modeling and data analysis activities built up.

The interdisciplinary funding, consisting of model development and data analysis, increased steadily, if slowly, from the beginning of the project and is anticipated to remain steady through 1993. In 1991 a new dear-colleague letter was released inviting a new round of competitive proposals to continue the analysis of FIFE data. The total funding from 1986 through 1991 was $16,782,000, which for 29 investigator teams works out at $116,000 per team per year. Of that, roughly $3,980,000 went for staff support, about $27,000 per team and the remainder for investigations, about $88,000 per team.

Looking at Figure 17*b*, we see the numbers of refereed journal articles per year. There were three papers as early as 1987, documenting the experiment and publishing some preliminary data analyses. The publication numbers increased steadily from 1988 to 1991, consisting primarily of papers confined within disciplines. Not shown are 48 publications for the 1990 American Meteorological Society conference [*Hall and Sellers*, 1990] as well as 30 other publications in conference proceedings. The number of publications jumped in 1992 to 75 publications, more than 60 of which are to be found in this special issue. Thus almost 4 years after the first FIFE data release (December 1987) the publication rate is still increasing but is still confined primarily to within-discipline studies. With the advent of the FIFE follow-on funding, it is anticipated that the content of papers will shift more toward interdisciplinary aspects of the experiment, including the combination of atmospheric boundary layer and surface data sets and models, further exploration of the utility of satellite data, and wider investigation of different scale-integration methodologies. Thus we would anticipate the most important results of FIFE to appear nearly 6 years following the initial data collection and continue beyond that as non-FIFE investigators continue to mine the FIFE data set.

NOTATION

Scientific Nomenclature and Acronyms

A assimilation rate, mol m^{-2} s^{-1}.
a_L leaf area, m^2.
B soil pore size distribution index.
C heat capacity, J m^{-3} K^{-1}.
c_p specific heat, J kg^{-1} K^{-1}.
d displacement height, m.
d_E evaporation capacity, m s^{-1}.
d_I infiltration capacity, m s^{-1}.
D thermal diffusivity, m^2 s^{-1}.
e vapor pressure, Pa.
e_r air vapor pressure, Pa.
$e^*(T)$ saturation vapor pressure at temperature T, Pa.

E evaporation, kg m^{-2} s^{-1}.
E_c transpiration.
E_s soil evaporation, kg m^{-2} s^{-1}.
F CO_2 flux, mol m^{-2} s^{-1}.
F_c canopy CO_2 flux, mol m^{-2} s^{-1}.
F_s soil CO_2 flux, mol m^{-2} s^{-1}.
g_c canopy conductance, m s^{-1}.
g_s stomatal conductance, m s^{-1}.
g_c^* unstressed canopy conductance, m s^{-1}.
G soil heat flux, W m^{-2}.
H sensible heat flux, W m^{-2}.
I_{par} intercepted photosynthetically active radiation, W m^{-2}.
k von Karman's constant, 0.41.
K eddy diffusivity, m^2 s^{-1}.
K_H eddy diffusivity for heat, m^2 s^{-1}.
K_E eddy diffusivity for moisture, m^2 s^{-1}.
K_m eddy diffusivity for momentum, m^2 s^{-1}.
$K\uparrow$ upward flux of shortwave radiation, W m^{-2}.
$K\downarrow$ downward flux of shortwave radiation, W m^{-2}.
$K\downarrow_b$ direct beam solar radiation flux, W m^{-2}.
$K\downarrow_d$ diffuse solar radiation flux, W m^{-2}.
$K\downarrow_{\text{par}}$ downward flux of photosynthetically active radiation, W m^{-2}.
K_s saturated hydraulic conductivity, m s^{-1}.
K_s soil thermal conductivity, W m^{-1} K^{-1}.
L Monin-Obukhov length, m.
$L\uparrow$ upward longwave radiation flux, W m^{-2}.
$L\downarrow$ downward longwave radiation flux, W m^{-2}.
$L\uparrow_s$ thermal soil surface radiation flux, W m^{-2}.
$L\uparrow_c$ thermal canopy radiation, W m^{-2}.
N number of samples.
[N] nitrogen concentration, mol mol^{-1}.
p precipitation, mm.
p pressure, Pa.
P_c canopy photosynthesis, mol m^{-2} s^{-1}.
P_c^* unstressed canopy photosynthesis, mol m^{-2} s^{-1}.
q specific humidity, kg m^{-3}.
Q_{bs} storm flow of base flow, m^3 s^{-1}.
Q_g groundwater discharge, m^3 s^{-1}.
Q_s streamflow, m^3 s^{-1}.
r correlation coefficient.
r_a aerodynamic resistance, s m^{-1}.
r_c canopy resistance, s m^{-1}.
R gas constant, J kg^{-1} K^{-1}.
R_n net radiation, W m^{-2}.
s sorptivity.
S_g water storage in groundwater, m.
S_s water storage in surface water bodies, m.
S_u water storage in unsaturated zone, m.
t time, s.
T temperature, K.
T transmittance.
T_b brightness temperature, K.
T_c canopy temperature, K.
T_d dew-point temperature, K.
T_r air temperature, K.
T_s surface temperature, K.
T_v virtual temperature, K.
u, v, w wind components, m s^{-1}.
u', v', w' wind fluctuation, m s^{-1}.
u^* friction velocity, m s^{-1}.
U wind speed, m s^{-1}.
U wind vector, m s^{-1}.
V_c vegetation cover fraction.
w mixing ratio, kg kg^{-1}.
W soil wetness (Θ/Θ_s).
z_c canopy height, m.
z_i inversion height, m.
z_0 roughness length, m.
z_w water table depth, m.
α albedo.
β Bowen ratio.
γ psychrometric constant, Pa K^{-1}.
γ temperature lapse rate, K m^{-1}.
ε emissivity.
ϕ_s solar azimuth angle, degrees.
ϕ_v view azimuth angle, degrees.
ϕ_p $\phi_p = \phi_s - \phi_v$.
Θ incidence angle, degrees.
Θ_s solar zenith angle, degrees.
Θ_v view angle, degrees.
Θ soil moisture, m^3 m^{-3}.
Θ_d moisture at dry soil surface, m^3 m^{-3}.
Θ_s saturated soil moisture or porosity, m^3 m^{-3}.
Θ potential temperature, K.
Θ_e equivalent potential temperature, K.
Θ_v virtual potential temperature, K.
λ wavelength, nm.
λ latent heat of vaporization, J kg^{-1}.
Λ expected value of a topographic variable.
λE latent heat flux, W m^{-2}.
ρ density, kg m^{-3}.
ρ_B soil bulk density, kg m^{-3}.
$\rho(\Theta_s, \Theta_v, \phi_p)$ bidirectional reflectance.
σ standard deviation.
σ_0 radar scattering coefficient.
τ momentum flux, kg m^{-1} s^{-2}.
τ optical depth.
Ψ suction pressure, Pa.
Ψ_B bubbling pressure, Pa.
Ψ soil water potential, Pa.
Ψ_L leaf water potential, Pa.
Ψ_P plant water potential, Pa.
Ψ_S soil water potential at saturation, Pa.
$\cdot$ superscript is $\partial/\partial t$.
$-$ superscript is time-mean.
$<>$ space-mean.
c subscript for canopy.
s subscript for soil (e.g., total CO_2 flux is $F = F_c + F_s$).

Acronyms

ABL atmospheric boundary layer.
agl above ground level.
AMS automated meteorological stations.
APAR absorbed photosynthetically active radiation by the vegetation canopy.
ASAS advanced solid state array spectroradiometer (SRB-4).
ASCII American standard code for information interchange.

ATSP airborne tracking sunphotometer (CC-4).
AVHRR advanced very high resolution radiometer (NOAA 9, 10, and 11).
BR Bowen ratio.
BRDF bidirectional reflectance distribution function, W m^{-2} sr^{-1}.
BRF bidirectional reflectance function, W m^{-2} sr^{-1}.
CC correction/calibration.
CD-ROM compact disk-read-only memory.
CMP 1 coordinated mission plan for diurnal experiment.
CMP 2 coordinated mission plan for single overpass.
CMP 3 coordinated mission plan for soil moisture survey.
C-130 four-engine NASA research aircraft (remote sensing).
EC eddy correlation.
EF evaporative fraction, kg m^{-2} s^{-1}.
ESA European Space Agency.
EXPLAN 87 Experiment Plan 87.
EXPLAN 89 Experiment Plan 89.
FIFE First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment.
FIS FIFE information system.
FPAR fraction of absorbed photosynthetically active radiation.
FTIR Fourier transform infrared spectroscopy.
GCM general circulation model.
GIS geographic information system.
GPS global positioning system.
GOES Geostationary Operational Environmental Satellite.
GSFC Goddard Space Flight Center.
HRV high-resolution video (SPOT instrument).
H-1 NASA (Huey) helicopter.
ICSU International Commission of Scientific Unions.
IGBP International Geosphere-Biosphere Program.
IPAR fraction of intercepted photosynthetically active radiation.
IS integrative science.
ISLSCP International Satellite Land Surface Climatology Project.
LAI leaf area index.
LIDAR light (laser) direction and ranging.
LSP land surface parameterization.
LTER Long-Term ecological research site.
METEOSAT Meteorological satellite (ESA).
MIR mid-infrared radiometer.
MMR modular multispectral radiometer.
MSS multispectral scanner (Landsat).
NAE National Aeronautical Establishment (Canada).
NASA National Aeronautics and Space Administration.
NCAR National Center for Atmospheric Research.
NDVI normalized difference vegetation index.
NIR near infrared.
NOAA National Oceanographic and Atmospheric Administration.
NSF National Science Foundation.
NRC National Research Council (Canada).
PAM portable automatic mesonet (NCAR AMS device).
PAR photosynthetically active radiation.
PARABOLA portable apparatus for rapid acquisition of bidirectional observations of land and atmosphere (SRB-3).
PBL planetary boundary layer.
PBMR push broom microwave radiometer (SM-5).
RF reflectance factor.
RH relative humidity, %.
RWC relative water content, %.
SAI stem area index, m^2 m^{-2}.
SAMS super-AMS.
SAR synthetic aperture radar.
SF surface flux.
SM soil moisture.
SP sunphotometer.
SPOT Systeme Probatoire pour l'Observation de la Terre.
SR simple ratio vegetation index.
SRB surface radiances and biology.
SLAR sideways looking airborne radar (SM-6).
SVI spectral vegetation index.
TIMS thermal infrared multispectral scanner.
TIR thermal infrared.
TM thematic mapper (Landsat).
TMS thematic mapper simulator (NS001on the C-130).
TOV TIROS operational vertical sounder.
VAS/VISSR VISSR atmospheric sounder (GOES)/visible infrared spin-scan radiometer.
UNEP United Nations Environmental Program.
UWY University of Wyoming.
WAB wind-aligned blob.
WMO World Meteorological Organization.

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