Remote Sensing May Provide Unprecedented Hydrological Data

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Use of remote sensing technology to collect data in water resource management and basic hydrological research may reap tremendous benefits, studies are showing. Satellite coverage may allow unprecedented accuracy in the quantification of the global hydrological cycle, for example.

Yet despite such benefits, few hydrologists currently use such data. Among other reasons for this, the needed tools and algorithms are not fully developed. Many field experiments already have been performed to this end but further large-scale field experiments must be conducted for algorithm development and validation over different climatic regimes.

Recent experiments have had as a major objective the evaluation of the utility of remote sensing in modeling large-scale hydrologic and atmospheric processes. Specific details of several well-known and lesser-known examples of such field experiments are provided in Table 1. Most of these experiments highlight the use of long-wave microwave sensors, which have great potential for hydrology. Unfortunately, no space-based missions are planned employing the microwave sensors most useful for hydrological studies (although soil moisture measurement missions, such as HYDROSTAR, are being proposed). Consequently, the only current microwave data available for such studies are the data collected in these field experiments.

Hydrologists have recognized the potential of satellite remote sensing technology since the 1970s. Remote sensing offers a way to avoid the logistical and economic difficulties associated with obtaining continuous in situ measurements of various hydrologic variables, difficulties that are particularly pronounced in remote regions. Microwave instruments in particular can potentially provide all-weather, areally averaged estimates of certain variables (such as precipitation, soil moisture, and snow water content) that have been essentially unattainable in the past.

The hydrological cycle integrates atmospheric, hydrospheric, cryospheric, and biospheric processes over a wide range of spatial and temporal scales and thus lies at the heart of the Earth's climate system. Studies of the integrative, global nature of the cycle are crucial for an understanding of natural climate variability and for predictions of climatic response to anthropogenic forcing. Unfortunately, the breadth of such studies, which began with the seminal work of M. I. Budyko several decades ago, has always been constrained by a paucity of relevant hydrological data (precipitation and soil moisture, for example) at the global scale. The logistical and economic difficulties associated with obtaining continuous in situ measurements of hydrological variables across the globe, particularly in remote regions, are simply insurmountable. Only in recent years, with the advent of satellite remote sensing, have the required global data seemed within reach.

Although many hydrologists believe that remotely sensed data should be valuable for global hydrological studies and even for regional hydrological modeling and operations, few currently use these data. For one thing, most lack the necessary technical background to use the data comfortably. For another, remote sensing data take the form of emitted and reflected radiances and thus are not the type of data traditionally used to run and calibrate models. Remotely sensed data also represent averages over finite areas, or pixels, and thus obliterate much of the point detail to which hydrologists are accustomed. In addition, current remotely sensed observations are rarely optimized to provide the temporal resolution needed to measure certain changes in hydrological processes---the 2-week-plus revisit time of Landsat orbits, for example, can only provide unrelated snapshots of an area's hydrology. On top of all this, algorithms for converting these reflectances into physical quantities are often empirical in nature and are subject to noise in the calibration data, which can lead to potentially significant errors.

Nevertheless, remote sensing is beginning to prove effective in providing hydrologically useful information. Hydrologic remote sensing can reveal complex spatial variations that cannot be readily obtained through traditional in situ approaches. Development of such datasets and models that can use them requires field experiments that combine appropriate remote sensing measurements with traditional in situ measurements in regions that are already well understood hydrologically. Once the hydrological models are developed for use with remote sensing data in the heavily monitored basins, they can possibly be "transported" for use in regions having little or no in situ measurement system.

HAPEX-MOBILHY (1986)

The objective of the Hydrologic Atmospheric Pilot Experiment and Modelisation du Bilan Hydrique (HAPEX-MOBILHY) program in 1986 was to improve the parameterizations of land surface processes in atmospheric general circulation models (GCMs). These processes operate at scales of hundreds of kilometers over heterogeneous landscapes. A measurement program was designed to observe relevant processes, particularly those related to the water and energy budgets, using a number of different and independent techniques over a 100 x 100 km area in southwestern France. A third of the area was covered by a pine forest, and the remainder was covered by mixed agriculture, allowing for studies of contrasting surface behavior. Preliminary results are summarized by Andre et al. [1990].

The study area and its surroundings are shown in the upper frame of Figure 1. The darker red triangular area extending east from the sea is the Landes forest which occupies 40% of the HAPEX square. The Landes forest is nearly flat, and the dominant land cover (65%) is pine forest. The study area is a 1· square, and over this area were distributed more than a dozen flux stations and numerous meteorological stations. The spatial variation of the fluxes was observed using an airborne eddy correlation system.

The lower frame of Figure 1 is a Thermal Infrared Multispectral Scanner (TIMS) image acquired from the NASA C-130 aircraft over the central site. In addition to the satellite remote sensing observations, the C-130 acquired data at multiple wavelengths including visible, near-infrared, thermal infrared, and microwave. The image was taken in midafternoon from an altitude of 6 km, yielding 15-m resolution and is roughly 15 x 10 km. Temperature range is from the high 20s to the low 50s in degrees C. Three fields are identified for which surface flux measurements were made: a well-irrigated oat field (30·C), a corn field with significant bare soil showing (45·C), and a pine forest (30·C). The sensible heat flux for the corn and oat fields reflect the differences in surface temperature, while for the pine forest the sensible heat was much greater, because of its more efficient heat transfer. These results show that it is possible to estimate the heat flux from surface temperature measurements provided we know something about nature of the surface that we are observing. The redness in the fields is due to the emissivity differences amongst the three TIMS channels shown. The spectral information can be used to obtain information on the surface minerals in addition to the surface temperatures.

FIFE (1987-1989)

The overall aims of the First International Satellite Land Surface Climatology Project Field Experiment (FIFE) in 1987-1989 was to improve the currently crude representations of energy, water, heat, and carbon transfer between the land surface and the atmosphere in climate models and to develop satellite remote sensing algorithms that can generate global fields of governing biophysical variables. Emphasis was placed on determining the extent to which soil-plant-atmosphere models, which were originally designed for use at the millimeter-to-meter scale, can be adapted to the much larger scales (kilometers to hundreds of kilometers) appropriate to atmospheric models and satellite remote sensing. The experiment was centered on a 16 x 16 km2 tallgrass prairie site near Manhattan, Kansas. An extended program of satellite, aircraft, and in situ measurements collected meteorological, biophysical, and hydrological data, with several multiweek intensive field campaigns mostly under wet conditions. See Sellers et al. [1992] for further information.

A complex, interdisciplinary dataset was collected at leaf-plant, field-plot, and catchment-site scales using hand-held instruments, meteorological towers, aircraft, and satellites on various geophysical variables (such as soil moisture; latent, sensible, and ground heat fluxes; radiation; precipitation; air and surface temperature; humidity; and wind speed). A major focus was the development of remote sensing algorithms to monitor surface energy balance. More than 300 journal articles based on the FIFE dataset have already been published, including two in *Journal of Geophysical Research* special sections [*Sellers et al*., 1992; *Hall and Sellers*, 1995]. In addition, the NASA Goddard Space Flight Center has published the FIFE dataset on a five-volume CD-ROM available through the Oak Ridge National Laboratory Data Analysis and Acquisition Center (http://www-eosdis.ornl.gov/).

MACHYDRO-90 (1990)

The Multisensor Aircraft Campaign for Hydrology (MACHYDRO-90) experiment used passive and active microwave sensors to retrieve soil moisture information in humid regions. The experiment was conducted July 9-20, 1990, at the Northeast Watershed Research Center of the U.S. Department of Agriculture's (USDA) Agricultural Research Service (ARS) near Klingerstown, Pennsylvania. Hydrology in the experimental watershed is characterized by frequent rainfall, evapotranspiration at or near the potential rate, and continuous streamflow over most of the year. The annual streamflow hydrograph consists of storm hydrographs superimposed on base flow resulting from shallow groundwater and drainage of soil water. Such humid area hydrology is spatially very variable and is affected by topography and soil-controlled moisture patterns.

The weather was nearly ideal for a hydrological study. Very dry initial conditions were followed by several days of rain and then 5 days of gradual drying. Extensive ground data were collected to support the microwave sensors as well as thermal and multispectral data [*Wood et al*., 1993].

Monsoon 90

Arid and semiarid rangelands make up a significant portion of the Earth's land surface, yet little is known about surface-atmosphere interactions in these environments and how they are influenced by the hydrological cycle. Monsoon 90 was designed to investigate these interactions, particularly the ways in which the temporal and spatial variability of surface soil moisture affects the hydrologic cycle, the energy balance, and the feedbacks to the atmosphere via thermal forcing.

The experiment took place in the USDA-ARS Walnut Gulch Experimental Watershed (about 120 km southeast of Tucson, Arizona), a hydrologically instrumented semiarid rangeland watershed operated by the ARS. Field campaigns covered both the dry season during May and June and the wet, or "monsoon," season during July and August. During the dry season, investigators obtained baseline measurements of the optical and thermal properties of the surface, as well as the energy balance components under senescent vegetation and dry soil conditions. Similar but more extensive measurements were made during July and August when the vegetation is at peak greenness, the soil moisture is highly variable both spatially and temporally, and significant precipitation events frequently occur producing runoff in the catchment. A collection of preliminary research results for Monsoon 90 was published in May 1994 as a special section of *Water Resources Research.*

CaPE (1991)

The Convection and Precipitation/Electrification (CaPE) Experiment was a multiagency field program conducted in central Florida between July 8 and August 18, 1991. It was set up to study the development of mesoscale meteorological conditions and consequent storm characteristics and to develop improved techniques for performing short period forecasts of convection initiation, downbursts, and tornadoes [*Williams et al*., 1992]. CaPE resulted in a diverse data set that spawned additional research projects, including the CaPE Hydrometeorology Project (ChymP).

ChymP involved developing a strategy for application of a land surface model using in situ observations and remotely sensed data for diagnosing large-scale (about 25,000 km2) land and atmosphere water budget components. The idea was that these techniques could then be tested and applied over larger-scale areas in conjunction with the Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project (GCIP) [*Leese*, 1993]. High resolution remotely sensed data are useful to characterize small-scale variability of surface properties and to examine scaling issues relevant to the coupling of land-surface process models to atmospheric general circulation models.

Data used in CHymP were obtained from many sources, including supervised field measurements, unsupervised temporary and permanent gauging stations, surface radars, radiosondes, aircraft-based instruments, and aircraft and satellite remote sensing instruments (see Table 1). As part of the CHymP investigations, a land surface-atmosphere water and energy exchange model was used in conjunction with high-resolution remotely sensed data to study the sensitivity of surface fluxes, soil moisture, and runoff to the variability of soils and landcover classification.

Washita 92

The goals of a MACHYDRO experiment in June 1992 in the Little Washita Watershed were to evaluate the ability of microwave sensors to capture quantitatively the spatial and temporal variability of soil moisture and to incorporate remotely sensed data (including soil moisture data) into catchment-scale hydrologic models. The Little Washita Watershed, a 610 km2 drainage basin in the southern part of the Great Plains in southwest Oklahoma, near Chickasha, is the site of a long-term (more than 24 years) USDA-ARS hydrologic monitoring facility currently being rejuvenated through instrumentation upgrades and the addition of new measurement stations. The local climate is classified as moist and subhumid, with an average annual rainfall of about 640 mm.

Remote sensing instruments (see Table 1) were flown aboard various aircraft. Flight lines were designed to satisfy two requirements: complete, wall-to-wall observations of the entire area, and low altitude, high resolution flights over selected sites for use in instrument evaluation and algorithm development. The soil was very wet at the beginning of the experiment, following 26 days of rainy weather in Oklahoma. During the campaign, no rain fell over the study area between June 10 and June 18, allowing the monitoring of an extended drydown period. Extensive ground data were taken to characterize surface, vegetation, and hydrologic conditions [*Jackson et al*., 1995].

HAPEX-Sahel (1991-1993)

HAPEX-Sahel was an international experiment carried out during 1991-1993, with an intensive observation period from mid-August to mid-October 1992 within a 100 km square area (2·-3· E longitude, 13·-14· N latitude) in Niger in western Africa. The overall objective was to study the regional-scale water and energy balance of the Sahel and to improve the predictions of climate change in the semiarid tropics by using, for example, the coordinated program of measurements to develop large-scale land surface parameterizations for GCMs.

HAPEX-Sahel was specifically designed to allow the development and application of remote sensing methods for scaling surface processes. The strategy was to use aircraft-mounted sensors to develop methods for scaling point measurements to averages at the "super-site" scale (10-20 km, the scale at which the atmospheric boundary layer responds to changes in the land surface), and then satellite sensors to develop methods for further scaling up to the GCM grid scale. The varied landscape of the Sahel was measured with several instruments (Table 1) in the visible, infrared, and microwave regimes [*Goutorbe et. al*., 1994]. Research results were published in a special issue in the *Journal of Hydrology* (Vol. 188-189) in 1997.

Washita 94

In April, August, and October 1994, the Little Washita Watershed in Oklahoma was the site for the Spaceborne Imaging Radar (SIR) experiment. This was largely a repeat of the Washita 1992 campaign in terms of aircraft coverage and ground data collection programs; the experiment, however, also employed radar measurements from aboard the space shuttle. Aircraft-mounted sensors took measurements during April 5-11, and the shuttle radar took measurements April 11-17. The soil was initially dry, but rain on April 9 and 10 allowed a study of drydown during the remainder of the period. Diurnal soil moisture variations were examined, with early morning and midafternoon Electronically Scanned Thinned Array Radiometer (ESTAR) flights and shuttle radar data collection. An aborted shuttle launch cut short the planned August campaign; however, Airborne Synthetic Aperture Radar (AIRSAR) was flown 2 days, and a USDA-ARS aircraft made visible, near-infrared and thermal infrared measurements in support of radiosondes and multiple surface flux station observations.

BOREAS (1993-1996)

The Boreal Ecosystems Atmosphere Study (BOREAS) was a large-scale international field experiment designed to improve the understanding of the radiation, heat, water, CO_2, and trace gas exchanges occurring between the boreal forest and the lower atmosphere [*Sellers et al*., 1995]. As part of the 1993-1996 experiment, a continuous set of meteorological, hydrological, and satellite remote sensing measurements (see Table 1) were gathered during the period August 1993 through September 1994 over the 1000 x 1000 km^2 study region, covering most of Saskatchewan and Manitoba, Canada.

The 6 field campaigns (totaling 123 days) involved 300 scientists and aircrew and 11 research aircraft. Over 350 missions were flown during 1994. Satellite and airborne remote sensing studies and airborne flux measurements were focused on two 10,000 km^2 study areas within the BOREAS domain, one north of Prince Albert, Saskatchewan, and the other west of Thompson, Manitoba.

SGP 97

The Southern Great Plains 1997 (SGP 97) Hydrology Experiment originated from an interdisciplinary investigation whose main objective was to establish that the retrieval algorithms for surface soil moisture developed at higher spatial resolution, using truck- and aircraft-based sensors, can be extended to the coarser resolutions expected from satellite platforms. As part of this investigation, a field experiment, built upon the success of a previous experiment of much smaller scale [*Jackson et al.*, 1995], was proposed for 1997. The core of the 1997 experiment involved the deployment of the L-band ESTAR instrument for daily mapping of surface soil moisture over an area greater than 10,000 km^2 for a month.

The experiment took place in the subhumid environment of Oklahoma June 18-July 17, 1997. It became a collaboration by a team of interested scientists largely based on existing sponsored scientific investigations and research projects. Cooperation and contributions by many have resulted in a comprehensive opportunity for multidisciplinary research (see http://hydrolab.arsusda.gov/sgp97/). Version 1 of the SGP97 data is available for general research use on the Goddard Distributed Active Archive Center Web site (http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/SGP97/sgp97.html).

SALSA

The primary goal of the Semi-Arid Land-Surface-Atmosphere Program (SALSA) is to understand, model, and predict the consequences of natural and human-induced change on the basin-wide water balance and ecological complexity of semiarid regions at event, seasonal, interannual, and decadal timescales. SALSA is a long-term program whose research and integrated measurement efforts are currently focused on the San Pedro River basin of northeastern Sonora, Mexico, and southeastern Arizona. The SALSA San Pedro study area is also being used as validation and test sites for NASA and European satellite sensors. The main SALSA program objectives during 1996-1998 were to improve the diagnosis of surface flux measurements for use in real-time atmospheric models; to initiate development and validation of coupled soil-vegetation-atmosphere and vegetation growth models that assimilate remotely sensed data; to acquire in situ and remotely sensed measurements of groundwater, surface water, and meteorological processes in order to evaluate riparian evapotranspiration on a seasonal basis; to develop and validate aggregation schemes for highly heterogeneous surfaces; and to develop multiscale landscape condition indicators using remotely sensed data. Preliminary findings of the 1996-1997 research were presented at a special symposium of the American Meteorological Society and will be published in a special issue of the *Journal of Agricultural and Forest Meteorology* in 1999. Information is also available at the SALSA Web site (http://www.tucson.ars.ag.gov/salsa/salsahome.html).

Certain other programs, particularly in Europe, are complementary to those summarized. For example, see the GEWEX Web site overview (http://www.cais.com/gewex/gewex_overview.html).

Remote sensing, of course, will not replace conventional data or concepts. Rather, it can provide a new perspective on historical hydrological problems and new data types to augment traditional models and methods. Those interested are encouraged to contact any member of the AGU Remote Sensing in Hydrology Committee for more information. The committee members are Ghassem Asrar, Wilfried Brutsaert, Bhaskar J. Choudhury, Ralph Dubayah, Edwin T. Engman, Jay Famiglietti, Steven J. Goodman, Paul R. Houser, Shafiqul Islam, Randal D. Koster, William P. Kustas, Chip Laymon, Danny G. Marks, Drew Pilant, Dale Quattrochi, Thomas J. Schmugge, Larry L. Wilson, and Eric F. Wood.

References

Andre, J. C., P. Bougeault, and J.-P. Gouturbe, Regional estimates of heat and evaporation fluxes over non-homogeneous terrain: Examples for the HAPEX-MOBILHY programme, *Boundary Layer Meteorol., 50*, pp. 77-108, 1990.

Dubois, P. C., J. van Zyl, and T. Engman, Measuring soil moisture with imaging radars, *IEEE Trans. Geosci. and Remote Sens., 33*, pp. 915-926, 1995.

Goutorbe, J.-P., et al., HAPEX-Sahel, A large-scale study of land-atmosphere interactions in the semi-arid tropics, *Ann. Geophysicae, 12*, pp. 53-64, 1994.

Goutorbe, J.-P., et al., An overview of HAPEX-Sahel: A study in climate and desertification, *J. Hydrol., 188-189*, pp. 4-17, 1997.

Hall, F. G., and P. J. Sellers, First international satellite land surface climatology project (ISLSCP) field experiment (FIFE) in 1995, *J. Geophys. Res., 100*, pp. 25,383-25,395, 1995.

Jackson. T. J., D. M. LeVine, C. T. Swift, T. J. Schmugge, and F. R. Schiebe, Large area mapping of soil moisture using the ESTAR passive microwave radiometer, *Remote Sens. Environ., 53*, pp. 27-37, 1995.

Leese, J. A., Implementation plan for the GEWEX Continental-scale International Project (GCIP), Volume 1, Data collection and operational model upgrade, *International GEWEX Project Office Publication Series No. 6*, GCIP Office NOAA/OGP, 83 pp., Silver Spring, MD, 1993.

Sellers, P., F. G. Hall, G. Asrar, D. E. Strebel, and R. E. Murphy, An overview of the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE), *J. Geophys. Res.*, *97*, pp. 18,345-18,371, 1992.

Sellers, P., et al., The boreal ecosystem-atmosphere study, an overview and early results from the 1994 field year, *Bull. Am. Meteorol. Soc.*, *76*, pp. 1549-1577, 1995.

Williams, S. F., K. Caesar, and K. Southwick, *The Convection and Precipitation/Electrification (CaPE) Experiment, Operations summary and data inventory*, 425 pp., NCAR/OFPS, Boulder, Colo., 1992.

Wood, E. F., D.-S. Lin, M. Mancini, D. Thongs, P. A. Troch, T. J. Jackson, J. S. Famiglietti, and E. T. Engman, Intercomparisons between passive and active microwave remote sensing and hydrological modeling for soil moisture, *Adv. Space Res., 13*, pp. 167-176, 1993.

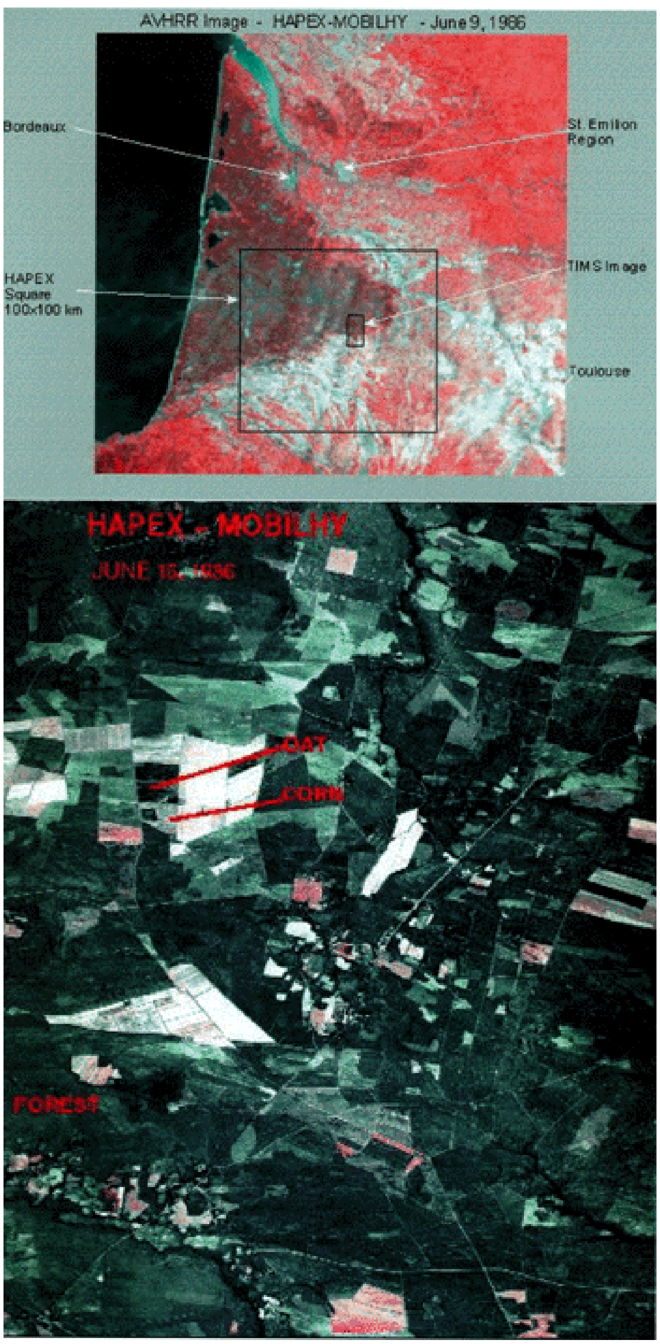

Fig. 1. (Upper panel) An Advanced Very High Resolution Radiometer (AVHRR) false color image of the HAPEX-MOBILHY area. (Lower panel) A Thermal Infrared Multispectral Scanner (TIMS) image acquired from the NASA C-130 over the central site.

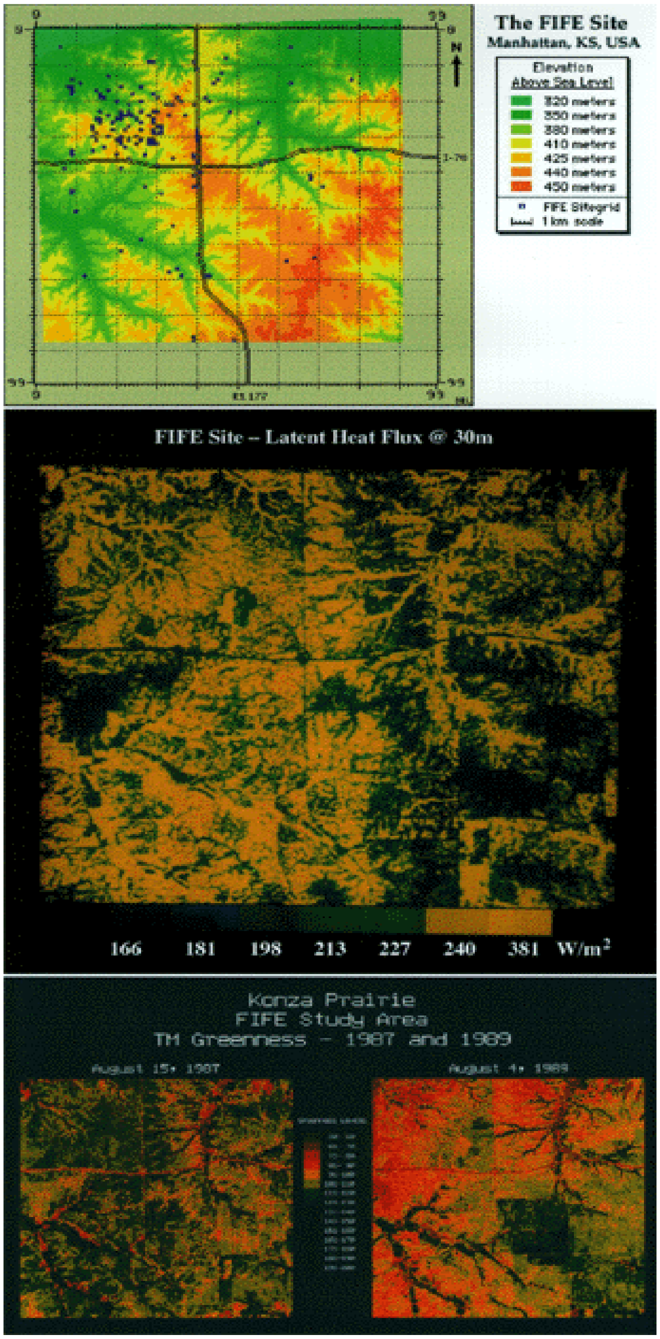

Fig. 2. (Upper) The elevation of the FIFE site as well as the location of the field sites that were instrumented for various land and atmosphere observations. The stream network at the site is evident from the digital elevation map. (Middle) The greenness index as derived using the Thematic Mapper of the FIFE site between August 1987 and August 1989 is shown. The site had much less green vegetation in August 1989. (Lower) The FIFE site latent heat flux for June 6, 1987, at 30-m resolution. The computed latent heat flux shows a great deal of spatial heterogeneity depending on soil moisture and vegetation. In addition, man-made features such as roads are clearly visible (running north-south and east-west). Areas of high soil moisture and high vegetation correspond to larger latent heat flux.

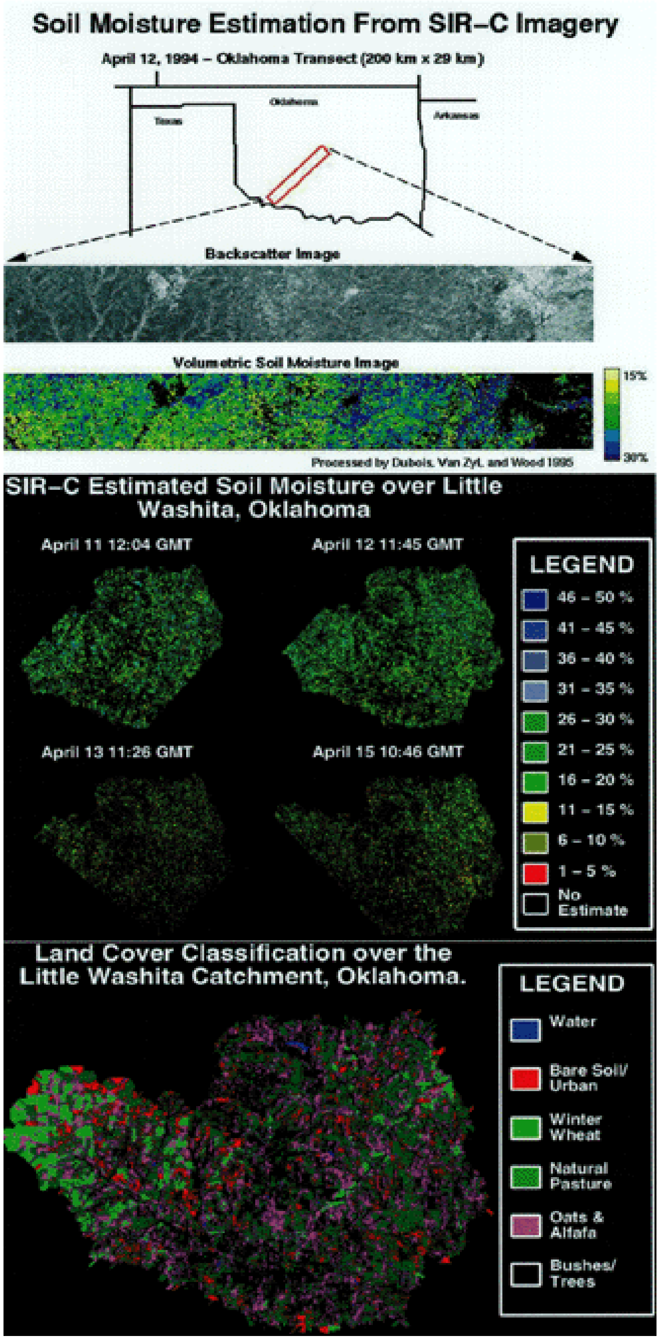

Fig. 3. (Upper) Soil moisture estimation from Spaceborne Imaging Radar (SIR-C). Using the inversion algorithm of Dubois et al. [1995], SIR-C vv and hh backscatter images (L-band) can be processed into estimations of soil dielectric values. In turn, soil dielectric values can be converted into volumetric soil moisture estimates through empirical relationships. Black areas in the soil moisture image represent surfaces where the vegetative cover is too heavy for the accurate application of the Dubois et al. algorithm. Such regional soil moisture imagery provides information about the spatial structure of soil moisture fields within the southern Great Plains. (Middle) SIR-C estimated soil moisture over Little Washita, Oklahoma. SIR-C overflights April 11, 12, 13, and 15 clearly show the drydown over the course of Washita 1994. (Lower) Land cover classification over the Little Washita. Combined with thematic mapper (TM) imagery, SIR-C backscatter imagery was used to construct a land classification map of the catchment. The SIR-C data were used to identify forested pixels, overcoming a critical shortcoming of classifications based solely on TM data.

Table 1

Table 1. Recent hydrological field experiments using remotely sensed data.

Experiment	Dates	Location	Brief Description	Remote Sensing Instruments (See Table 2)	Hydrologic and Ground Data Collected (See Table 3)	Reference
HAPEX/MOBILHY	1986	100 km x 100 km area in Southwestern France	Measurements of surface fluxes at the GCM grid scale	PBMR, TIMS, SPOT, NSOO1,AVHRR, TM,Flux A/C	EB(15), SM, P(60), Q(33), Sonde, Lysimeter, SP, ST, LC	Andre et al. (1988)
FIFE	1987-1989	16 km x 16 km area in the Konza Prairie, near Manhattan, KS	Surface flux and remote sensing measurements to improve land surface parameterizations	PBMR, TIMS, SPOT, TM, NS001, AVHRR, AIRSAR, GOES, Flux A/C	EB(23: 17-B, 6-EC) SM, P, Q, Sonde, Veg/Bio, SP, ST, LC	Sellers et al. (1992)
MACHYDRO-90	July 9-20, 1990	USDA-ARS Northeast Watershed Research Center, near Klingerstown, PA	Testing of microwave remote sensing of soil moisture in a humid environment	PBMR, AIRSAR, NS001, TIMS	P(16), Q(4), Met, Veg/Bio, GW, LC, SP, SM	Wood et al. (1993)
MONSOON 90-91	June-August, 1990 and August 1991	USDA-ARS Walnut Gulch Experimental Watershed, Tombstone, AZ	Characterization of hydrology and surface-air interaction in a semi-arid environment	EXOTEC, Laser, IRT, PBMR, ESTAR, AIRSAR, NS001, TIMS, TM, AVHRR, GOES	EB(17:2-B, 7-EC, 8-O), Veg/Bio, LC, SP, Met(8), SM, ST, P(92), Q(11), Sonde	Kustas and Goodrich (1994)
CaPE/CHymP	July 8 - August 18, 1991	25,000 km² area in central Florida	Characterization of mesoscale meteorology and storms, surface water and energy balance	MAMS, AMPR, LIP, HIS, MTS, SPOT	EB(7), SM, ST, Met, P(200), PAM(47), Sonde	Williams et al. (1995)
Washita-92	June 10-18, 1992	USDA-ARS Little Washita Watershed, near Chickasha, OK.	Evaluation of soil moisture measurements with microwave sensors	AIRSAR, NS001, ESTAR, TIMS, Laser	EB(4), Micronet(42), Q(4), SM, LC, Veg/Bio, GW, SP, Sonde, WQ, P	Jackson et al. (1995)
HAPEX-Sahel	1991-1993	Niger, West Africa	Characterization of water and energy balance in the Sahel	PBMR, POLDER, PORTOS, NS001, TIMS, Laser, TM, EXOTEC	P(110), Q(12), SM, EB(12), Sonde, Veg/Bio, ST, Reflectance	Goutorbe et al. (1994)

Washita-94 (SIR-C/X-SAR)	April 4-18, Aug, Oct, 1994	USDA-ARS Little Washita Watershed, near Chickasha, OK.	Evaluation of soil moisture measurement with microwave sensors	SIR-C/X, ESTAR, NS001, TIMS, Photography, AIRSAR	EB(6), Micronet(42), SM, LC, WQ, SP, Veg/Bio, GW, Sonde, P	Dubois et al. (1995)
BOREAS	1993-1996	Saskatchewan & Manitoba Canada	Measurement of the energy, water and carbon cycle in the Boreal forest	SIR-C/X, AIRSAR, SAR-X, TIMS, NS001, AVIRIS, MAS, ASAS, CASI, MMR, LIDAR, TM, AVHRR, GOES	EB(12-EC), SM, P, Q, Sonde, Veg/Bio, Met(10), SP, ST, LC	Seller et al. (1995)
SGP97	June 18- July 1997	40 x 260 km area in Oklahoma	Soil Moisture mapping and surface-air interaction for the Southern Great Plains	ESTAR, Flux A/C, LIDAR, CASI, TIMS, AVHRR, TM, GOES, Radarsat, SSM/I, JERS, ERS	EB(21: 12-EC, 9-BR), SM, P, Q, Sonde, Met (114), Micronet (42), SP, ST, LC	Jackson (1997)
SALSA	1996-2002	50 x 129 km area in South Eastern Arizona (San Pedro Basin)	Measurement and modeling for semi-arid hydro-eco-Atmospheric Interaction and ASTER validation site	TIMS, SPOT, AVHRR, TM, EXOTEC, IRT, MASTER, ERS-2, GOES-8	EB(4), Veg/Bio, LC, SP, Met(19), SM, ST, P(102),Q(35), Sonde	Goodrich et al. (1998)

Table 2

AIRSAR	Polarimetric Synthetic Aperture Radar (C, L, and P band)
AMPR	Advanced Microwave Precipitation Radiometer
ASAS	Advanced solid-state array sprectroradiometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne visible infrared imaging spectrometer
CASI	Compact airborne spectrographic image
ERS	European Remote Sensing Satellite
ESTAR	Electronically Steered Thinned Array Radiometer (L-band, HH)
EXOTEC	4 band radiometer with SPOT and TM filters
Flux A/C	Sensible and Latent heat flux measurements via aircraft-based sensors
GOES	Geostationary Operational Environmental Satellite
HIS	High resolution Interferometer Sounder
IRT	Infrared radiometer thermometer
JERS	Japanese Environmental Satellite
Laser	USDA laser profiler
LIDAR	Light Detection and Ranging
LIP	Lightning Instrument Package
MAMS	Multispectral Atmospheric Mapping Sensor
MAS	MODIS airborne simulator
MASTER	MODIS Advanced Spaceborne Thermal Emission and Reflection Radiometer
MMR	Modular multichannel radiometer
MODIS	Moderate-Resolution Imaging Spectroradiometer
MTS	Millimeter-wave Temperature Sounder
NS001	Thematic Mapper (TM) Simulator
PBMR	Push Broom Microwave Radiometer (L-band, HH)
POLDER	Polarization and Directionality of Earth Reflectances
PORTOS	Five-channel microwave profiling radiometer
Radarsat	Canadian C band Synthetic Aperture Radar
SIR-C/X SAR	Shuttle Imaging Radar (C, L-bands polarimetric, X-band VV), Synthetic Aperture Radar
SPOT	Satellite Pour d'Observation de la Terre
SSM/I	Special Sensor Microwave Imager
TIMS	Thermal Imaging Multispectral Scanner
TM	Thematic Mapper

Table 3

Table 3. **HYDROLOGIC AND GROUND DATA COLLECTION** (Number of sites is enclosed in parentheses)

EB	Energy balance, using Bowen ratio (B), eddy correlation (EC) or other (O) techniques
GW	Groundwater and piezometer elevation
LC	Land Cover
MET	General Meteorological data
Micronet	Air temperature, humidity, soil temperature, soil moisture and solar radiation data
P	Precipitation
PAM	Portable Automated Mesoscale meteorological network
Q	Runoff
SM	Soil Moisture
Sonde	Radiosondes for atmospheric boundary layer definition
SP	Soil physical properties
ST	Soil temperature
VEG/BIO	Vegetation characteristics and biomass
WQ	Water quality