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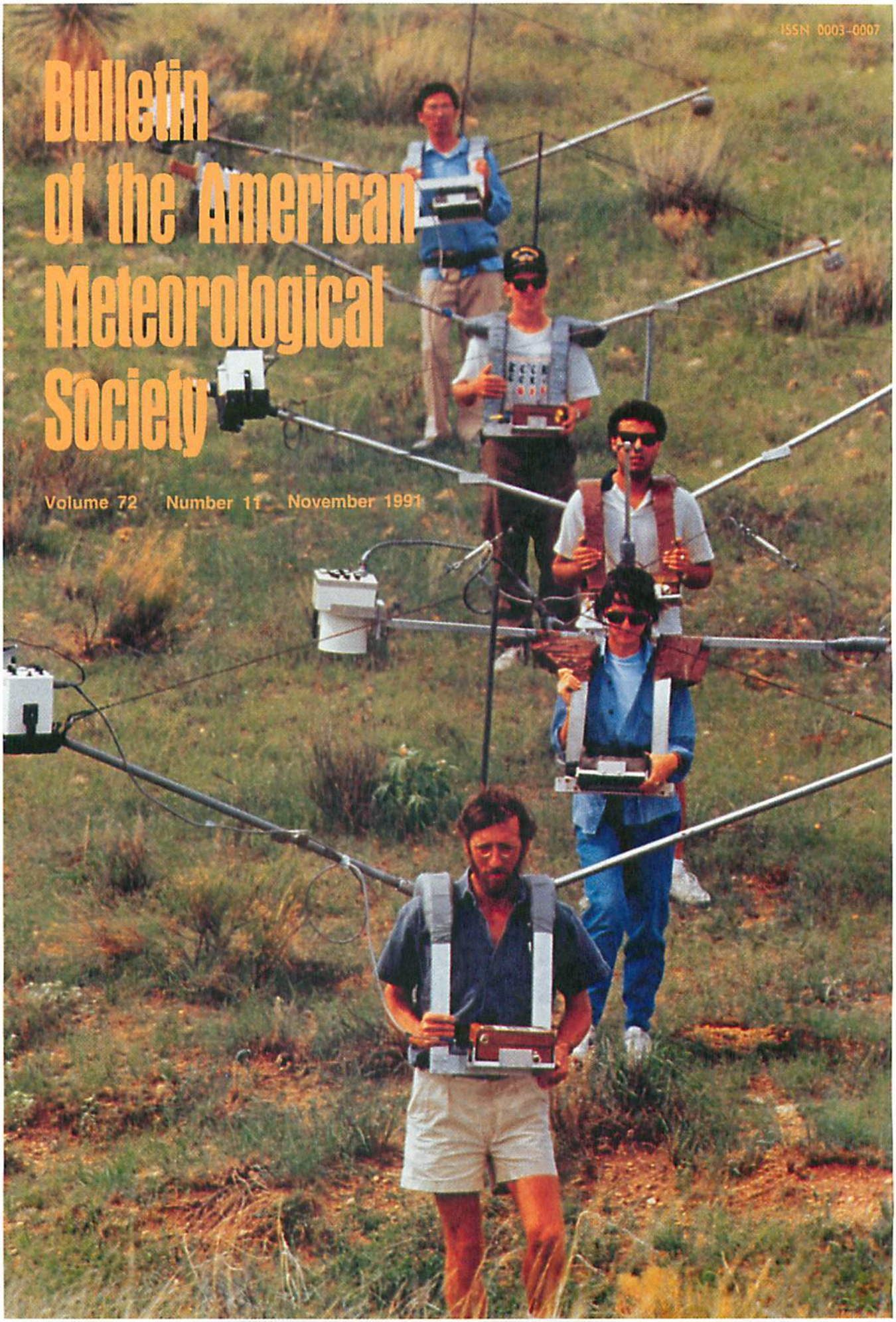

Cover: Investigators preparing to collect remote-sensing data over designated targets concurrent with aircraft and satellite overpasses. The yoke-supported instruments collect radiance data in the visible near-infrared and thermal-infrared wavelengths. These observations will be used for ground-truthing the satellite and aircraft data and for investigating the effects of spatial variability in surface spectral properties on integrated values obtained for a range of sensor pixel resolutions. See article, p. 1683.

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ı Interdisciplinary Field Study the Energy and Water Fluxes in e Atmosphere–Biosphere System over emiarid Rangelands: Description and ome Preliminary Results

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ıtract

nd semiarid rangelands comprise a significant portion of the s land surface. Yet little is known about the effects of temporal ɔatial changes in surface soil moisture on the hydrologic cycle, y balance, and the feedbacks to the atmosphere via thermal g over such environments. Understanding this interrelation- s crucial for evaluating the role of the hydrologic cycle in :e–atmosphere interactions.

ıis study focuses on the utility of remote sensing to provide ırements of surface soil moisture, surface albedo, vegetation biomass, and temperature at different spatial and temporal scales. Remote-sensing measurements may provide the only practical means of estimating some of the more important factors controlling land surface processes over large areas. Consequently, the use of remotely sensed information in biophysical and geophysical models greatly enhances their ability to compute fluxes at catchment and regional scales on a routine basis. However, model calculations for different climates and ecosystems need verification. This requires that the remotely sensed data and model computations be evaluated with ground-truth data collected at the same areal scales.

The present study (MONSOON 90) attempts to address this issue for semiarid rangelands. The experimental plan included remotely sensed data in the visible, near-infrared, thermal, and microwave wavelengths from ground and aircraft platforms and, when available, from satellites. Collected concurrently were ground measurements of soil moisture and temperature, energy and water fluxes, and profile data in the atmospheric boundary layer in a hydrologically instrumented semiarid rangeland watershed. Field experiments were conducted in 1990 during the dry and wet or "monsoon season" for the southwestern United States. A detailed description of the field campaigns, including measurements and some preliminary results are given.

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1. Introduction

Accurate determination of the proportion of radiation received at the surface, which is released back into the atmosphere either in the form of sensible or latent heat or stored in the subsurface over different land types, is paramount for understanding how energy is distributed at regional and global scales. Recent experiments with general circulation models (GCM) suggest that water vapor content in the atmosphere, especially clouds, can have a significant impact on model predictions (e.g., Cess and Potter 1987; Wetherald and Manabe 1988). Satellite observations also support the importance of clouds to climate (Ramanathan 1987;

ıthan et al. 1989). Moreover, GCM results that large-scale changes in vegetation and sture, both leading to changes in the surface ı budget, have a significant impact on synoptic · patterns (e.g., Roundtree and Bolton 1983; ɜt al. 1990; Sud and Molod 1988). Thus reliable ɔation of the hydrologic cycle, namely the on of precipitation that goes into runoff, soil, ɔund water storage and back into the atmo- as water vapor (evaporation), as a function of : characteristics of the catchment, is indeed ary for understanding climate (Eagleson 1986). fficulty faced in hydrologic modeling is that for runoff, which can represent integrated ɔgic processes, all other variables measured ıe ground (e.g., precipitation, evaporation, soil re) are essentially point measurements. These ɔt easily extrapolated to other areas of the

e the vegetation in semiarid range- s is fairly sparse compared to humid ɔns, the soil plays a major role in the ɜtive and hydrologic balance.

ment (Dyck 1984). This is an unfortunate condi- iven the fact that precipitation and evaporation at ıtchment and regional scale are the driving fluxes ɜ hydrologic cycle.

ɜmote sensing in the microwave (Jackson et al. ; Schmugge 1990; Wang et al. 1990) and optical ·ns (Jackson 1985; Taconet et al. 1986; Jackson 1987) may provide many of the measurements ıssary to obtain integrated values of the hydro- components at catchment and regional scales. h of this work is still in its infancy, but it is being ɔusly addressed through large interdisciplinary experiments in different climatic regions. Ex- ıles include the study of agricultural and forested ıs in France (HAPEX-MOBILHY; Andre et al. 1986), e Konza Prairie, Kansas, under FIFE (Sellers et al. 8), and in the semiarid Botswana Savanna (van de ɜnd et al. 1989).

ɔ addition to remote sensing, the estimation of ıonal evaporation using the integrating properties he atmospheric boundary layer (ABL) is another ·nue of research (Brutsaert 1986, 1988; Shuttleworth 38; McNaughton and Spriggs 1986; Wetzel and ang 1988). Indeed, only when proper parameter- tion of the interaction of integrated land surface ıcesses and the ABL is completed, is there hope to ɜain reliable predictions of general weather patterns h climate models.

The purpose of this study is to explore the utility of remote sensing coupled with surface–atmosphere energy balance and hydrologic models for watershed and regional scale assessment of the water cycle in semiarid rangelands.

Approximately one-third of the earth's surface is land, with roughly 40% classified under the broad category of rangeland. The rangeland classification contains many different ecosystems (i.e., grasslands, savannas, shrublands, most deserts, tundra, alpine communities, coastal marshes, and meadows) and climatic zones. But over 80% of rangeland is within arid and semiarid zones (Branson et al. 1972). These lands are characterized by larger extremes in components of the hydrologic cycle and surface energy balance than humid climates. They include: 1) low annual precipitation but high-intensity localized storms, 2) high evaporation potential, 3) high albedo, 4) high soil-heat flux, and 5) low annual runoff but short-term high-volume runoff. Given the relatively large areal extent of these surface characteristics compared to other land types, it is imperative that we understand the hydrologic cycle and its impact on local and regional climate. Moreover, semiarid rangelands are very sensitive to climate anomalies and land-use practices. Hence, it is important that we be able to monitor changes that occur in the surface energy balance and hydrologic cycle because these are strongly correlated to changes in the ecosystem (Schlesinger et al. 1990).

2. Specific concerns for semiarid rangelands

Since the vegetation in semiarid rangelands is fairly sparse compared to humid regions, the soil plays a major role in the radiative and hydrologic balance. For radiation, this is manifested through the soil albedo, thermal conductivity, and heat capacity; the last two combine to form the thermal inertia of the soil. Soil moisture produces the largest change in magnitude of these parameters. In fact, the thermal forcing of the surface is strongly coupled to soil moisture (e.g., Carlson et al. 1981; Idso and Ehrler 1976). As a result, soil moisture is implicitly one of the major factors in driving the development of the ABL, the turbulent properties of which govern local and regional weather patterns (Rabin et al. 1990).

The localized nature of the precipitation in semiarid rangelands results in soil moisture changes commonly occurring over area scales 1 to 2 orders of magnitude smaller than the resolution of mesoscale models (i.e., of order 100 km^2). Perturbations in the fluxes caused by advection at these smaller-length scales may be important to local surface–atmosphere

interaction, but the influence of localized moisture variations on regional boundary-layer development is probably less of a concern. This conclusion, however, has not been thoroughly investigated.

Variations in the surface radiative balance due to changes in soil moisture at the catchment scale, and the subsequent feedbacks to the atmosphere, have not been significantly explored (Eagleson 1981). In terms of the hydrologic cycle, the condition of the soil surface influences the magnitude of the runoff component. This is especially evident in semiarid and arid rangelands, where infiltration may be one of the most important factors in determining the amount of runoff (Keppel and Renard 1962). Although rainfall duration and intensity are the major contributing factors to the quantity of runoff, antecedent soil moisture or evaporation can play a major role in the amount of runoff at the watershed scale (Hino et al. 1988; Loague and Freeze 1985).

3. Project objectives

The environmental conditions associated with semiarid rangelands pose a great challenge to accomplishing scientific objectives associated with the application of remote-sensing data for energy and water balance modeling. For this study, the objectives are:

1) Integrate remote sensing observations over a wide range of pixel resolutions from ground-, aircraft-, and satellite-based systems over a heterogeneous area to assess the effects of a complex surface on sensor integration.

2) Investigate the utility of remote sensing at various wavelengths for mapping the spatial distribution of soil moisture and vegetation such as leaf area index (LAI), and its temporal trend over length scales from meters to kilometers.

3) Quantify the effects of advection caused by local precipitation on large area fluxes and atmospheric boundary-layer development.

4) Determine whether the effects of topography and vegetation type on the vertical distribution of soil moisture can be quantified over a range of length scales using remote-sensing observations with models.

5) Evaluate the use of remotely sensed soil moisture and vegetation data as input into a rainfall-runoff model for determining the hydrologic response of a semiarid basin to a significant precipitation event.

6) Determine what physical parameters can be measured by remote sensing that are critical in modeling the exchange of water vapor and energy across the soil–plant–atmosphere interface of semiarid basins over a broad range of spatial and temporal resolutions.

4. Site description

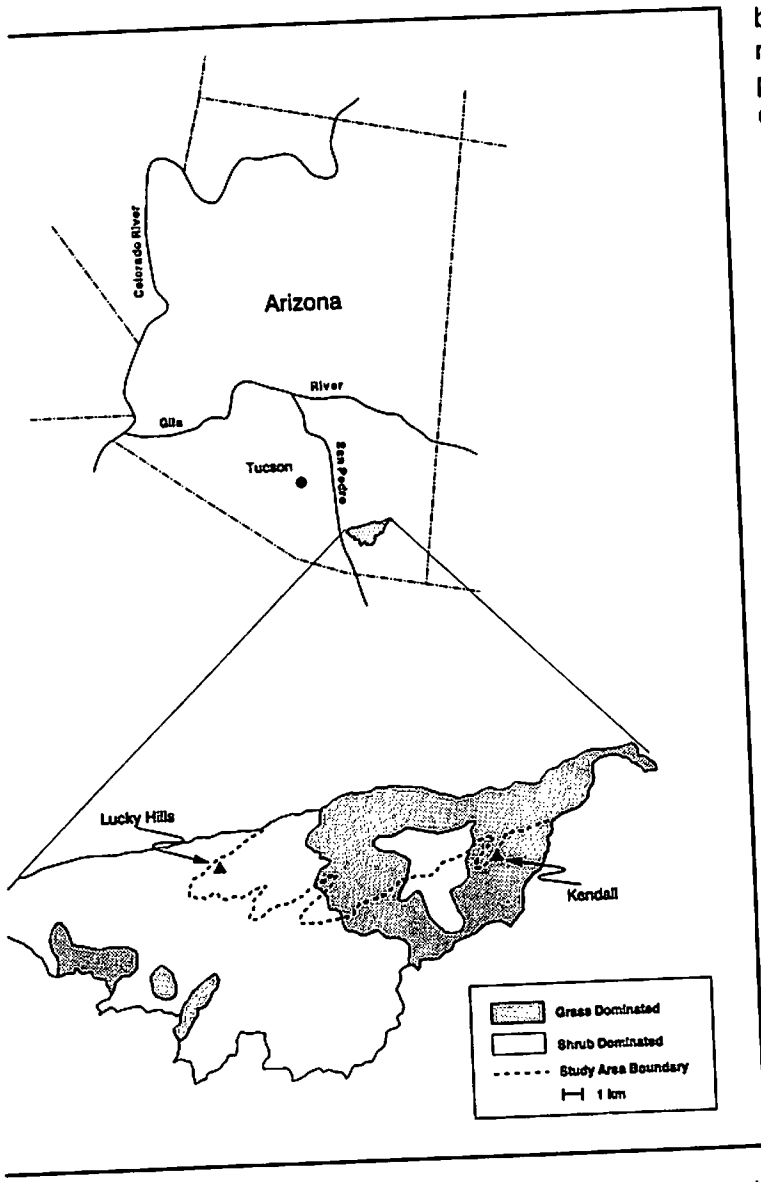
To investigate the effects of changing soil moisture on the surface radiation balance, the hydrologic cycle, and the feedbacks to the atmosphere, a hydrologically instrumentated semiarid rangeland watershed was selected. This catchment, the Walnut Gulch Experimental Watershed (31°43'N, 110°00'W) operated by the USDA-Agricultural Research Service, is located in the southwestern United States about 120 km southeast of Tucson, Arizona.

In this region, annual precipitation is 250–500 mm, with two-thirds of it falling during a summer "monsoon season" that encompasses the months of July and August. The precipitation is usually in the form of high-

Although rainfall duration and intensity are the major contributing factors to the quantity of runoff, antecedent soil moisture or evaporation can play a major role in the amount of runoff at the watershed scale.

intensity thunderstorms of limited areal extent. The runoff in the ephemeral streams is of short duration, carrying a relatively large sediment load. The channels are also relatively steep, resulting in flows being near critical depth.

The catchment is an ephemeral tributary of the San Pedro River, with the instrumented area comprising the upper 150 km^2 of the Walnut Gulch drainage basin (Fig. 1). The soils range from clay and silts to well-cemented boulder conglomerates. The topography can be described as gently rolling hills incised by rather steep drainage channels, which are more pronounced at the eastern end of the watershed. The vegetation is mixed grass–brush rangeland typical of southeastern Arizona and southwestern New Mexico. Figure 1 gives the approximate boundaries of the main vegetation biomes in the watershed. The lowest gauging station, at the west end of the watershed, is around 1300 m above mean sea level (MSL), while the elevation of the upper end 20 km east is about 1800 m MSL. There are 98 raingages and 11 runoff-measuring stations on the watershed. The raingages are a weighing type with a 20-cm-diameter orifice. Each raingage (temporal resolution ~2 min) produces an analog recording of accumulated rainfall with time. The raingage network at Walnut Gulch has resulted in a number of important papers on estimating precipitation over semiarid rangelands (e.g., Islam et al. 1988;



ı. 1. Location of the Walnut Gulch Experimental Watershed in Arizona and approxi-
ocations and areas in the Walnut Gulch Watershed occupied by the two main types
ıetation, i.e., grass and brush. The boundary of the study area (- - -) along with the
ɔn of the two main experimental subwatersheds (▲), Lucky Hills and Kendall, are

ɔbs et al. 1988; Osborn et al. 1979, 1980; Osborn
3). Walnut Gulch is divided into 12 subwatersheds
/ing in size from 2.3 km² to 150 km². A number of
ıller subwatersheds, ranging in size from 0.34 to
3 ha, exist within Walnut Gulch and are intensively
nitored with excellent hydrologic record and de-
ɜd basin characterization. The raingage and runoff-
asuring system was completed in 1966.
Several valuable databases covering the Walnut
lch watershed have recently been acquired. A high-
ɔlution Soil Conservation Service soil survey has
en completed that provides detailed soil type and boundary resolution. A large-scale mapping project is also underway to provide orthophoto map sheets covering the watershed at a scale of 1:5000 with a contour interval of 5 m. A digital elevation model (DEM) of the watershed is also being generated. This will facilitate a much more accurate computation of incident radiation than could be achieved by using current USGS DEM data (D.C. Goodrich, personal communication).

5. Experimental design

a. Field campaigns

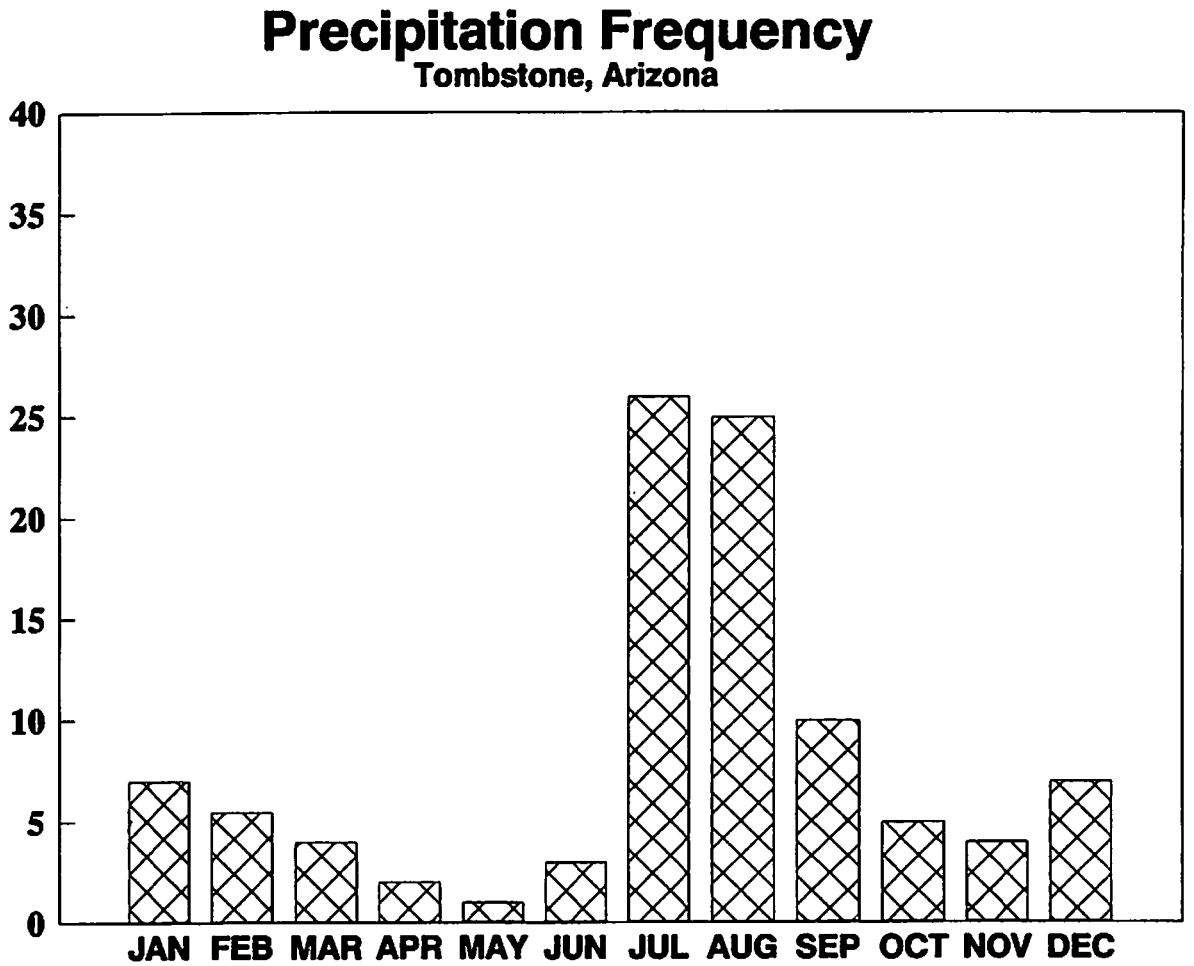
To address the remote-sensing issues raised in section 3, the experimental plan covered two distinct climatic conditions, namely the dry season in May–June and the wet or "monsoon season" in the July–August period (Fig. 2). The objective of the field campaign during the dry season was to obtain baseline measurements of the optical and thermal properties of the surface as well as energy-balance components under senescent vegetation and dry soil conditions. In the July–August field campaign, the objective was to collect data when the vegetation was in its peak greenness, soil moisture was highly variable both spatially and temporally, and there was a likelihood for several significant precipitation events producing runoff in the catchment. The dates of the field studies were 4–6 June 1990 and 23 July–10 August 1990.

The June campaign was significantly smaller in scale, both in the number of participants and in the number and length of time of the measurements. Nonetheless, during the observation period there were ground-, aircraft-, and satellite-based systems collecting remote-sensing data as well as surface energy flux measurements. The following description of the observations pertains mainly to the July–August campaign.

b. Ground-based observations

1) METEOROLOGICAL- ENERGY FLUX (METFLUX) STATIONS

There were eight sites containing instrumentation



2. Average monthly precipitation from 60 years of record for Tombstone, Arizona, located within Walnut Gulch Basin.

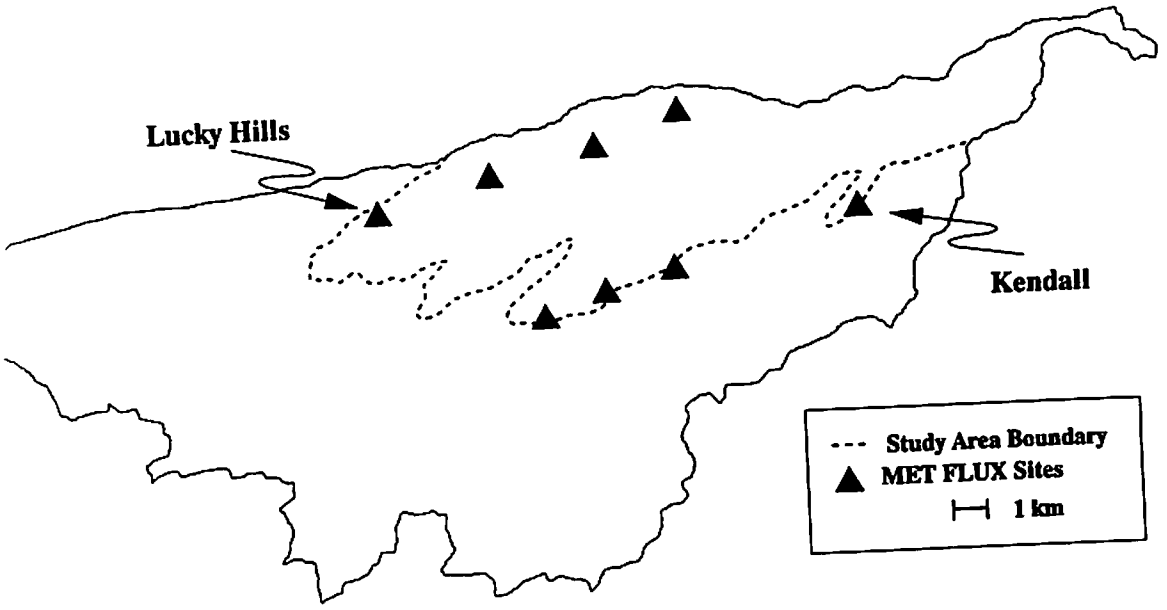
ıasuring both general meteorological conditions ır estimating the surface energy balance. A list of ınsors used at each site is provided in Table 1. ı METFLUX sites were located along two parallel ıcts so that the data collected by the stations be easily compared to the remote-sensing ob- tions from airborne sensors. The METFLUX ıs covered the two dominant vegetation types ı and grass) and the transition from one to the Figure 3 illustrates their location along with the ıtershed boundaries that demarcate the main area. The size of the main study site was about ı² or about one-third the area of the watershed. IETFLUX sites were situated along ridgetops to e spatially averaged turbulent energy flux values tive of the surrounding terrain. It was also felt ıe geophysical data collected by this network reflect the variation caused by vegetation differ- ı across the study area.

ı energy balance was determined by taking urements of net radiation (Rn), soil heat flux (G), ıe temporal variance of air temperature, which was used in computing sensible heat flux (H) (Tillman 1972; Weaver 1990; Wesely 1988). If one assumes energy-balance closure, the latent heat flux (LE) is solved as a residual (Brutsaert 1982), i.e.,

$$LE = -(Rn + G + H). \quad (1)$$

In Eq. (1), fluxes away from the surface are negative while fluxes towards the surface are positive. In addition to the variance method, five of the sites also measured the sensible heat flux with the eddy correlation technique using a tower with a propeller anemometer and a fine wire thermocouple at a height of approximately 9 m (Amiro and Wuschke 1987). Although these techniques are not as accurate as other more direct eddy correlation methods (e.g., Wesely et al. 1970), mainly due to the slower response times of the sensors, they are not as susceptible to damage caused by severe rain storms and require little maintenance. These are important considerations when designing a network of flux stations on a relatively small budget.

Walnut Gulch Watershed and Study Area



3. Location of the METFLUX sites within the study area. The intensively studied subwatersheds Lucky Hills and Kendall are labeled.

'o METFLUX sites contained other micrometeo-
cal instrumentation. One was located in Lucky
a brush-dominated ecosystem, while the other
n the Kendall subwatershed, which is a grass-
nated ecosystem (see Fig. 1). At each site the
t heat flux was evaluated using the Bowen ratio/
gy balance approach (Fritschen 1965). Wind-
speed measurements at multiple heights from 1 to 5 m above the surface were acquired for estimating the local surface roughness (Panofsky and Dutton 1984). Fluxes of latent and sensible heat were measured by one-dimensional eddy correlation systems using a sonic anemometer with a fine wire thermocouple and krypton hygrometer at about 2 m above the ground

ABLE 1. Automated measurements at the METFLUX stations. Data averaged over 20-minute intervals.

surement	Replications	Height/depth of sensor (m)
radiation	1	2.5
an air temperature	1	4.0
iance in air temperature	1	4.0
face temperature	1	2.5
d speed & direction	1	4.5
temperature/relative humidity	1	2.0
ar radiation	1	3.5
otosynthetically active radiation (PAR)	1	3.5
il heat flux	3	–0.05
il moisture	6	–0.05
il moisture	6	–0.025
il temperature	3	–0.025
il temperature	2	–0.05
il temperature	1	–0.15

ese measurements were only at the Kendall and Lucky Hills sites.

(Tanner 1988). The area around Kendall at the eastern end of the watershed has significantly rougher topography; hence, the measurements using a one-dimensional sonic are more difficult to properly interpret at this site. Lucky Hills, having significantly smoother topography, had more adequate fetch conditions. Momentum and sensible heat flux were also measured at the two sites using a three-dimensional sonic system. The 3D sonic data will allow the analysis of power spectra for investigating characteristics of the energy-carrying turbulent eddies (McBean and Miyake 1972).

In order to account for any potential biasing of the radiation measurements at the METFLUX sites, Lucky Hills and Kendall contained more-precise instruments for measuring incoming and outgoing radiation. The reduction of this bias or error is critical since net radiation, the largest source of energy, is used to derive the evaporative flux for the METFLUX sites. Also, net radiation can be used to assess the reliability of turbulent flux measurements made by the more-precise eddy correlation systems by checking for energy-balance closure (e.g., Massman et al. 1990). The additional radiation measurements included a 4-way system consisting of precision spectral pyranometers for measuring incoming and reflected shortwave radiation, precision pyrgeometers for measuring incoming and emitted longwave radiation, and an Eppley* pyranometer with a greater sensitivity over the shortwave energy spectrum than the sensors at the METFLUX sites. Furthermore, a Schenk net radiometer that is less susceptible to differences in longwave and shortwave calibrations associated with nonventilated net radiometers was located in Lucky Hills.

2) Vegetation and soils information

Soils and vegetation at all the METFLUX sites were characterized. For the soils, this included bulk density of the upper 5 cm, estimates of the surface and upper 5 cm rock fraction, soil-type pedon, and SCS pristine condition classification. For the vegetation, five line transects of 30 m each were measured. Information included a species list, percent cover, average plant height and volume by species, total LAI and biomass, litter standing and lying, and plant water content.

3) Soil-moisture measurements

Gravimetric soil-moisture samples of the upper 5 cm (three replications) were collected daily at each METFLUX site. Also, an automated system for measuring near surface soil moisture was incorporated at each site (see Table 1) using soil-moisture resistance sensors (Reynolds et al. 1987) calibrated with the soil from the METFLUX location. Since most of the METFLUX stations were on ridgetops, especially at the eastern end of the watershed, surface soil-moisture data were collected along two 3/4-km transects traversing several ridges and valleys at the eastern end of the study site. These data will provide useful information about the spatial distribution of surface soil moisture caused by topographic effects. The transect soil-moisture data were collected with a dialectric probe unit (Bruntfelt 1987) about every 50 m. Data collection for each transect took about 2 h.

Data on the vertical distribution of soil moisture were collected at Kendall and Lucky Hills using time domain reflectometry (TDR) (Topp and Davis 1985), as well as with the soil-moisture resistance sensors. The TDR sensors were positioned at multiple depths from about 5 to 50 cm, with some reaching close to 75 cm. At Lucky Hills, the measurements were made between and underneath the brush (three replications), while at Kendall the measurements were made on north- and south-facing slopes midway between the stream channel and ridge, and in grazed and ungrazed areas.

4) Soil-temperature measurements

For the METFLUX sites, soil-temperature observations were acquired at several depths (Table 1). Soil temperatures were also measured at the Kendall and Lucky Hills soil moisture profile sites at comparable depths with the TDR probes. All soil-temperature sensors were copper-constantan thermocouples.

5) Roving energy flux systems (ROVEFS)

Two techniques were employed for measuring evapotranspiration with instruments that could be transported to a number of sites. One already mentioned used the eddy correlation technique with a one-dimensional sonic anemometer and fine wire thermocouple, and a krypton hygrometer. This system was moved to several of the METFLUX sites that were amenable to this technique for comparing energy-flux measurements made by the more indirect approaches (i.e., variance and propeller). Furthermore, this ROVEFS was located in both dry and wet areas to ascertain the variability in the energy fluxes and assist in quantifying advection, which was also being monitored by tethered sonde systems (see section 5b.6).

The other ROVEFS was a ventilated chamber used to estimate soil evaporation and plant transpiration of the various plant species (Reicosky and Peters 1977; Denmead 1984; Stannard 1988). Measurements were made at Lucky Hills.

*Trade names and company are given for the benefit of the reader and do not imply endorsement of the product or company by the organizations with which the authors are affiliated.

/EASUREMENTS OF THE ATMOSPHERIC BOUNDARY LAYER
SING RADIOSOUNDINGS

) types of systems were used to collect ABL data watershed. Measurements included dry- and ılb air temperatures, pressure, wind speed, and lirection. One type was a tethered sonde that detailed observations (vertical resolution of less 0 m) of the lower atmosphere up to about 500 m. ystems positioned about 10 km apart along a line ɜl to the general wind direction in the lower ;phere were used to collect data simultaneously. ther system provided free soundings of the same as the tethered sonde. Measurements had a al resolution on the order of 20 m, but were ıed up to approximately 5000 to 6000 m (MSL) or ıd 4000 m above ground level (AGL). These ·vations will provide basic information on the ture and properties of the ABL.

ıere were multiple soundings by both systems on :ted days to study both local and mesoscale ction, regional roughness, and ABL development l 1988). Regional scale surface fluxes of sensible atent heat will be determined with these observa- using an approach described in Munley and s (1991). Free soundings were also performed ıg satellite overpasses with favorable weather litions to provide input data for models estimating ɔspheric attenuation of the radiance received by .atellite and high-altitude aircraft sensors (Kaufman ɜ).

) REMOTE-SENSING OBSERVATIONS

ıround-based remote-sensing observations were le over designated areas in Kendall and Lucky ; during satellite and aircraft remote-sensing mis- ıs. Multispectral instruments with SPOT and TM rs and infrared thermometers (IRT) were carried /okes (see cover fig.). This allowed measurement ısects to cover areas representing multiple pixel- ɜd footprints of the satellite and aircraft sensors. ɜrmal observations with hand-held IRTs were also orded along several transects used for the multi- ɜctral observations in Kendall. The observations re made at the approximate time of the minimum ɪ maximum surface temperatures, and near the ɜrpass times of the *NOAA 11* satellite AVHRR. ɜ emissitivities of the soil and vegetation around ɔh of the METFLUX sites were determined using approach developed by Fuchs and Tanner (1966). Bidirectional reflectance measurements (Jackson al. 1990) were made at a site in the Kendall ıtershed using an SE590 Spectron spectral radiom- ɜr. This instrument measures reflectance between 38 and 0.90 μm in 0.01-μm bandwidth intervals. The ırpose of the observations is to assess the sensitivity of vegetation indices to the solar and view angle positions and the anisotropic nature of the surface.

A leaf area meter using a fish-eye lense (LI-COR Model LAI-2000 Plant Canopy Analyzer) was employed. Measurements were made at each METFLUX site near the locations of destructive vegetation sampling for LAI. Observations were made along three to five transects approximately 50 m in length, with samples collected every several meters.

Sky-view photographs for assessing the amount and type of cloud cover (McGuffie and Henderson-Sellers 1989) were taken at half-hourly intervals from either Kendall or Lucky Hills. During satellite overpasses, the frequency was increased to every minute for a 10-min window around the scheduled overpass time.

Measurements of optical depth were performed on selected days corresponding to overpasses of the SPOT and LANDSAT-5 satellites. These data will be beneficial in correcting satellite observations in the visible and near-infrared wavebands (Biggar et al. 1990).

c. Aircraft observations

1) DESCRIPTION OF AIRCRAFT AND INSTRUMENT PACKAGES

Three aircraft were used on a regular basis during the July–August experiment with sensors covering the visible to the microwave electromagnetic energy spectrum. A Cessna flown by Aerial Images Corp., Tucson, Arizona, regularly carried an Exotech 4-band radiometer that had SPOT and TM filters, an Everest IRT, and a thermal-IR scanner. Other sensors included black-and-white video and multispectral video cameras. A description of the instruments on the Cessna is given in Table 2. This aircraft and instrument package (except for the thermal-IR scanner) has been used in other remote-sensing studies (e.g., Jackson et al. 1987; Moran et al. 1989).

An Aero Commander, which is owned and operated by USDA-ARS, Subtropical Agricultural Research Lab in Weslaco, Texas, flew a multifrequency (3-band) microwave radiometer system designed by the Institute of Radioengineering and Electronics (IRE) of the Academy of Sciences, USSR. Description of the instrument is given in Table 2. The IRE scientists have developed algorithms for assessing several types of land surface variables, including surface and profile soil moisture, soil salinity, and vegetation biomass (Mkrtchjan et al. 1988). Also on board the aircraft was a color video camera for recording flight-marker locations.

The NASA C-130 based at Ames Research Center, California, carried a multifrequency radiometer covering from the visible to the thermal-IR wavelengths (NS001), a multifrequency thermal-IR sensor (TIMS), and a passive microwave sensor (PBMR). A video

ABLE 2. General description of instruments flown on the Cessna, Aero Commander, and C-130 aircraft

craft	Instrument	Number of bands	Wavelength Range
ssna	Exotech radiometer IFOV: 15°	4	0.50 – 0.89 μm (SPOT Filters) 0.45 – 0.90 μm (TM Filters)
ssna	Everest IRT IFOV: 15°	1	8 – 14 μm
ssna	Multispectral Video Camera IFOV:15°	6	0.48 – 0.90 μm
ssna	Thermal Infrared Scanner IFOV: 2.4 mrad	1	8 – 12 μm
o Commander	Multifrequency Microwave Radiometer	3	2.25 – 27 cm
30	NS001 Thematic Mapper Simulator IFOV: 2.5 mrad Scan Angle: 100°	8	0.458 – 12.3 μm
30	TIMS Thermal Imaging Multispectral Scanner IFOV: 2.5 mrad Scan Angle: 76°	6	8.2 – 11.7 μm
30	PBMR Push Broom Microwave Radiometer IFOV: 17° FOV: 50°	1	21 cm

em for locating aircraft and georeferencing the and a camera system for visible and color-IR tos were also part of the data-acquisition system. ore detailed description of the instrument package iven in Table 2. Analysis of the data from these sors have shown them to provide valuable infor- ion for hydrologic applications (Carlson et al. 1990; man et al. 1989; Jackson and Schmugge 1989; mugge 1990; Wang et al. 1990).

fourth aircraft, the NASA DC-8, which is also out mes Research Center, flew once during the July– ust campaign. On board the aircraft was the thetic aperture radar (SAR), an active microwave em having high spatial resolution (Evans et al. 8).

) SUMMARY OF FLIGHTMISSIONS

light lines for the Cessna and Aero Commander are illustrated in Fig. 4a. Flight-line markers placed approximately every kilometer were used to maintain proper course. The two parallel lines orientated nearly east–west generally ran along the ridges, especially on the eastern end of the watershed. A third north–south flight line (line 3 in Fig. 4a) traversed several ridges and valleys and gave an opportunity to assess topographic effects. The flying altitude for the Cessna and Aero Commander was a nominal 150 m AGL. This produced about a 40-m pixel for the sensors on the Cessna (except for the thermal scanner; see Table 2) and about a 100-m pixel for the Aero Commander sensors. The Cessna flights were normally scheduled to coincide with satellite overpass times or the high-altitude C-130 mission (see below). The Aero Commander flew once a day between 0800 and 0900 Mountain Standard Time (MST).

The C-130 flew two distinct missions. One was

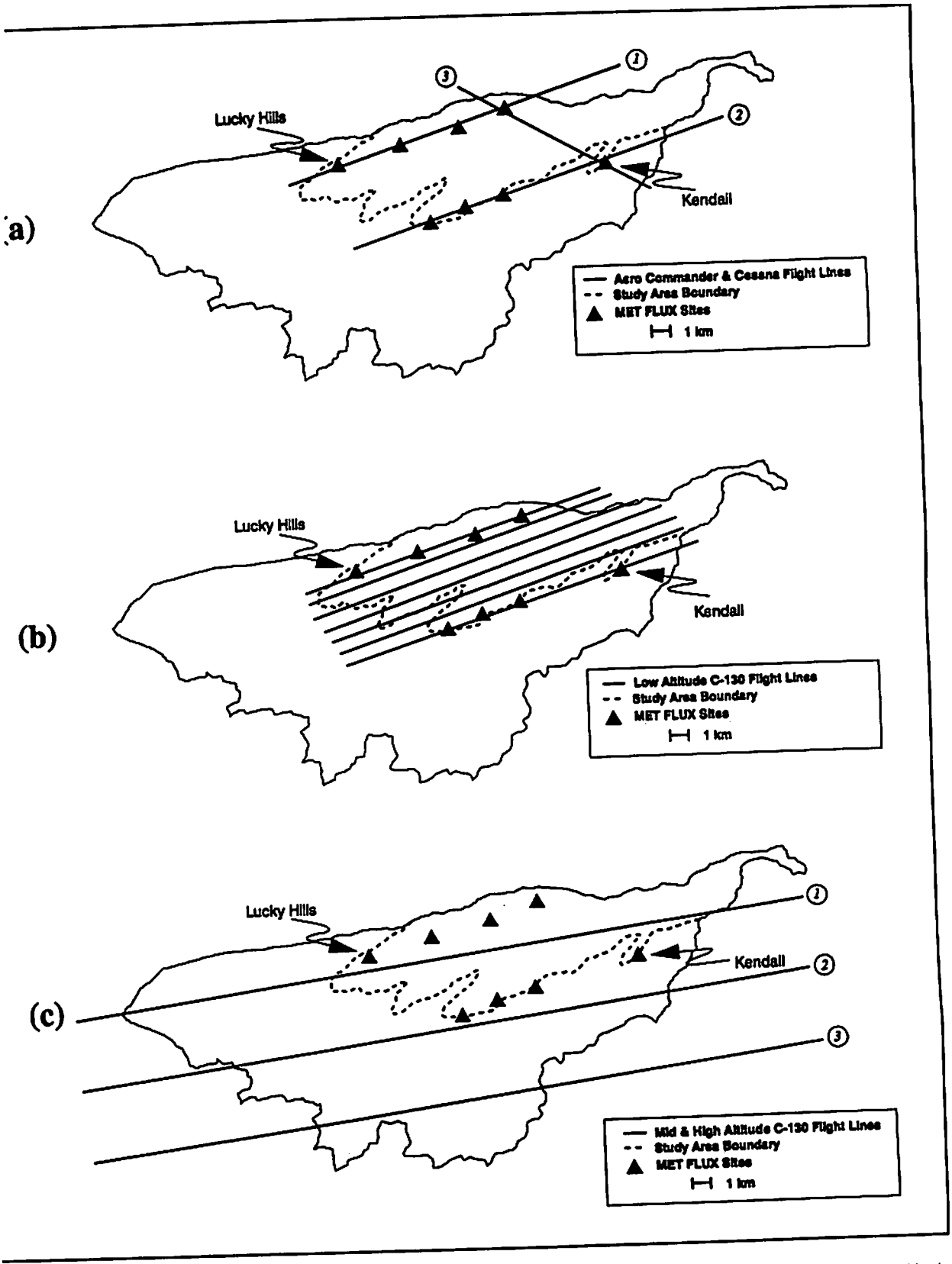


FIG. 4. Flight lines for (a) the Cessna and Aero Commander, (b) the low-altitude C-130 PBMR mission, and (c) the mid- and high-altitude 130 TIMS/NS001 observations. Flight line 3 in (a) was also used for the dialectric probe measurements (see text). The flight lines in (b) spaced 450 m apart and include lines 1 and 2 in (a). Flight lines 1 and 2 in (c) provide overlapping coverage of the study area. The proximate locations of the METFLUX sites and study-area boundary are illustrated.

TABLE 3. Information on sensor resolution, spectral range, number of channels, and temporal frequency for the satellite platforms used ıis study.

ellite	Number of channels	Approximate spectral range (μm)	Pixel resolution	Temporal frequency
OT-2	4	0.50 – 0.89	20 m	5 days
NDSAT-5 1)	7	0.45 – 12.5	30 m Vis & IR 120 m Thermal-IR	18 days
AA-11				
HRR-LAC	5	0.58 – 12.5	1.1 km	12 hrs
-GAC	5	0.58 – 12.5	4.5 km	
ES-6	2	0.55 – 0.75 10.5 – 12.5	8 km	*

even visible and five infrared observations over a 24-h period.

fined as a low altitude mission (600 m AGL), which llected PBMR and NS001 data. A total of seven ıht lines equally spaced and parallel, including the ssna and Aero Commander flight lines 1 and 2 in ı. 4a, were flown (see Fig. 4b). A flying height of 600 AGL resulted in a PBMR pixel size of about 200 m d a NS001 pixel of about 1.5 m. Distance between ı flight lines was about 450 m, which produced ough overlap in sensor integration that relatively v gaps in data collected over the whole study site ve been found.

The C-130 second mission for mid- and high-itude are illustrated in Fig. 4c. This design allowed coverage of the whole watershed and overlapping verage of the intensive study site. The TIMS and 3001 sensors as well as the metric camera were erated at the higher altitudes. The C-130 flew at a minal 2000 m and 5000 m AGL for the mid- and ıh-altitude mission. This gave pixel sizes for the MS and NS001 of about 5 and 12.5 m for the mid- d high-altitude missions, respectively.

The low-altitude mission was scheduled to be flown ı a daily basis starting around 0900 MST, unless soil-ɔisture conditions had not significantly changed or vere weather conditions existed. Mid- and high-itude flights followed the low altitude mission. Devia-ns in this program would result on days with SPOT ıd LANDSAT overpasses, in which case the mid- ıd high-altitude missions would take precedence er the low altitude. If there was significant cloud ver, only the low-altitude mission collecting data th the PBMR was scheduled.

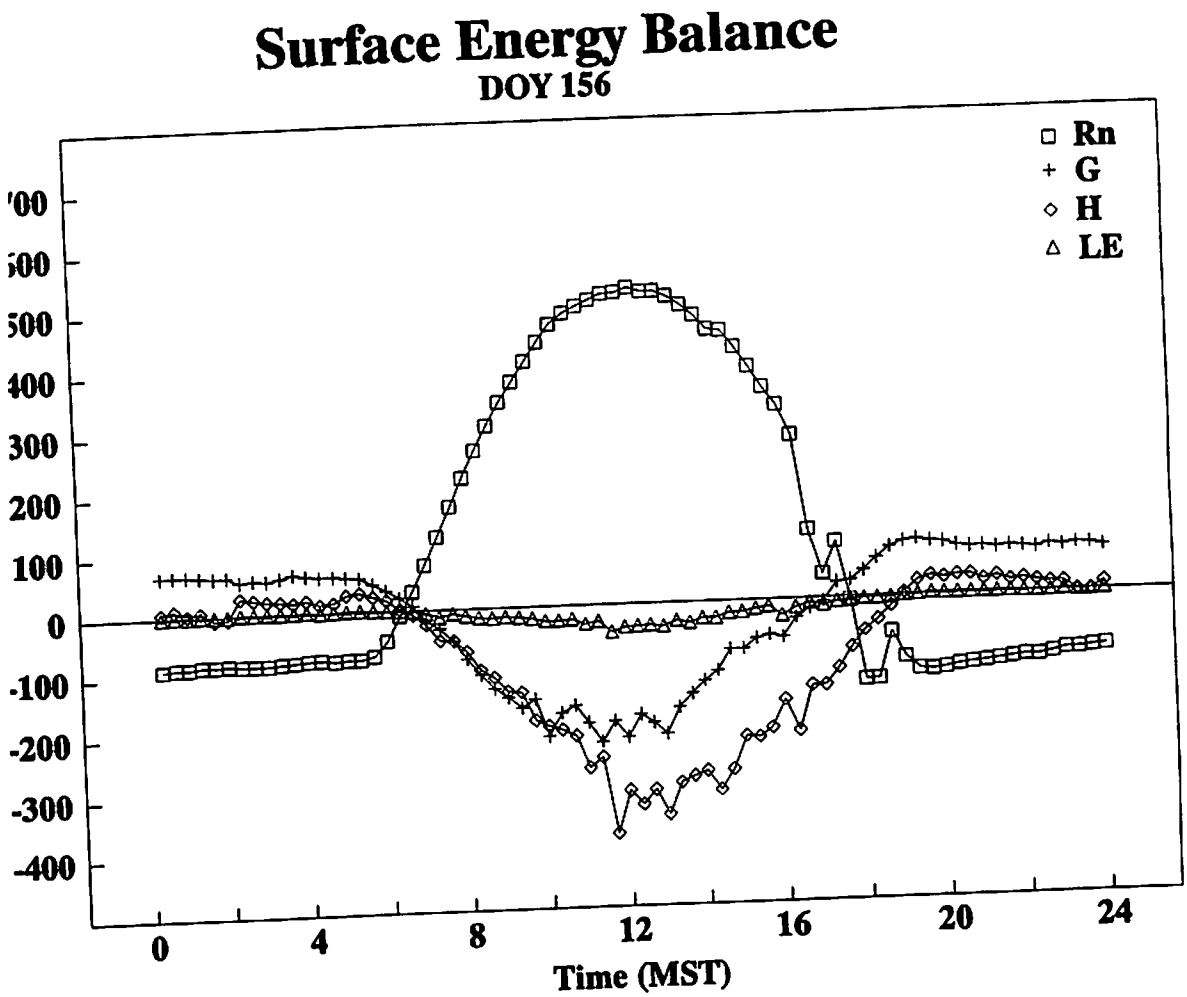
Satellite observations

ır the June and July–August field campaign, several attempts were made to collect satellite data from *SPOT-1* and *SPOT-2, LANDSAT-5, NOAA-11* AVHRR, and *GOES-6*. Table 3 provides general information regarding sensor frequency, and spatial and temporal resolution of the satellites used (see also Ohring et al. 1989; van de Griend et al. 1989). Due to the unusually high frequency of cloud cover and the low frequency of *SPOT-2* and *LANDSAT-5* coverage, no usable data from these two satellites were acquired during the July–August campaign. A similar problem in acquiring adequate SPOT and LANDSAT coverage for hydrologic and biophysical applications have been voiced by others (e.g., Hall et al. 1990). Preliminary analysis of images from the NOAA AVHRR and GOES satellites suggests an adequate number of overpasses had minor cloud contamination over the Walnut Gulch region. Hence the application of satellite data for hydrologic modeling will be tested, albeit primarily at coarser spatial resolutions.

6. Summary of field campaigns and some preliminary observations

a. The June campaign

The June campaign was generally hot and dry. The METFLUX measurements produced Bowen ratios (H/LE) on the order of 10 during daylight hours and gravimetric soil samples of the upper 5 cm gave surface soil-moisture values of less than 5%. The vegetation was senescent. Typical energy-balance components [cf., Eq. (1)] during the field experiment are shown in Fig. 5. In Fig. 6 is a comparison of the sensible heat flux during unstable conditions at Lucky Hills for several days between the variance or indirect



5. Energy-balance components during the June campaign (DOY 156). Fluxes are measured by an eddy correlation system at Lucky Hills.

ɔd and the eddy correlation technique. The preɪry results look encouraging. The points generɜll along the 1-to-1 line with a correlation coeffi- of 0.9 and a root-mean-square error of 40 -2. On 5 June 1990 (DOY 156) data from *SPOT-*ɜ *LANDSAT-5* satellites were collected together ɜround- and aircraft-based remotely sensed data. age surface-temperature values over sites taken with the ground-based units (i.e., yokes) for Kendall and Lucky Hills, along with continuous IRT observations at the METFLUX sites and a mean value for the two subwatersheds estimated with LANDSAT-TM data, are shown in Fig. 7. The data have not been adjusted for differences in emissivity. The fairly close agreement between the various observations may suggest that the variation in surface temperature across the watershed under these environmental conditions is relatively small. However, data from the METFLUX sites also reveal that significant differences in surface temperatures between Lucky Hills and Kendall did occur during the time of maximum heating. Future investigations with the meteorological and aircraft observations will be helpful in interpreting the results in Fig. 7.

ABLE 4. Monthly rainfall totals from a raingage in Walnut Gulch ı for the dry and wet "monsoon" seasons in 1988, 1989, and .

th	1988 rainfall total (mm)	1989 rainfall total (mm)	1990 rainfall total (mm)
e	15	0	17
,	72	79	123
just	134	51	85
tember	48	6	45

b. The July–August campaign

1) Weather conditions

The monthly rainfall for June and July of 1990 was significantly higher than in previous years. In Table 4 are the monthly totals from a raingage in Walnut Gulch

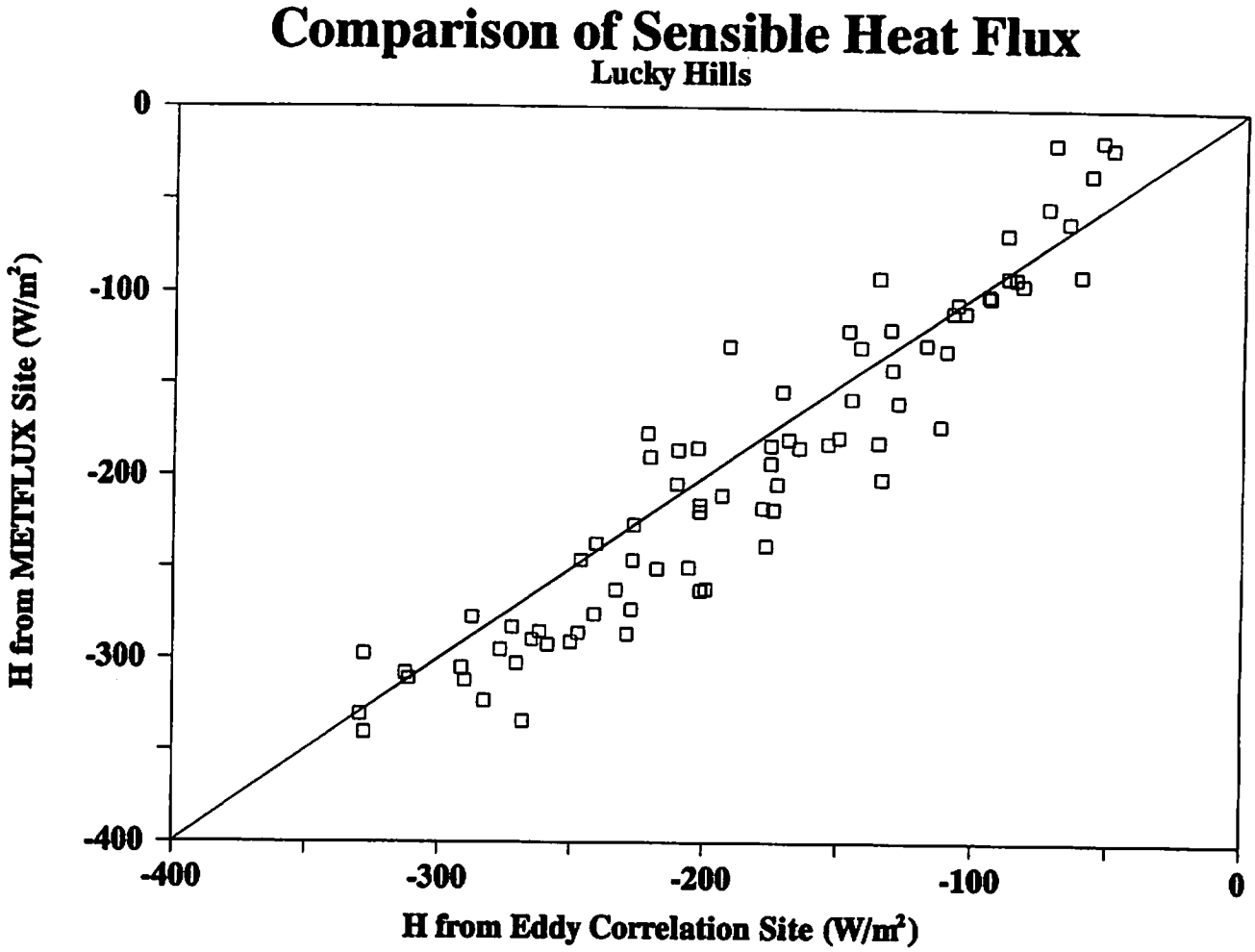
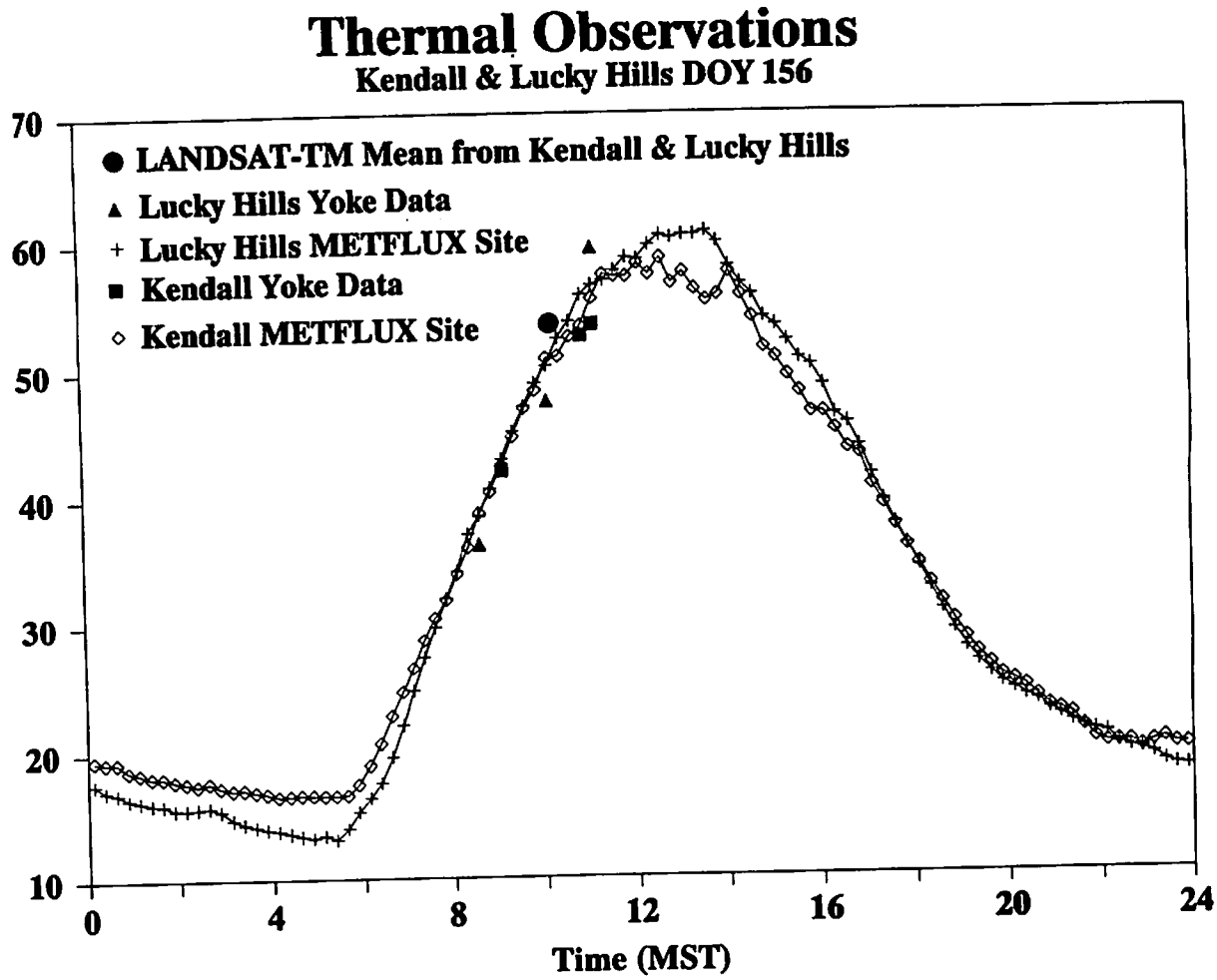


FIG. 6. Comparison of sensible heat flux (H) between the eddy correlation technique and variance method (daytime values).

for June through September of 1988, 1989, and 1990. The 1988 rainfall amounts represent typical monthly totals for the wet and dry seasons, while 1989 typifies a "dry year" for the same period. In 1990, significant rainfall amounts began earlier in the "monsoon season," resulting in a relatively large increase in green biomass at the start of the campaign in late July. In addition, moisture flow came predominately from the northwest instead of the southwest and southeast, producing atypical weather conditions. This included a high frequency of cirrus and stratocumulus cloud cover even in the morning hours, which deviated from the more common scenario of clear mornings followed by convectively generated cumulus clouds in the afternoon. Although the cloud cover created difficulties with the collection of spectral data, the synoptic moisture flow did induce several significant rainfall events in the watershed. One storm occurred in the afternoon on 1 August 1990 (DOY 213), producing over 25 mm of rain over most of the study area. Significant runoff resulted in all the subwatersheds within the study site; one gauging station recorded the stage peaking close to 1 m. Another storm came through over the night of 3 August 1990 (DOY 215), rewetting primarily the Lucky Hills area with about 13 mm of rain. A period of drying out then occurred, allowing for a good dynamic range in observable soil-moisture conditions. Figure 8 illustrates the rainfall patterns for the two major storms.

2) SATELLITE DATA

No useable *SPOT-2* and *LANDSAT-5* data were collected during the July–August field campaign. Yet the persistence of wet conditions through the end of August prolonged the growing season and allowed for the acquisition of SPOT and LANDSAT data in early September. The ground and aircraft data collected in September were similar in scope to the June campaign. The higher overpass frequencies of the GOES and NOAA AVHRR satellites provided more opportunities for useable images. In fact, preliminary analysis suggests that six pair of day–night *NOAA-11* AVHRR scenes have minimal cloud cover over the region of interest. These same days will also be appropriate for



. 7. Thermal infrared observations from Kendall and Lucky Hills for 5 June, DOY 156. The noncontinuous data are from the yoke ›ations averaged over the pixel and from the LANDSAT TM image, while the diurnal data come from the fixed infrared thermometer ıt each METFLUX site.

ing the GOES satellite, which can provide up to 11 le and 5 infrared images per a day.

ı Aircraft data

here was some flexibility in scheduling the aircraft ;ions; hence, optical data collected with instru- ıts that are similar to the satellite-based sensors ɜ acquired under acceptable atmospheric condi- ɜ. For the microwave data, clouds do not affect the ısurements so that observations continued during nging soil-moisture conditions.

.) Preliminary findings

Figure 9 shows typical flux data for the study area ɔre and after the 1 and 3 August storms. The ven ratio changed from approximately 1.5 when soil surface was dry to about 0.5 after the rains. st of the drop in Bowen ratio is probably attributed ;oil evaporation. This will be explored in detail since soil surface in this environment strongly influences the surface energy balance. Daytime estimates of the turbulent fluxes for DOY 216 using the variance method and Eq. (1) versus 1D eddy correlation measurements are shown in Fig. 10. Differences in flux estimates are generally within 50 W m^{-2}, which is quite good for 20-min averages. More comparisons for a wide variety of environmental conditions are under way to assess the reliability and accuracy of energy-balance estimates from the METFLUX sites. In Fig. 11 the ground-based remotely sensed data show a significant change in surface temperatures before and after the rainfall. In particular, the diurnal range in temperature values after the storms was reduced. An indication of the spatial variation in surface temperature is given by the Cessna IRT observations for DOY 216 (Fig. 12). The data have not been georeferenced or adjusted for emissivity. The most striking feature of this plot is the relatively large variation in surface temperature even for adjacent pixels. Fourth-order polynomial curves fit to the data from flight lines 1 and 2 (see Fig. 4a)

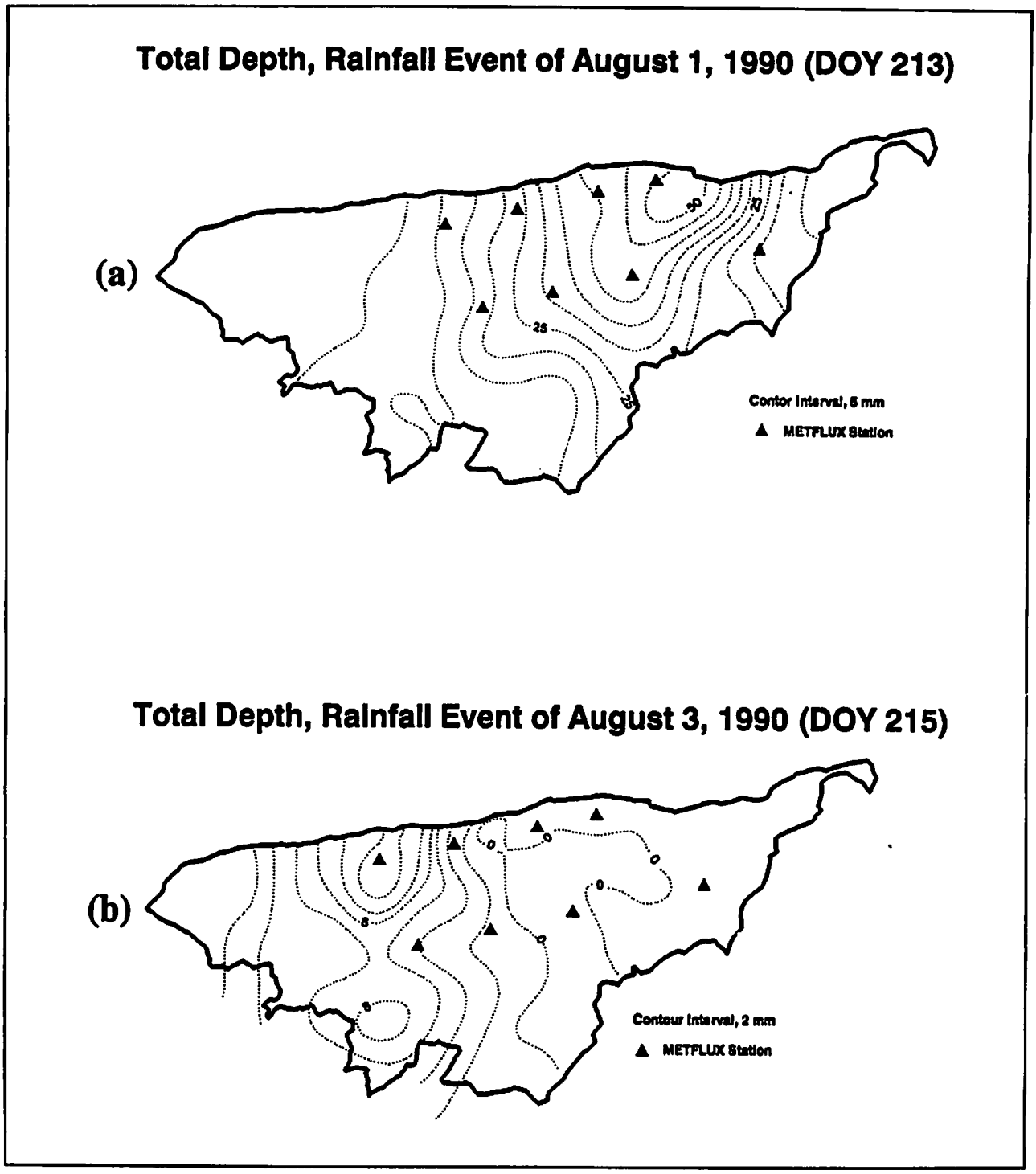
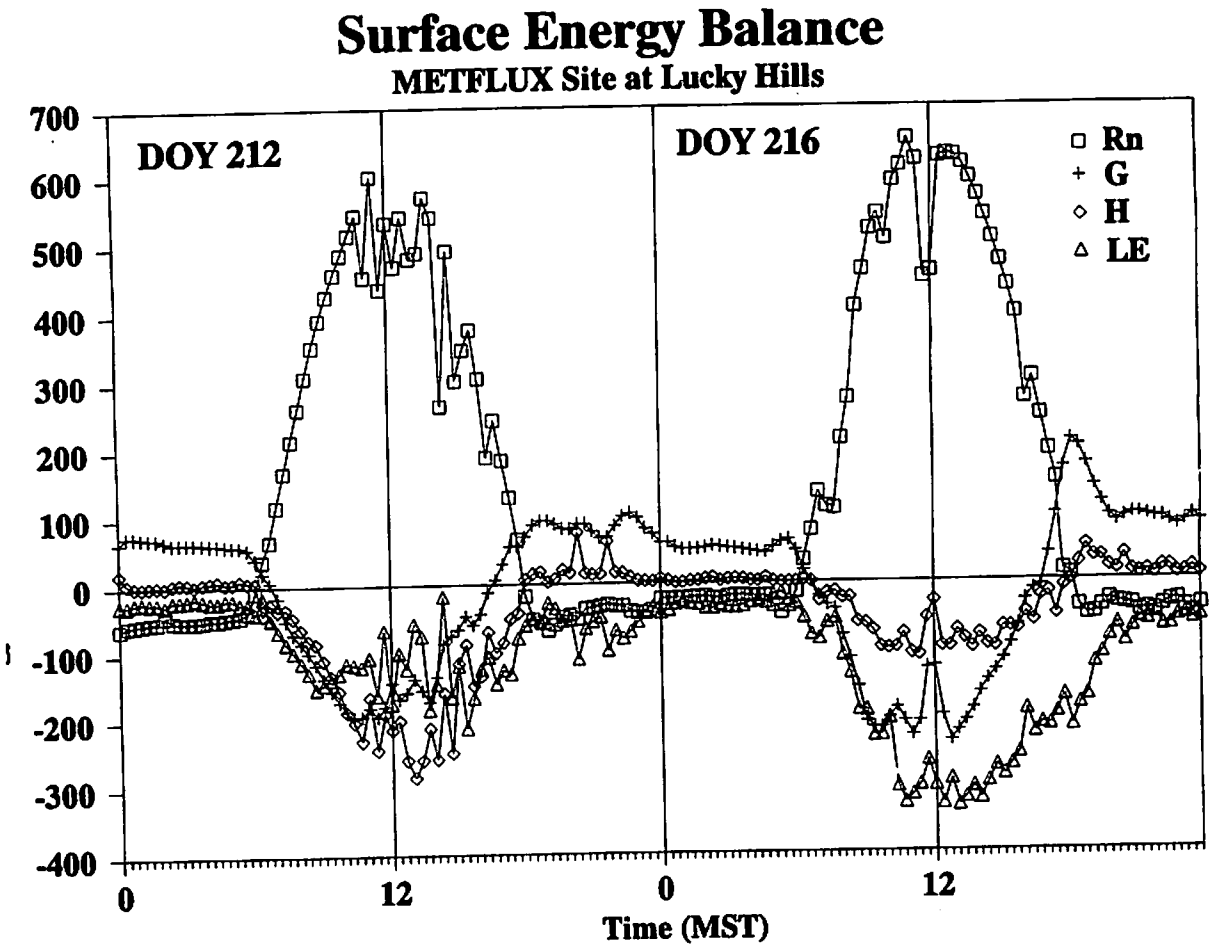


FIG. 8. Cumulative rainfall amounts from the storm on 1 August, DOY 213 (a) and on 3 August, DOY 215 (b). Isohyets were drawn using rainfall totals from the network. The locations of the METFLUX sites are illustrated.

indicate synoptic trends. The curves suggest a spatial dependence of surface temperature, the length scale of which may be related to the rainfall distributions from the 1 and 3 August storms. Other factors include the variation in vegetation cover and in the radiation balance caused by clouds. Ground-based surface-temperature, soil-moisture, and energy-flux data from the METFLUX sites and the brightness temperature data from the PBMR and IRE multifrequency microwave radiometer will assist in the interpretation of these large-scale trends.

Figure 13 compares the volumetric soil moisture at



IG. 9. Energy-balance components from the METFLUX site at Lucky Hills on 31 July (DOY 212) and 4 August (DOY 216) following the ıs on DOY 213 and 215. Surface soil moisture is less than 5% on 31 July and greater than 10% on 4 August.

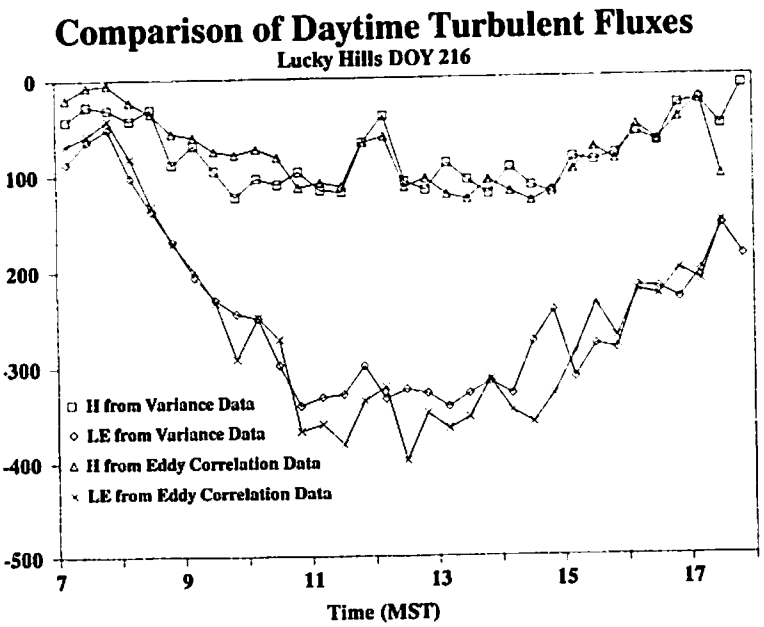


FIG. 10. A comparison of daytime values of the latent (LE) and sensible (H) heat fluxes imated from the METFLUX station at Lucky Hills and a collocated 1D eddy correlation ·tem.

Lucky Hills and Kendall, estimated from the 5-cm gravimetric samples. The larger increases in soil moisture at Kendall after the 1 August (DOY 213) storm may be due to several factors. The most obvious is the difference in rainfall received at the two sites on 1 August (see Fig. 8), while vegetation and soil textural differences will also contribute to this dissimilarity. The increase in soil moisture for Lucky Hills on DOY 216 is the result of the 3 August (DOY 215) storm, which primarily rewetted this area.

Figure 14 shows the vertical distribution of soil moisture on the north- and south-facing slopes of Kendall, collected using TDR. Distinctly different profiles are measured on the two slope aspects. This is likely due to some variations in soil properties with depth. Observations on DOY 213 are

ıdicative of soil-moisture condi-
ons following a relatively dry
eriod. Measurements on DOY
14 show increases in surface
oil moisture following the 1 Au-
ust rainfall event. As a result of
storm local to the Kendall area
n August 2, soil moisture val-
es on DOY 215 increase down
ı a depth of approximately 0.30
ı for both north- and south-fac-
ıg slopes. Below approximately
.30 m, only slight changes in
ɔil moisture are observed. The
rofile data for DOY 216–218
emonstrate a dry-down during
ıin-free conditions.

Changes in the brightness
ımperatures with bands 2 (21
n or L-band) and 3 (2.25 cm or
-band) of the IRE multifre-
ıency microwave radiometer
ıd the PBMR (21 cm or L-
ınd) were documented. Figure
5 shows a one-dimensional plot
X- and L-band brightness tem-
ɜrature data collected along
ght line 1 for four consecutive
ıys covering the two main rain-
ll events. For the X-band in-
rument, variation in brightness
mperature with distance is
ainly the result of the flight
ıck traversing several ephem-
al streams. The streams are
ɔically wetter than the sur-
unding terrain, hence the re-
ılting drop in brightness tem-
ırature. The lack of any tempo-
l variation in brightness tem-
ırature suggests that the X-
ınd sensor has little sensitivity
changes in soil moisture re-
lting from rainfall, but may be
eful for separating areas that
main relatively high in soil
ɔisture. The L-band data
ows a much greater sensitiv-
to the changes in soil mois-
e as a result of the rainfall
ents. Notice the decrease in
ghtness temperature measured by the radiometer
er the Lucky Hills area after the 3 August (DOY 215)
ırm, which was where most of the precipitation fell
ɜe Fig. 8). Even more dramatic are the brightness

Thermal-Infrared Observations

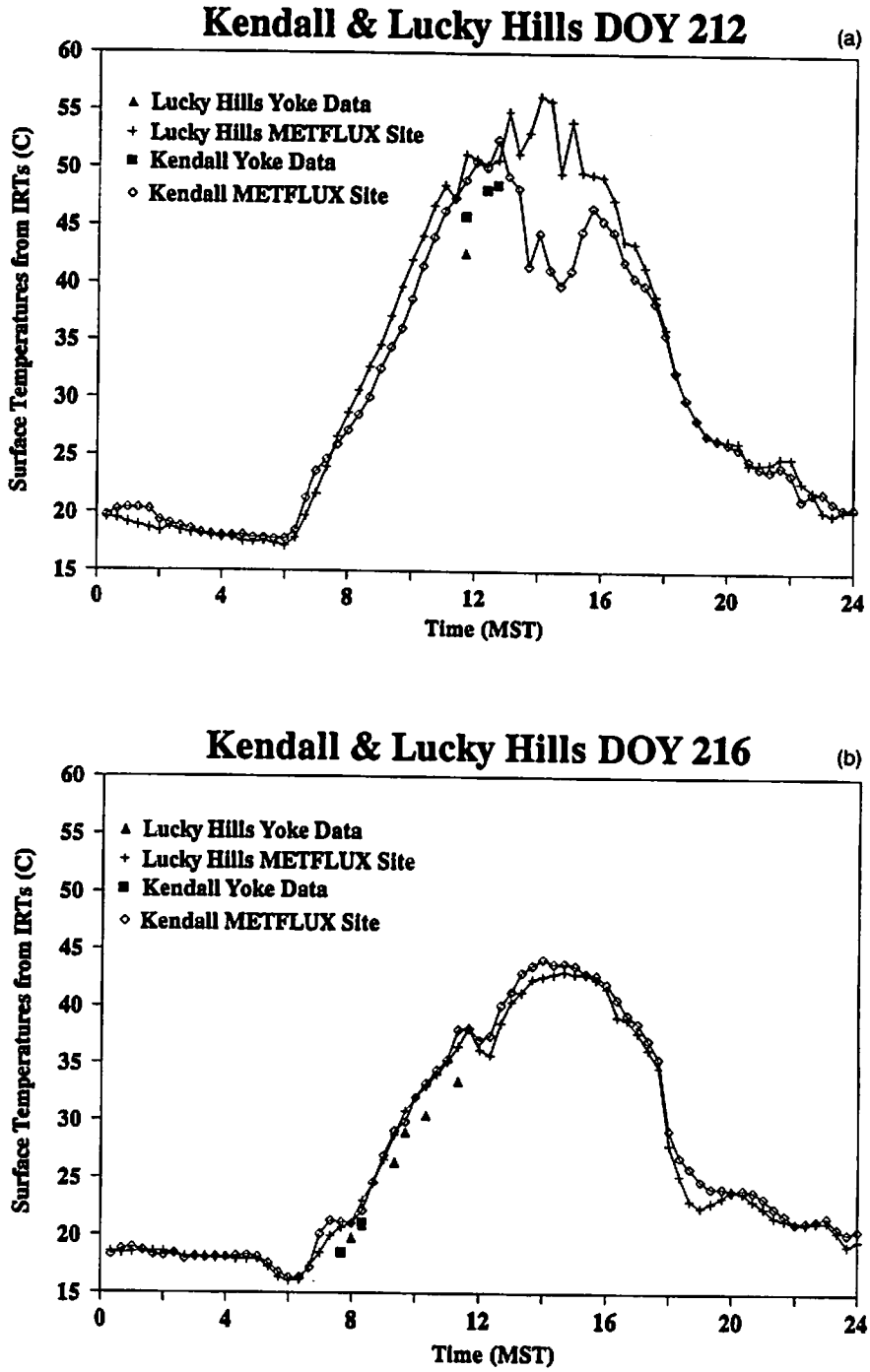
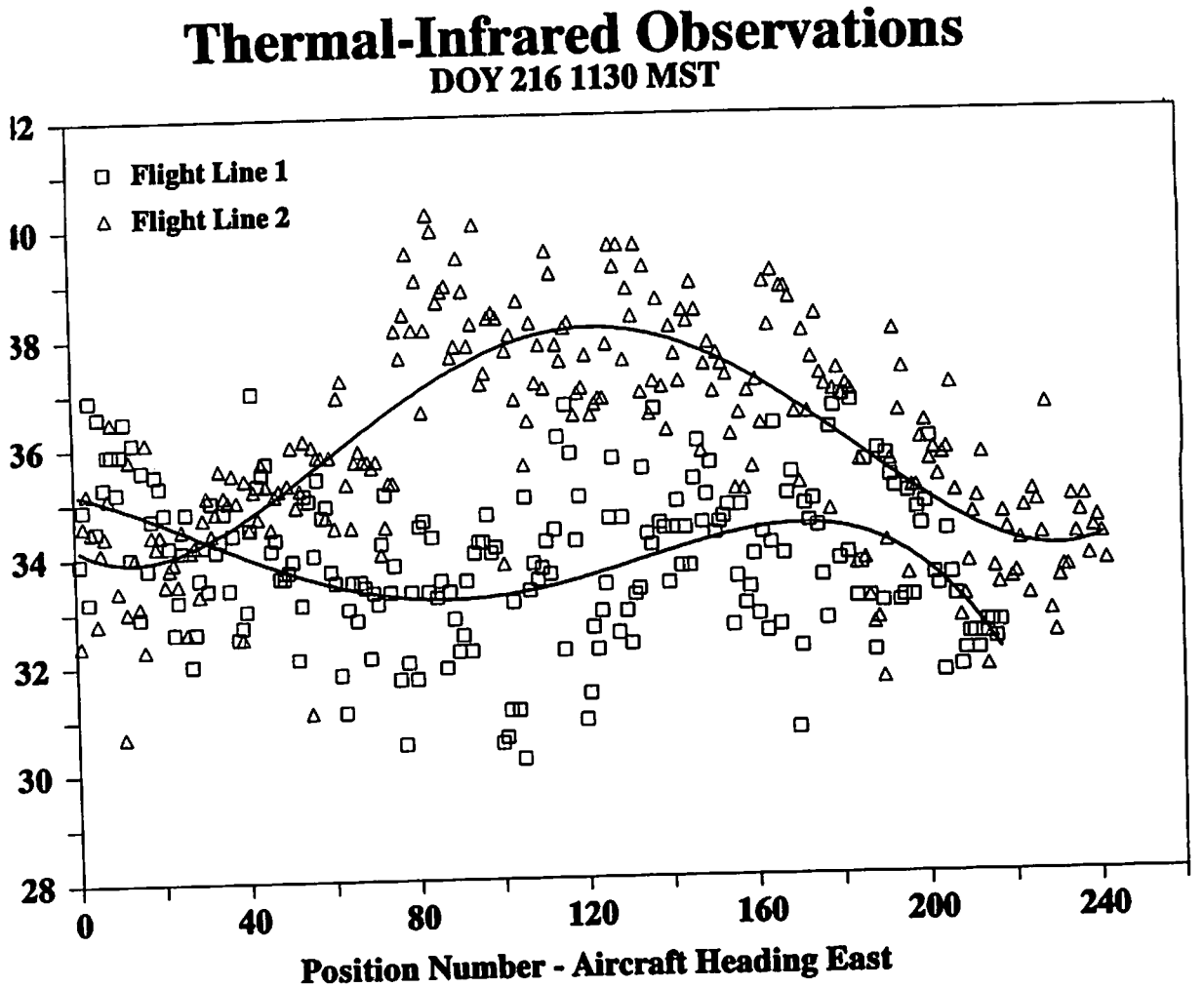


FIG. 11. Thermal observations from Kendall and Lucky Hills for 31 July, DOY 212 (a) and for 4 August, DOY 216 (b). The noncontinuous data are from the yoke observations averaged over the pixel, while the diurnal data come from the fixed IRTs at the METFLUX sites.

temperature maps from the PBMR in Fig. 16 that reveal qualitatively the spatial and temporal variation in surface soil moisture caused by the 1 and 3 August storms and the return to almost uniform soil moisture



IG. 12. Surface-temperature observations from the IRT sensor aboard the Cessna aircraft. Observations along flight lines 1 and 2 (see 1a) were taken on 4 August (DOY 216) around 1130 MST. The position numbers with the aircraft video will be used to georeference lata. The curves are fourth-order polynomials fit to the observations.

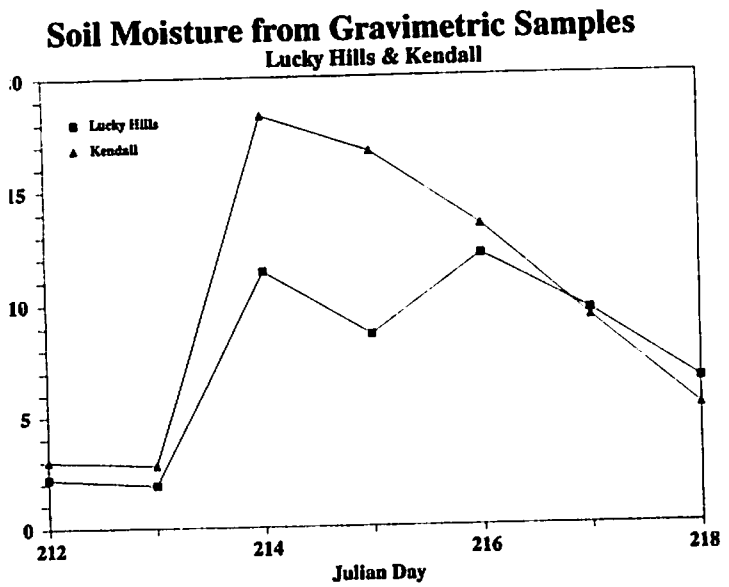


FIG. 13. Volumetric soil moisture of the upper 5 cm, estimated with the daily ıvimetric samples collected at Lucky Hills and Kendall.

conditions. Notice in this figure that the rewetting of Lucky Hills is also observed (image for DOY 216) and that the persistence of lower brightness temperatures in the northeast corner of the scenes is probably the result of significantly higher rainfall amounts received in that area from the 1 August (DOY 213) storm and additional amounts from several minor rainfall events on 2 August (DOY 214). With some further analysis, these data should provide detailed maps of antecedent soil-moisture distributions for use in rainfall-runoff modeling.

Remote-sensing information in Fig. 16 will also be used in linking important geophysical parameters like surface soil moisture to ABL processes. Figure 17 is an example of a time series in atmospheric data processed to reveal the rate of ABL development and growth over the course

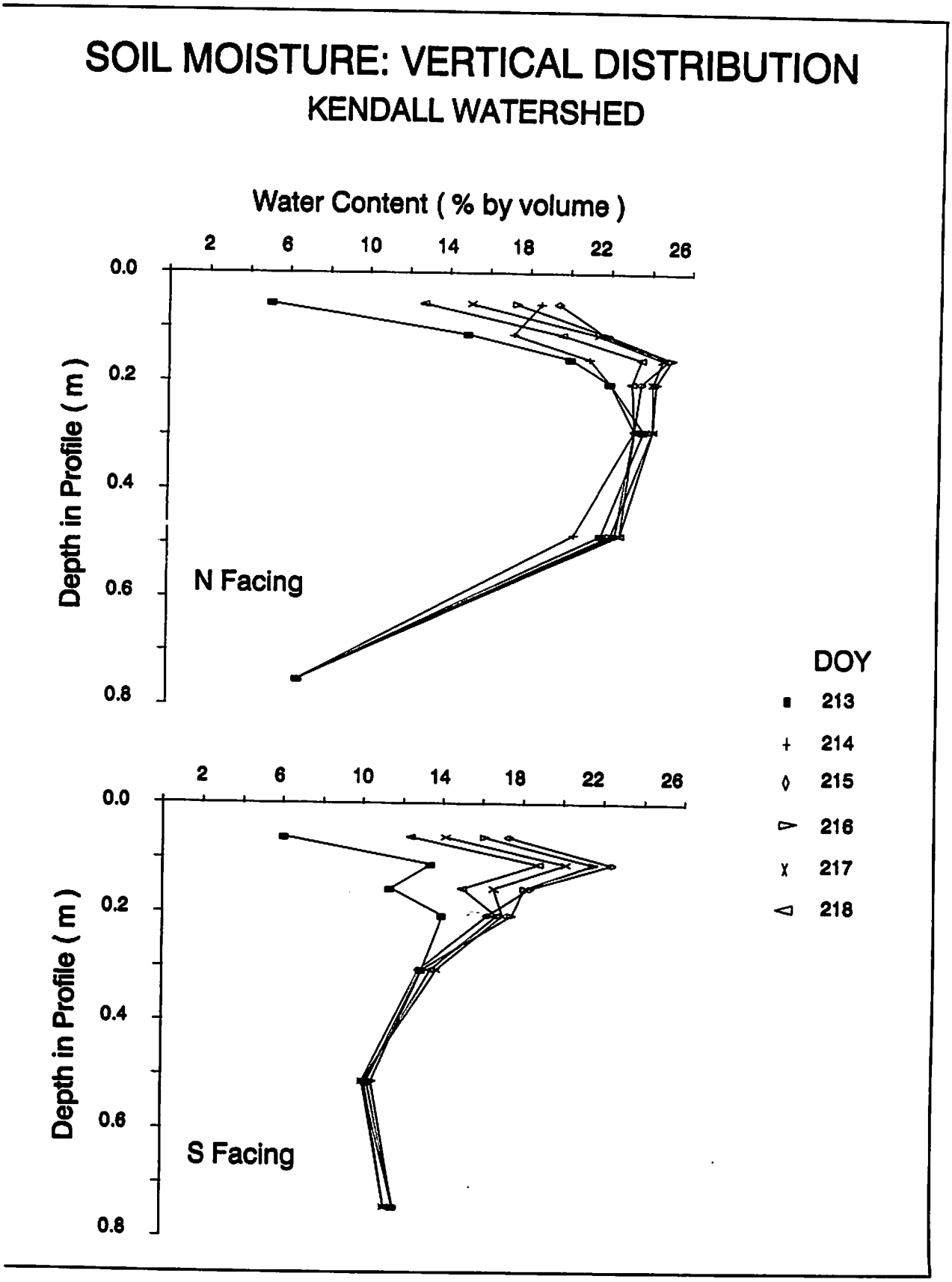
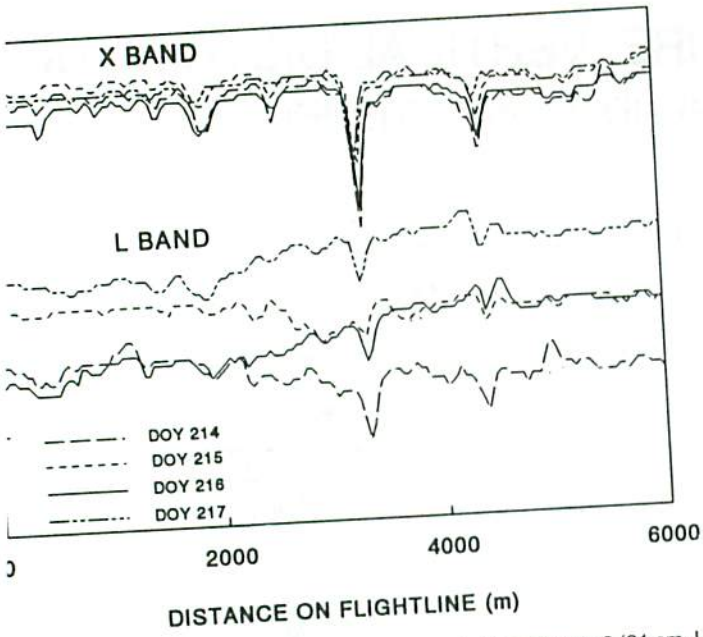


FIG. 14. Vertical distributions of soil moisture on the north- and south-facing slopes of the Kendall watershed for DOYs 213–218. a: No data collected on the south-facing slope for DOY 214.



. Brightness temperatures along line 1 (see Fig. 4a) from bands 2 (21 cm, L-
3 (2.25 cm, X-band) of the 3-band microwave radiometer on the Weslaco Aero
ler. Measurements follow the 1 August (DOY 213) and 3 August (Doy 215)
ents. Note that the lower the brightness temperature, the higher the soil
see Jackson and Schmugge 1989).

y. This data, along with profiles of water vapor
t, will be used to evaluate regional fluxes of latent and sensible heat using a variety of ABL formulations (Brutsaert and Kustas 1987; Kustas and Brutsaert 1987; McNaughton and Spriggs 1986; Munley and Hipps 1991).

7. Summary

The initial phase of this study, the field campaigns, was successful. Remote-sensing and ground truth data over a range of spatial and temporal scales were collected. Although cloud cover reduced the planned collection of remote-sensing data in the optical wavelengths, enough cloud-free opportunities existed for adequate ground, aircraft, and satellite coverage to test project objectives. Moreover, several precipitation events during the July–August field campaign produced significant runoff, and spatial and temporal variation in soil moisture. This will provide a wide variety of surface and atmospheric conditions for assessing energy and water balance algorithms. The processing of ground, air-

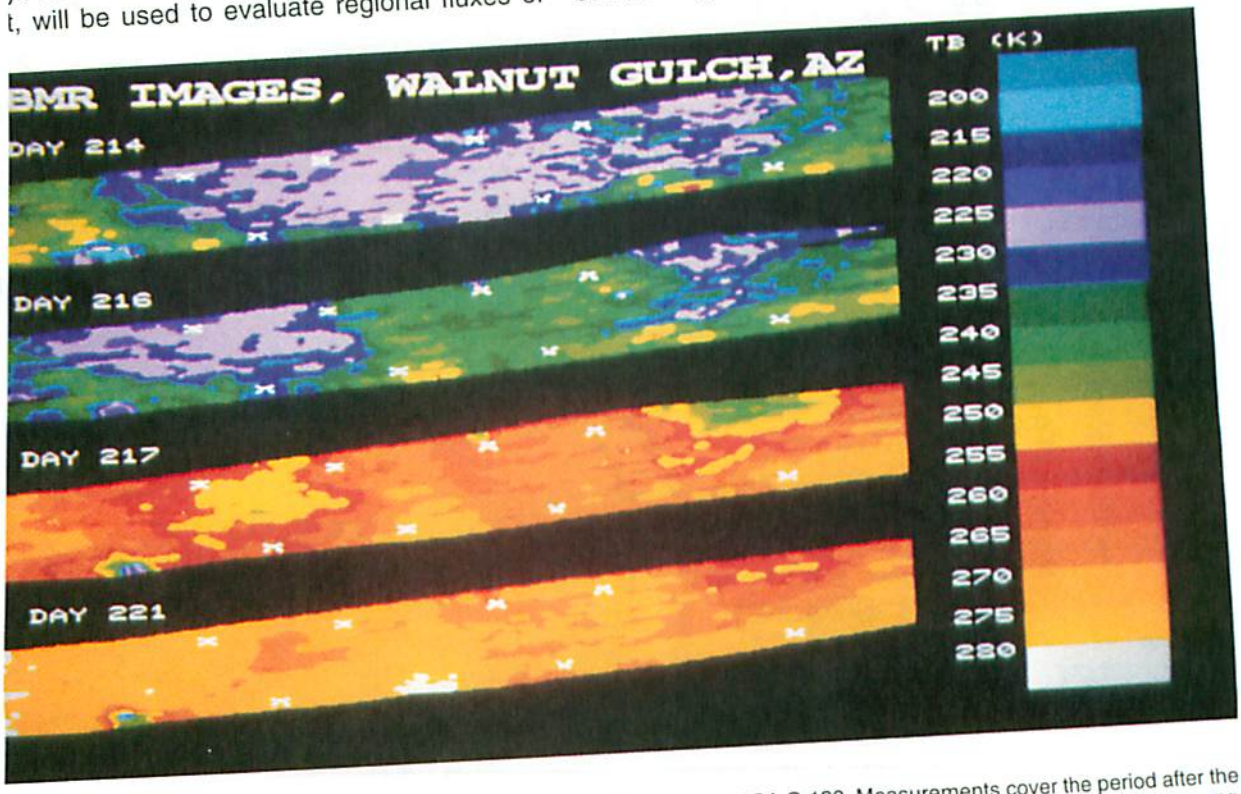


FIG. 16. Brightness temperature map from the PBMR (21 cm, L-band) on the NASA C-130. Measurements cover the period after the
ugust (DOY 213) storm and subsequent dry-down after the 3 August (DOY 215) storm. The locations of the eight METFLUX sites (X)
provided.

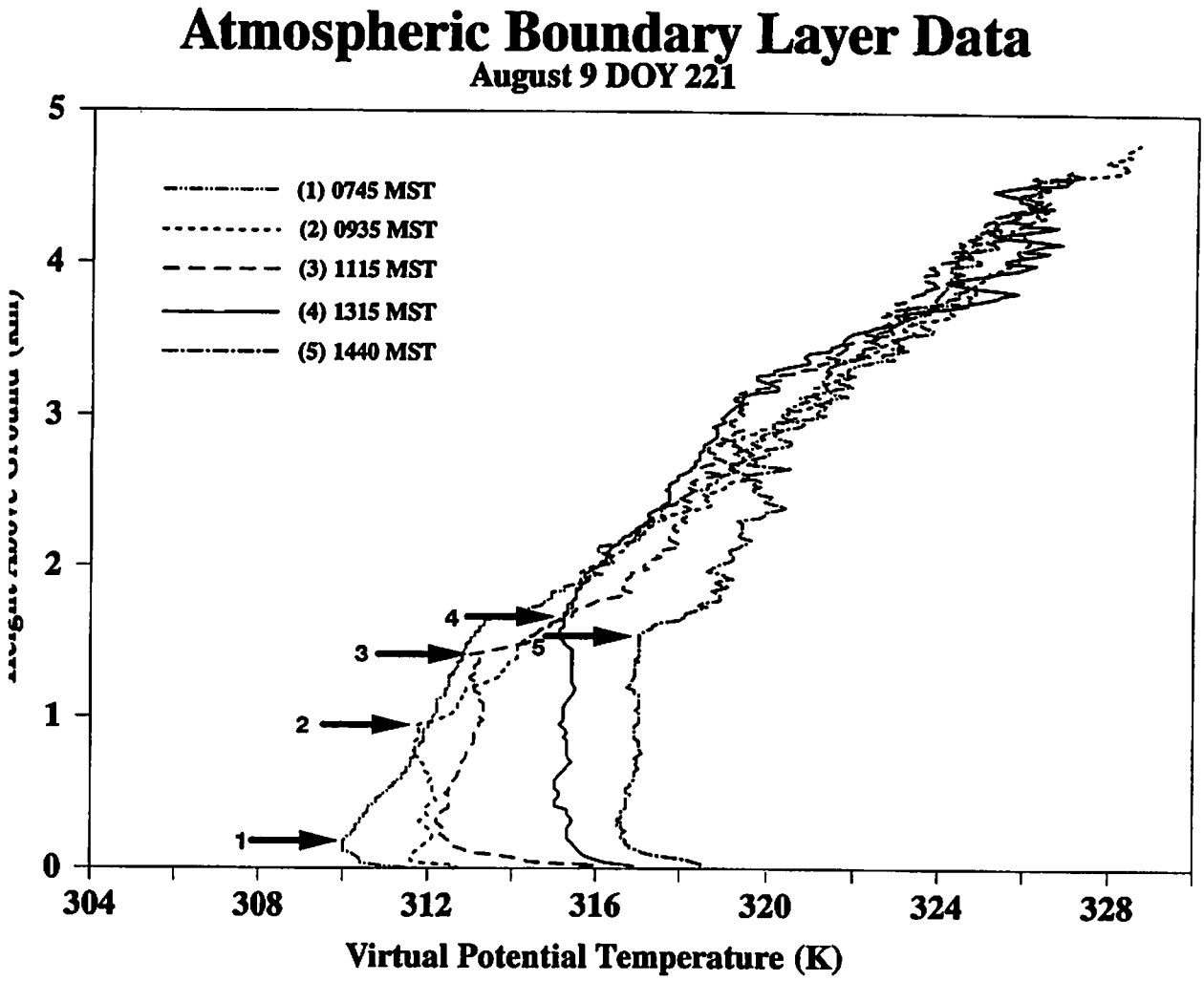


FIG. 17. Atmospheric-boundary-layer development for 9 August (DOY 221) represented by the change in the magnitude and shape of virtual potential-temperature profile with time. The arrows give the approximate height of the capping inversion or the depth over which st of the turbulent mixing occurs (see e.g., Stull 1988).

aft, and satellite data is continuing. A significant mber of preliminary results papers were presented the AMS-sponsored Special Session on Hydrom- orology meeting in September of 1991 in Salt Lake y, Utah (e.g. Kustas et al 1991).

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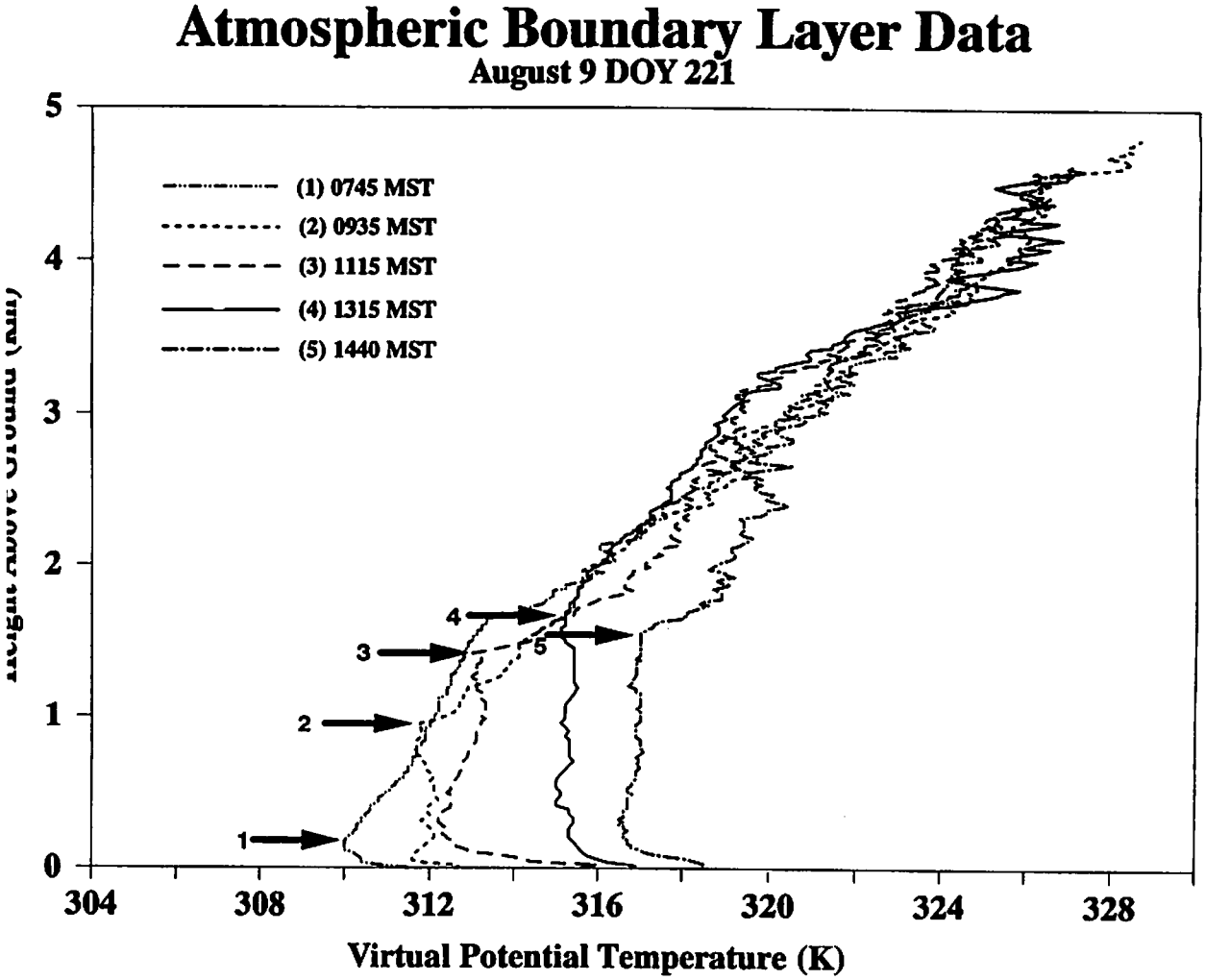

FIG. 17. Atmospheric-boundary-layer development for 9 August (DOY 221) represented by the change in the magnitude and shape of › virtual potential-temperature profile with time. The arrows give the approximate height of the capping inversion or the depth over which ›st of the turbulent mixing occurs (see e.g., Stull 1988).

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