VEBEX: Vegetation and surface energy balance experiment for the tropics

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Surface features such as soil moisture and vegetation have a profound impact on the surface energy balance and the atmospheric boundary layer. To quantify this effect for a tropical location, a detailed field experiment, VEBEX, was designed and successfully executed in a tropical site at Bangalore, India. VEBEX was a joint experiment between the North Carolina State University, Indian Institute of Science (IISC), and the University of Agricultural Science (UAS) at Bangalore, India. Continuous surface meteorological measurements were taken over an entire crop period (pre-sowing to post-harvest). During different stages of the plant growth, intensive observations of surface turbulence, and measurements of physiological and soil moisture measurements were also conducted. The results obtained provide an insight into the unusually strong variability for the tropics. Interpretation of the observations and an overview of the analysis procedure and future research initiatives are also presented.

1. Introduction

One of the pivotal components of present research efforts is to improve numerical model performance by accurately understanding and representing the effects of soil moisture and vegetation changes in the boundary layer. Consequently, various vegetation and soil moisture schemes are being used for soil vegetation atmosphere transfer (SVAT) studies. Some examples of such SVAT schemes for general circulation models (GCMs) are, Jarvis (1976); BATS (Dickinson et al 1986); SiB (Sellers et al 1986); SSiB (Xue et al 1991); Viterbo and Beljaars (1995); PLACE (Wetzel et al 1995); SiB2 (Sellers et al 1996). Examples for the planetary boundary layer (PBL) or mesoscale analysis include, Deardorff (1978); Noilhan and Planton (1989); Acs (1994); and Alapaty et al (1997a). Some of the recent studies are at the microscale, to evaluate the plant-to-plant response and leaf-scale interactions, using observational (Niyogi and Raman 1997; Katul et al 1997) as well as modeling approaches (cf. Baldocchi 1994; Nikolov et al 1995; Su et al 1996; Niyogi et al 1997a). The SVAT schemes, though developed from sound physics and understanding of the biosphere-atmosphere mechanisms, need to be simplified (and often tuned) through empirical equations, ‘constants’, and regionally representative features. For example, in Noilhan and Planton (1989), much of the physiological simplification and ‘tuning’ is done based on the empirical relations developed from HAPERX-MOBILHY observations (André et al 1986). Such a scheme could thus be a better representative of a mid-latitudinal geography and pasture-like landscape with relatively abundant moisture availability (consistent with HAPERX). Such empirical simplifications however, may not have an ubiquitous applicability, for they represent a somewhat limited (as against global) hydrological and landscape regimes. Thus, any biospheric scheme developed needs to be evaluated tested with global datasets. Unfortunately, such a global dataset is not available with the same information and high resolution, so as

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to allow a robust testing of the surface parameterizations and biospheric representations. To ascertain the confidence within such schemes or models, various micrometeorological point measurement validations need to be carried out regionally (cf. Sellers and Dorman 1987 for SiB). Though such validations may have limitations, such as homogeneity: a feature never accounted in reality, one cannot deny their significance towards an advanced understanding of surface layer turbulence or SVAT mechanism. Hence, this has lead to application of micrometeorological analysis to various similar atmospheric turbulence and SVAT related experiments related to atmospheric turbulence and SVAT studies such as FIFE (Sellers and Hall 1992), and HAPEX-MOBILHY (André et al 1986), and the recent land surface experiment in Anand, India (K G Vernekar, personal communication 1997).

VEBEX was designed to understand the significant energy balance features in the tropics through micrometeorological field measurements. This field program, as in the earlier other experiments, was designed to achieve several objectives. Some of the expectations from VEBEX included:

- validation of existing land surface and vegetation/SVAT schemes,
- development of ‘constants’ or ‘tuning’ of the simplified models, statistical or empirical equations based on local (tropical) landscape and geography,
- development of a coupled physiological-hydrological-micrometeorological modeling framework,
- evaluate, and interpret the tropical hydrological cycles for diurnal, seasonal and inter-annual changes, with parallel measurements of soil moisture, temperature, plant-scale transpiration and soil evaporation,
- experimentally quantify the changes in the surface turbulence as a function of the surface features such as soil moisture and vegetation resistance and roughness (using spectral and energy balance approach) and
- increase the strength of the existing global dataset through information on climatic parameters on physiological processes such as stomatal behavior, evapotranspiration and photosynthetic and nutrient control.

The attainment of the above mentioned objectives for the tropics, is a useful step in PBL/SVAT modeling for the tropics. The tropics cover nearly 50% of the earth’s surface and ecological features. The dynamics of the tropical atmospheric flows in tropics, is known to be different than in the midlatitude flows. Even the sustainability, and plant-to-plant response may be much more non-linear than one perceives for the midlatitudes (cf. Meinzer et al 1995; Hacker and Bertsness 1995). Thus similarly, in terms of the biosphere-atmosphere interaction, our present knowledge is rudimentary and patchy. The harshly contrasting regimes, induced by the dry and wet spells through the monsoon, are the key features of the tropical domain. Under these regimes, various significant surface changes (such as soil moisture change from wilting to saturation, and rapid plant and vegetation growth from earlier barren landscape) take place. Understanding of these regimes and their interactive effects cannot be developed from observations made in midlatitudes. Hence GCM and PBL studies in the tropics have always been assigned a high degree of uncertainty in terms of their predictions. Consequently, the genesis of VEBEX lies in the need to develop an understanding of some of the biosphere-atmosphere processes in tropics using in situ micrometeorological observations and field measurements.

2. Experimental setup

The observation setup for VEBEX included micrometeorological instrumentation, data acquisition, and physiological and soil surface related measurements. In collaboration with the University of Agricultural Science (UAS) at Bangalore (12.59⁰N, 77.40⁰E), an experimental agricultural field of about 5.0 x 10⁵ m² was assigned for this study. Within this field, two adjacent plots were selected for the tower observations. One plot was maintained bare while the other had vegetation during the course of the study. The crop grown was Dolichos Biflorus (horse gram). Each of these plots had a 6m tower. (Details of atmospheric instrumentation installed on the towers is given in table 1). Some of the motivating factors for keeping the two experimental plots contrasting (bare against vegetated) were: (a) the difference in the surface layer features could be due to different surface forcing alone (such as changes in vegetation cover, LAI, stomatal resistance and soil moisture change), (b) the need for developing an independent dataset for bare soil surface turbulence, and hydrology, (yet another feature not too well understood for the tropics), (c) to assist data quality control by using spectral and turbulence checks developed for bare surfaces (cf. Kaimal and Finnigan 1994) (d) to utilize advanced data analysis procedures using statistical techniques such as Factor Separation (Stein and Alpert 1993), or Fractional Factorial approach (Henderson-Sellers 1993; Niyogi 1996; Niyogi et al 1995, 1996. 1997b,c,d) or Response Surface techniques (Niyogi et al 1997c,d) applied successfully for land surface schemes. These techniques require a ‘base state’ data for analyzing the indirect and interactive effects and developing or testing statistical hypotheses (see Niyogi 1996 for details). Other aspects one could achieve with the combination of vegetated and bare plot are (a) estimating effective fluxes or area averaging of the fluxes (b) evaluate turbulence kinetic
Table 1. Tower component applied in VEBEX observations.

<table>
<thead>
<tr>
<th>Sr</th>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Tower</td>
<td>6 m. uniform triangular guyed to withstand 180 km/hr wind with three levels of retractive booms for instruments.</td>
</tr>
<tr>
<td>2.</td>
<td>Wind speed anemometers</td>
<td>Operating range: 0–10 m/s; Accuracy: 1.5–2% of full scale; Threshold: 0.1 m/s; Distance constant 0.3 m; Rotor: 160 mm dia; Cup: 50 mm dia; Output: Digital pulse train.</td>
</tr>
<tr>
<td>2b.</td>
<td>Wind Translators</td>
<td>Conversion accuracy: 0.4%; Output impedance: less than 100; Operating temperature: −10 to 60°C; Voltage −5 to 5 V; Operating voltage: +/− 12 V; Operating current &lt; 0.4 mA.</td>
</tr>
<tr>
<td>3.</td>
<td>Wind direction vane</td>
<td>Operating range: 0–360°; Accuracy: +/− 3°; Threshold: 0.3 m/s; Dist. Const: 1 m; O/P: Analog 10 mV/deg; Arm length: 0.45 m.</td>
</tr>
<tr>
<td>3b.</td>
<td>Wind direction translator</td>
<td>Output impedance: &lt; 100; Operating temperature: −10 to 60 deg; Output 0–5 V for 360; On site calibration option.</td>
</tr>
<tr>
<td>4.</td>
<td>Air temperature sensor</td>
<td>Platinum RTD type; Operating range: −50 to 50°C; Accuracy +/− 0.05°C.</td>
</tr>
<tr>
<td>4b.</td>
<td>Air temperature translator</td>
<td>Time constant: &lt; 1 s; Conversion accuracy: 0.4%; Operating Temperature: −10–60°C; Output voltage: +/− 5 V; Operating Voltage: +/− 12 V; Operating Current: &lt; 4 mA.</td>
</tr>
<tr>
<td>4c.</td>
<td>Radiation shield</td>
<td>Mechanically aspirated radiation shield of aluminium on smooth revolving sealed bearings.</td>
</tr>
<tr>
<td>5.</td>
<td>Air humidity sensor</td>
<td>Thin-film capacitance, Range: 0–100%; Accuracy: +/− 1%; Response time: &lt; 10 sec for 5 to 95% change in RH; output 10 mV/% RH.</td>
</tr>
<tr>
<td>5b.</td>
<td>Air humidity translators</td>
<td>Conversion accuracy: 0.4% Output impedance: &lt; 100; Operating temperature: −10 to 60°C; Output: +/− 5 V; Other features same as air temperature translator including on-field calibration option.</td>
</tr>
<tr>
<td>6.</td>
<td>Soil temperature</td>
<td>RTD Pt-100 type, Operating range: −10 to 60°C; Accuracy: +/− 0.1°C; response time &lt; 0.05 sec.</td>
</tr>
<tr>
<td>7.</td>
<td>Fast temperature sensor</td>
<td>Platinum type; Accuracy: 0.1°C, response time &lt; 0.05 sec., Time constant: 0.01 s; Resistance range: 100–200.</td>
</tr>
<tr>
<td>8.</td>
<td>Gill propeller anemometer (u, v, w)</td>
<td>Range +/− 10 m/s for u, v and +/− 5 m/s for w; 10 Hz sampling frequency, IR emitter detector pair with chopper for each component using RM Young Propellers.</td>
</tr>
<tr>
<td>9.</td>
<td>Constant temperature hot wire</td>
<td>Pt wire, nonlinear signal output for a preset range. Built-in overheat ratio, Range +/− 10 m/s for u, v, w; 10 Hz sampling frequency.</td>
</tr>
<tr>
<td>10.</td>
<td>Data handling</td>
<td>Campbell Scientific Inc. data logger 21X. Data stored on tape recorder. Different programs used for the acquisition: (a) 10 Hz at specified time, (b) 1 Hz round the clock. PCM telemetry package IBM compatibility 32 channel collection and data visualization system.</td>
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energy dissipation with step change in surface features. Such features, closely representing the problems of sub-grid scale heterogeneity and turbulence energy balance, could be studied through the detailed turbulence and physiological/hydrological observations as described in the following section.

3. Observations

After the tower was erected in 1994, the site scientists have been recording micrometeorological profile data and utilizing the tower for developing and testing better data acquisition and data collection procedures. From July 1995, the researchers involved were ready both in terms of requisite infrastructure and technical support, and the field campaign was resumed. Accordingly from August 14, 1995, five Intensive Observation Periods (IOPs) were conducted. The last IOP ended in January 1996. Table 2, lists the IOPs and various measurements made during this period. For this maiden attempt, emphasis was on collecting every possible information that would be required at least for satisfactorily validating existing vegetation and soil moisture parameterizations.

Some principal features of the measurements done during VEBEX include:

- Profiles of wind speed, temperature, humidity at three levels. These data (1 Hz frequency, averaged
over 3 minutes) was nearly continuous for the entire experiment (July 1995 to January 1996). Additional instantaneous psychrometer data were collected for keeping a check on the humidity measurements.

- 10 Hz sampling of wind components, temperature, and humidity during the IOPs. This sampling time for the turbulence measurements was for 30 minutes and the measurements were generally made at 0600, 0900, 1200, 1500, 1800, 2100, and 2400 h LT. During some special observations (such as the partial solar eclipse of October 24th 1995, or the crop harvesting, near continuous fast data acquisition was done). The wind components were measured by using a Gill propeller type anemometer, and in the later stage supplemented with constant temperature hot-wire measurements.

- Soil temperature was recorded continuously in the vegetated plot every three minutes at three depths (0.08, 0.16, and 0.32 m below the surface). In the bare plot, manual observations were also recorded taken from pre-existing thermometers embedded in the soil at the three depths. Additionally, during the IOPs, leaf temperature and surface skin temperature was measured using a hand-held infra-red (IR) thermometer. Net radiation (both incoming and outgoing) was also continuously measured at the two towers using net radiometers.

- Soil moisture was estimated at three depths in both the plots. This was done for at least two locations in each plot using gravimetric method during the IOPs. The gravimetric samples, had to be limited to the depth of about 0.5 m below the surface. This was done during the IOPs. Additionally, continuous soil moisture measurements (hourly) were made using gypsum blocks. The gypsum blocks were embedded at three depths (0.1, 0.3 and 0.6 m) in the vegetated plot, and at 0.6 m depth in the bare plot.

- Physiological parameters measured during VEDEX include leaf area index (LAI), fractional vegetation cover, leaf-shoot-root dimensions and weight, canopy nutrient status based on leaf nitrogen and phosphorus content, stomatal resistance, evapotranspiration and assimilation rates based on porometric as well as nutrient empirical estimates (Schulze et al 1994; Niyogi et al 1997a), micrometric stomatal aperture estimates (S S Joshi, personal communication, 1995), and foliage and crop surface temperatures. These measurements were instantaneous and replicated with at least three sets of measurements (see Niyogi et al 1997a).

Additional data collected on a routine basis included: Pan evaporation from the bare ground from a pre-existing facility, precipitation and estimation of height above ground level for dew formation measurements, and estimates of cloud cover. Soil characterization was
also performed with information on particle size distribution, water retention characteristics, infiltration rates, Keen-Raczkowski measurements for soil expansion, pore spaces, water holding capacities, and chemical properties with conductivity. Thus, a comprehensive observational database was generated during VEBEX.

4. Typical results and ongoing analysis

Collecting the data and recording measurements, is just one part of the experiment. This data collection, needs a follow-up in terms of data analysis, quality control and validation, and archival. Thus presently, the VEBEX researchers are still in the process of collecting some missing background information such as the regional landscape, precipitation pattern which will be useful in the overall understanding of the complex tropical SVAT mechanism. However, analysis of the data for information on fluxes, spectral or turbulence characteristics has resumed. In particular, the data collected over the seven months, and during the five IOPs will have to be processed such that we have reliable data on surface fluxes and physiological features.

Figures 1–7 present some of the typical features obtained during VEBEX. Figure 1 shows the variation of fractional vegetal cover (VEG) and the leaf area index (LAI) over the experimental plot for 117 crop days. LAI was estimated from five replicates using destructive sampling procedure in the Plant Physiology Lab at the UAS. The fractional vegetal cover was estimated using in situ measurements by scaling the length and number of plants grown (and their coverage area) in a 1 m² zone. The experimental period was divided into five IOPs based on the crop growth stage as shown in intensive observational periods indicated in figure 1 (solid horizontal bars). Before sowing, the LAI and VEG values were assigned to be zero (bare surface). After sowing (indicated by S along the X-axis), the change of LAI was rather sluggish for the open canopy but the fractional vegetal cover changed rapidly. The maximum LAI obtained (figure 1) for the study period is relatively small as expected for the open canopy. An interesting subsurface hydrological and temperature variability as a function of the crop stage could be seen from the measurements. Figure 2 shows the typical soil moisture variation observed in the vegetated field during IOP IV (maximum green phase) for a period of 8 IOP days. Some features stand out distinctly. First is the strong diurnal variability. The observations were made at three depths of 10 cm, 30 cm and 60 cm. Diurnal variations could even be seen up to a depth of 0.6 m for this tropical site. Such strong diurnal forcing on the soil moisture were not observed for the midlatitude sites of FIFE and HAPEX. A second feature is the apparent vertical diffusion between the different soil layers (cf. Ek and Cuenca 1994). That is, the 0.6 m soil moisture shows a negative trend over the IOP and the upper soils (at 0.3 m and 0.1 m) correspondingly exhibit an increased amplitude in the diurnal variability and a slightly positive trend. The root-zone for the experimental crop was estimated to be around 0.3 to 0.4 m from destructive measurements during this IOP. Such strong diurnal forcings on the soil moisture were not observed for the midlatitude sites of FIFE and HAPEX. Thus the evapotranspirative demand could provide an upward flux for the deeper soil moisture resulting in the depletion in the below-root layer.
and an increase in the above root-zone. These results suggest a strong radiative as well as physiological control over the local hydrology in the tropics. This has important implications for assigning higher uncertainty to results from simple slab models which do not have detailed soil hydrology and vertical diffusion (see Alapaty et al. 1997b; Niyogi et al. 1997c).

Figure 3 shows a typical surface and subsurface temperature data obtained during VEBEX IOP IV (day 342). The subsurface observations are from soil-embedded sensors. Hourly temperature measurements of bare soil, foliage temperature, and surface (combined foliage and bare ground) at multiple locations were obtained using a hand held IR thermometer. As expected, the deep soil temperature (0.32 m below surface) shows a weak amplitude of diurnal variation and this amplitude increases as one reaches the surface, with a maximum for the top soil surface. An important feature of the observation is the large difference between the bare soil, foliage and the surface (combination of the patchy crop and bare soil). For a convective period around noon, the surface temperature (as estimated in the remote sensor radiances) was found to be typically 5 K higher than the freely transpiring leaf or foliage temperature and about 5 K lower than the bare ground. It is expected that the range of such surface temperature extremes (fully vegetated to entirely bare ground) will have a seasonal component with cloudiness and soil moisture availability as well as a regional component with the
land use and the vegetation characteristics (different photosynthetic pathways, open against closed canopy, and emissivity) and needs to be studied further apropos quantifying the tropical scenario. The strong vertical temperature gradients also indicate high surface energy fluxes in the experimental period. The measurements of surface turbulent energy fluxes were estimated made over the bare and vegetated field using eddy-correlation technique. On-site video-imagery and near-real time PCM telemetry setup developed at the Indian Institute of Science was utilized to obtain time-histories and aid quality control of the data procured. Further detrending, filtering, and statistical checks were also performed using standard algorithms (see Kaimal and Finnigan 1994). Figure 4 shows a typical detrended, convective moisture covariance time history over the vegetated plot. The covariance data were averaged to obtain energy fluxes in the surface layer as described in Stull (1986), and latent heat fluxes were estimated from such measurements. Figures 5 and 6 show the sensible and latent heat fluxes over the bare and vegetated fields respectively. As expected, the latent heat fluxes were larger and sensible heat fluxes smaller over the vegetated plot as compared to the bare plot due to surface evapotranspirative cooling. The values obtained are relatively higher than most mid-latitude sites (cf. André et al 1986) but are consistent with the observations reported for such tropical locations in the literature (cf. Raman et al 1990). Future efforts will address the issue of effective flux representation (treating the vegetation and bare plot as one ‘grid’). It will be interesting to investigate if the Bowen ratio would have a strong diurnal variability for this scenario. Also, it should be cautioned that the response period of the Gill Anemometer could make the estimates presented here slightly biased and would have to be compared with the flux estimates from other independent flux measurements such as through hot wire anemometer employed in the later part of the study. Both the results provide a fair estimate of the nature of diurnal variability one could estimate for the tropics as a function of surface forcing. Additionally, due to the changes in soil moisture, significant variation was obtained in the values of the surface albedo on diurnal (and seasonal) scales. Figure 7 shows the typical albedo changes over the bare and vegetated plots (for day 342) on 8th December 1995. Note that the vegetated field has a nearly constant albedo around 0.21 while the bare field albedo changed from 0.2 to 0.3 over the six hour period considered. The bare ground albedo shows a larger variation which can be principally attributed to the decrease because of the variation in the soil moisture over the bare plot during this period (cf. Idso et al 1975).

Thus, various interesting results were obtained for the bare against vegetated surface. These preliminary results also show a consistency of the comprehensive dataset. Additionally, the phase and amplitude of the changes over the two surfaces provide an insight in the non-linearity of the area averaging for the fluxes as would be required for various remote sensing and weather forecast algorithms under contrasting vegetation regimes.

The information generated from VEBEX, will be utilized for satisfying our pre-mentioned objectives and also explore the possibility of developing better parameterizations. Some of the schemes that are on the agenda for verification include: mesoscale-related schemes such as Deardorff (1978); Noilhan and Planton (1989), as well as photosynthesis-based detailed physiological schemes such as LEAF3 (Nikolov et al 1995), and the GCM-based schemes BATS, SiB, SSiB, and others. As for the Noilhan and Planton and Deardorff schemes, they are already incorporated within the North Carolina State University (NCSU) model (Huang and Raman 1991; Alapaty et al 1997a) and LEAF3 is presently being linked. Additionally, a higher order closure model with implicit heterogeneity (Rao et al 1974), along with a non-hydrostatic regional model with the Noilhan and Planton scheme (ARPS 1995) will also be used for simulating the turbulence features over the study region. Our objective is to thus provide a hierarchy of evapotranspiration schemes such as, Bowen ratio technique, Penman-Monteith technique, Priestley-Taylor method, Noilhan and Planton (1989) with implicit soil and vegetation fluxes, Deardorff (1978) or Bosilovich and Sun (1995) with explicit soil and vegetation fluxes, and Ball-Berry model (Ball 1988; Niyogi and Raman 1997) a physiological photosynthesis-evapotranspiration approach, for their predictability will be evaluated. Such evaluations are planned for different hydrological regimes (diurnal, weekly, and seasonal scales). Our starting hypothesis
is that for non-stationary soil moisture conditions (dry to wet or wet to dry) and for relatively long periods (few days), advanced schemes might perform better for tropics where the landscape undergoes a dramatic change. Conversely, for near-stationary hydrological and physiological conditions, the different approaches would have a similar outcome. Other significant results from VEBEX database include a development of a nutrient-based stomatal resistance mapping technique (Niyogi et al 1997b) following an approach adopted by Schulze et al (1994). Stomatal resistance controls the regional evapotranspirative demand and thus has tremendous implications for hydrological and agricultural as well as medium-range weather forecasting. Recent studies (Alapaty et al 1997b; Niyogi et al 1997c) have attributed a high range of uncertainty to this parameter in error propagation. Hence, it will be of interest to apply first-order approximation techniques developed during VEBEX for a regional thematic mapping framework in the future. Another problem that will be of interest to the VEBEX researchers is the area averaging of fluxes, and turbulence dissipation due to step-change of surface features, and will be discussed in future.

5. Conclusion

A focused field experiment with emphasis on surface energy budget and related plant physiology was successfully executed at a tropical site in Bangalore, India. Results indicate interesting non-linearities in the interaction between surface features and the resulting turbulent energy fluxes. The resulting impact of the surface characteristics is hypothesized to be a dominant forcing since the synoptic forcing is weak in the tropics. Also, results obtained from VEBEX revealed, that the absolute magnitude of the surface forcings had a large amplitude and significant diurnal variability. This further increases the significance of recognizing the role of surface features in the tropical scenario. Thus, modeling efforts will require a high degree of sophistication to simulate the non-linear interaction evident in the tropical scenario such as that over the Indian peninsula. Particularly, evapotranspirative parameters such as stomatal resistance, vertical diffusion of sub-surface soil moisture, and surface temperature estimation will be a challenging task in the medium range forecast and planetary boundary layer models. Future efforts from the VEBEX community will address these and related aspects.

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