Estimation of Tropical Forest Canopy Temperatures, Thermal Response Numbers, and Evapotranspiration Using an Aircraft-Based Thermal Sensor

Jeffrey C. Luvall†
National Aeronautics and Space Administration, Science and Technology Laboratory, Stennis Space Center, SSC, MS 39529
Diana Lieberman and *Milton Lieberman*
Department of Biology, University of North Dakota, Grand Forks, ND 58202–8238
*Gary S. Hartshorn** and *Rodolfo Peralta*
Tropical Science Center, Apartado 8–3870, San Jose Costa Rica

ABSTRACT: Thermal Infrared Multispectral Scanner (TIMS) data were collected at a resolution of 5 to 10 m from a tropical rain forest over an elevation gradient from 35 to 2700 m in the Braulio Carrillo National Park in Costa Rica. Flight lines were repeated with a 15 to 30 minute time difference for measurement of forest canopy thermal response over time. Concurrent radiosonde measurements of atmospheric profiles of air temperature and moisture provided inputs to LOWTRAN6 for atmospheric radiance corrections of the TIMS data. Techniques for using calibrated aircraft-based thermal scanner data to examine tropical forest canopy thermal properties are described. Forest canopy temperature changes over time assessed between repeated, duplicated flight lines were combined with estimates of surface radiative energy measurements from towers above the forest canopy to determine temperature spatial variability, calculate Thermal Response Numbers (TRN), and estimate evapotranspiration along the elevation gradient from selected one hectare forest inventory plots.

INTRODUCTION

With the advent of thermal remote sensing, it has become feasible for the first time to undertake detailed assessments of variability in microclimate and forest energy budgets over landscape scales (Heilman *et al.*, 1976; Pierce and Congalton, 1988; Seguin and Itier, 1983). Previous energy budget studies have made use of extrapolation from one or a few intensively sampled points using tower–based micrometeorological equipment (McNaughton and Black, 1973; McCaughey, 1985; Monteith, 1973; Moore and Fisch, 1986; Oke, 1987) or integration of hydrologic information over entire watersheds (Swift *et al.*, 1975). Neither approach has permitted an assessment of fine–scaled spatial variability in forest canopy temperatures which represents differences in canopy energy budgets over vast areas.

However, forest canopy temperatures clearly vary across the landscape (Sader, 1986; Holbo and Luvall, 1989). Forest canopy temperatures, which integrate the energy budget (Oke, 1987), vary in response to (1) solar radiation received by the canopy, which is largely determined by local topography (Garnier and Ohmura, 1968; Luvall and Holbo, 1990; Swift and Knoerr, 1973; Swift, 1976); and (2) attributes of the vegetation itself, including leaf and canopy morphology, biomass, species composition, and canopy water status (Monteith, 1973). Air temperature alone is often a poor predictor of canopy temperature, especially when such measurements from traditional meteorological shelters are extrapolated across the landscape.

Many of the world's remaining tropical forests occur in relatively inaccessible regions where it is not feasible to study forest canopy thermal budgets using conventional micrometeorological techniques. In this paper we apply models of forest canopy thermal response developed in temperate forests using thermal remote sensing (Jarvis, 1981; Luvall, 1988; Luvall and Holbo, 1989; Luvall and Holbo, 1990) to an area of tropical forest in Costa Rica with the following objectives:

- Use remotely sensed thermal data to examine the spatial variability in tropical forest canopy temperatures, and
- Develop estimates of forest canopy thermal response and evapotranspiration from remotely sensed thermal data.

Study Area

The study was conducted on the Atlantic slope of Volcan Barva, a dormant volcano in Costa Rica's Cordillera Volcanica Central (Figure 1 and Plate 1). The study area rises from around 30 m above sea level at La Selva Biological Station to 2900 m at the summit of Volcan Barva, and is believed to be the last remaining strip of uninterrupted tropical forest in Central America to cover such a wide range of elevations (Norman, 1985). The area is included within Braulio Carrillo National Park, and forms part of a recently designated UNESCO (United Nations Educational, Scientific and Cultural Organization) MAB (Man and Biosphere) Biosphere Reserve. Outside these protected areas, deforestation is widespread; lowland sites to the east of the study area are generally used in large-scale agriculture, and those to the west are primarily cleared for small farms and pastures (Sader and Joyce, 1988).

The elevational gradient passes through four life zones and two transition zones of the Holdridge Life Zone system (Holdridge, 1967; Peralta, 1985); (1) Tropical Wet Forest (30 to 250 m); (1a) Tropical Wet Forest–premontane transition (250 to 600 m); (1b) Premontane Rain Forest–perhumid transition (600 to 780 m); (2) Premontane Rain Forest (780 to 1450 m); (3) Lower Montane Rain Forest (1450 to 2500 m); and (4) Montane Rain Forest (2500 to 2900 m).

*Presently with the World Wildlife Fund, 1250 Twenty-Fourth Street, N.W., Washington, DC 20037.
†Presently with the Earth Science and Application Division, Marshall Space Flight Center, MSFC, AL 35812.

Photogrammetric Engineering and Remote Sensing,
Vol. 56, No. 10, October 1990, pp. 1393–1401.

0099-1112/90/5610–1393$03.00/0

Climate varies accordingly over the elevation gradient. Average daytime temperatures range from 27.1 °C at La Selva Biological Station at 35 m to 10.9 °C at 2600 m; water vapor density deficit (1×10^{-6}g cm^{-3}) varies from 5.391 at the La Selva Biological Station to 1.214 at 2600 m elevation. Solar radiation ranges from 237 Wm^{-2} at 500 m elevation to 337 Wm^{-2} at 200 m elevation (Luvall, unpublished).

Analysis of 25-year precipitation records from La Selva (Luvall, unpublished) shows a mean annual precipitation of 3993 mm, varying during that period from 2630 mm (1980) to 5659 mm (1970). Data from weather stations near the study area (Hartshorn and Peralta, 1988) indicate that rainfall is highest at middle elevations, reaching 5096 mm at an elevation of 970 m, and drops as it nears the summit to 3268 mm at 2260 m.

The seasonal distribution of rainfall at La Selva is bimodal, with peaks above 400 mm per month in June-July and November-December. Although significant rainfall is received in every month, the period from February-April is comparatively dry, with March receiving the lowest average precipitation of 153 mm (Luvall, unpublished). This seasonal pattern is characteristic of the Atlantic region of Central America (Gramzow and Henry, 1972; Portig, 1976).

Field Sites

A series of one-hectare permanent forest inventory plots have been established at intervals along the gradient. All stems ≥ 10 cm diameter at breast height (dbh) have been measured and identified for use in long-term studies of tropical forest structure and dynamics (M. Lieberman and D. Lieberman, unpublished). Five of these plots have been used in the estimation of thermal response and evapotranspiration. The plots represent all four of the Holdridge Life Zones and are identified by the elevations at which they are located (100 m, 1250 m, 1500 m, 2000 m, and 2600 m). The forest structure of the inventory plots vary over the elevation gradient. Basal area ranges from 42.9 m^2 ha^{-1} at the 2600 m plot to a low of 22.3 m^2 ha^{-1} at the 100 m plot. The number of stems per hectare vary from 654 at the 2600 m plot to 442 at the 100 m plot.

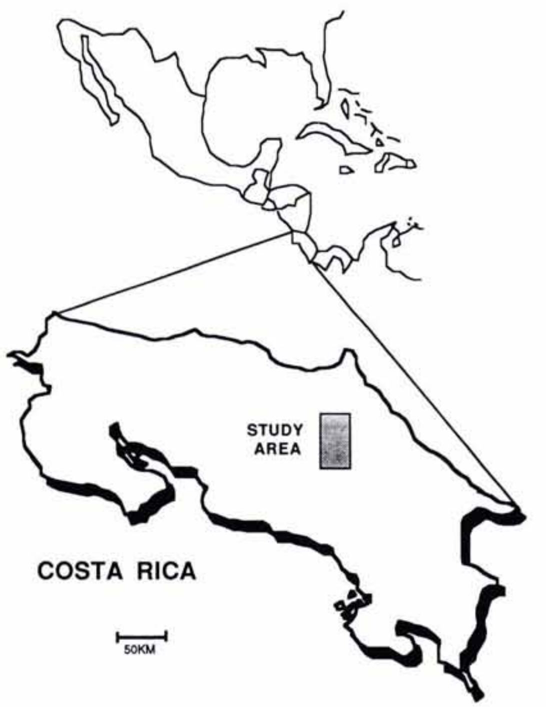

FIG. 1. Regional location of the study area.

DATA ACQUISITION AND PROCESSING

The TIMS Sensor

The Thermal Infrared Multispectral Scanner (TIMS) is a calibrated aircraft-mounted thermal scanner (Palluconi and Meeks, 1985), with six thermal channels in the wavelength regions of 8.2 to 12.2 μm (Figure 2). The instrument has a noise equivalent temperature (*NE* Δ *T*) as low as 0.1 °C for channel 2. A precision of 0.2 °C can be obtained over the temperature range of 10° to 65°C. The TIMS spectral response and blackbody temperature settings are determined by using pre-flight optical bench calibrations. Calibrated temperature readings are possible because on-board low and high temperature blackbodies which are referenced at the beginning and end of each scan line. The blackbody temperatures are selected to bracket the expected range of forest canopy temperatures in order to optimize TIMS temperature resolution. Information from the blackbodies recorded in the "housekeeping" data contained in the image data are used for making atmospheric radiance corrections and producing calibrated forest canopy temperatures. The TIMS usable swath width is ± 30° of nadir. Spatial resolution can be varied from a 5- to 30-metre pixel size, depending on aircraft altitude.

Atmospheric radiance must be accounted for in order to obtain calibrated forest canopy temperatures. Although the TIMS channels fall within the atmospheric window for atmospheric longwave transmittance (≈ 8.0 to 13.0 μm), the maximum transmittance is only about 80 percent. Depending on geographic location, the longwave energy flux density, $L\downarrow$, from the atmosphere can account for 300 to 425 Wm^{-2} of energy input. The amount of atmospheric radiance in the atmospheric window is mostly dependent on the atmospheric water vapor content, although there is an ozone absorbance band around 9.6 to 9.8 μm.

Atmospheric radiance can be determined in two ways: (1) direct measurement using a pyrgeometer (5 to 50 μm) which then is corrected for the specific wavelengths used by TIMS (Sweat and Carroll, 1983) and (2) use of atmospheric profiles of air temperature and vapor pressure. We have used on-site concurrent radiosonde launches to determine atmospheric profiles during the TIMS flights. The atmospheric profile is then incorporated in the LOWTRAN6 model for calculation of atmospheric radiance

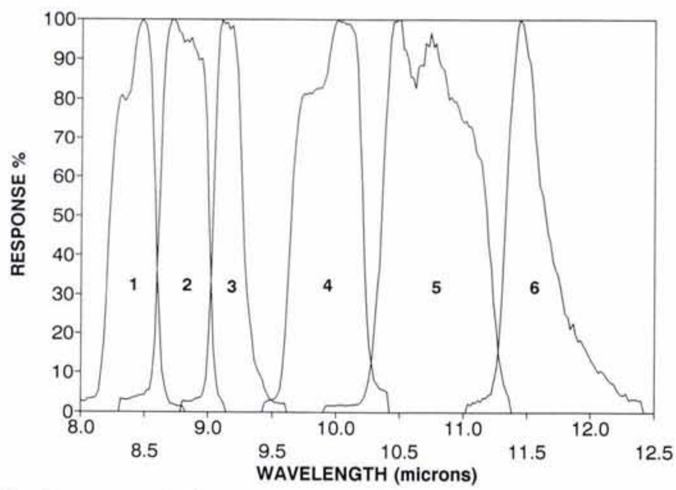

FIG. 2. TIMS spectral response curves. These curves represent optical bench pre-flight calibration curves and are used with the ELAS TRADE module to produce calibrated radiance values from the TIMS.

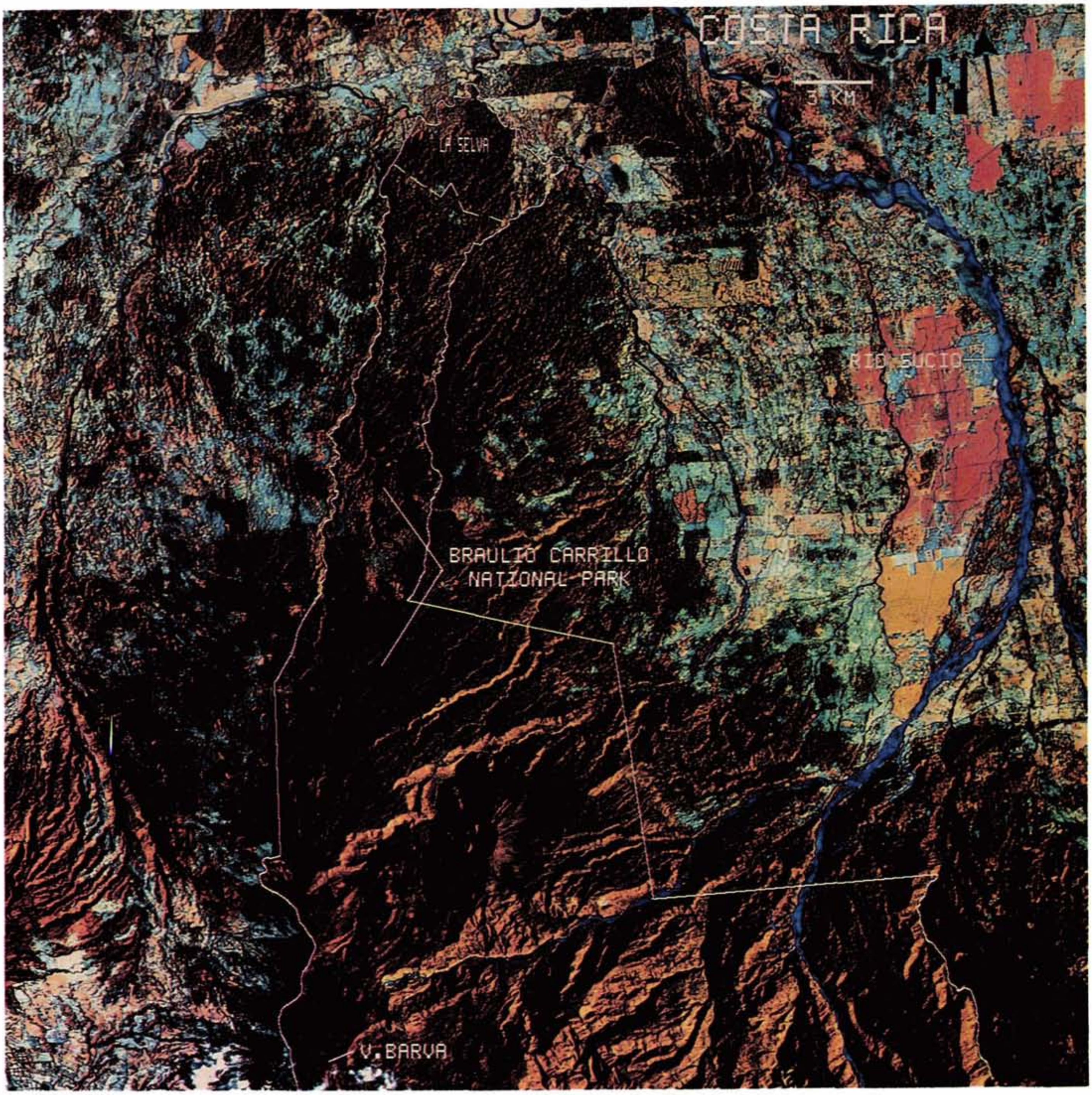

PLATE. 1. A 1986 Landsat TM false color composite (channels 3, 4, 5) image of the study area on the Atlantic slop of Volcan Barva in the Cordillera Volcanica Central in Costa Rica. The gradient extends from La Selva Biological Station at 30 m to 2700 m near the summit of Volcan Barva, a distance of 33 km. Boundaries of La Selva Biological Station and Braulio Carrillo National Park are shown.

(Kneizys *et al.*, 1983). Atmospheric longwave radiance values calculated by an earlier version, LOWTRAN5, have been shown to been in excellent agreement with measured atmospheric radiance values (Sweat and Carroll, 1983). Wilson and Anderson (1986) showed the validity of using LOWTRAN5 for atmospheric radiance corrections of aircraft-based thermal data collected over short atmospheric path lengths.

As shown in Figure 3, the output from LOWTRAN6 is combined with calibrated TIMS spectral response curves and blackbody information recorded during the flight, using the Earth Resources Laboratory Applications Software (ELAS) module TRADE (Graham *et al.*, 1986) to produce a look-up table for pixel temperatures as a function of TIMS values (Anderson, 1985). An $NE \Delta T$ is calculated for each channel from image "housekeeping" data. An $NE \Delta T$ of $\simeq 0.16$ was obtained for TIMS channel 4 (9.4 to 10.4 μm) used in this study.

TIMS flights (5- and 10-metre pixel resolution) were conducted within the Braulio Carrillo National Park in Costa Rica during February 1988 (Plate 1). Flights were made between 0700 and 0900 hours (local time) because of the development of clouds later in the day. Flight lines were duplicated a minimum of one time with a 17- to 25-minute time difference. Repeated flights allowed us to calculate ΔT for a series of forest sites along the gradient and to examine the magnitude of forest canopy temperature change over time.

The five forest inventory plots used in this study were first located on aerial photographs by field surveys. The plot locations from the photographs were then used to identify the plots in the TIMS data. Polygons of approximately one hectare in size were then extracted from the TIMS data and used for average polygon temperatures.

Meteorological Stations

Ground based meteorological stations were established at five sites (two towers and three clearings) along the elevational gradient to supplement aircraft measurements of forest canopy temperatures. Each station collected one-half hour averages of solar radiation, air temperature, relative humidity, and precipitation. In addition, data for net radiation, thermocouple leaf temperatures (four upper canopy leaves), and wind speed and direction were collected from the tower sites. Tower 1 was located at a elevation of 200 m and was 43.4 m tall. Tower 2 was located at a elevation of 2600 m and was 31.9 m tall. The forest canopy adjacent to tower 1 was 21.4 m tall and next to tower 2 the canopy was 20.9 m tall. The meteorological instruments were placed at the top of the towers, 22 m above the forest canopy for tower 1 and 11 m above the canopy for tower 2. In large clearings located at elevations of 35 m, 500 m, and 2000 m, instruments were mounted on a 2- m tall mast.

Surface Energy and Radiation Budgets

Use of energy terms in modeling surface energy budgets allows the direct comparison of various land surfaces encountered in a landscape, from vegetated (forest and herbaceous) to non-vegetated (bare soil, roads, and buildings) (Oke, 1987). The partitioning of energy budget terms depends on the surface type; in forested landscapes, the partitioning is dependent upon the vegetation characteristics and canopy moisture status. Forest canopy moisture status is in turn influenced by site conditions such as soil depth and soil moisture content.

The net allwave radiation balance (watts per square meter, Wm^{-2}) of forest canopies can be determined using (Oke, 1987):

Net solar radiation, K^*, is given by

$$K^* = (1 - \alpha)\, \phi\, (K\downarrow) \tag{1}$$

where

α = site albedo,
ϕ = site dependent slope and aspect solar gain coefficient (Garnier and Ohmura, 1968), and
$K\downarrow$ = solar radiation.

Albedo can be equated to

$$\alpha = K\uparrow / k\downarrow \tag{2}$$

where $K\uparrow$ = reflected solar radiation.

The longwave radiation emitted from a surface is dependent on surface temperature: i.e.,

$$L = \epsilon[\sigma(T)^4] \tag{3}$$

where

ϵ = emissivity,
σ = Stefan-Boltzman constant ($5.7 \times 10^{-8}\ Wm^{-2}\ T^{-4}$), and
T = forest canopy temperature (°Kelvin).

The net longwave radiation at the surface, L^* is given by

$$L^* = L\downarrow - L\uparrow \tag{4}$$

where

$L\downarrow$ = longwave radiation from the atmosphere and
$L\uparrow$ = longwave radiation from the surface.

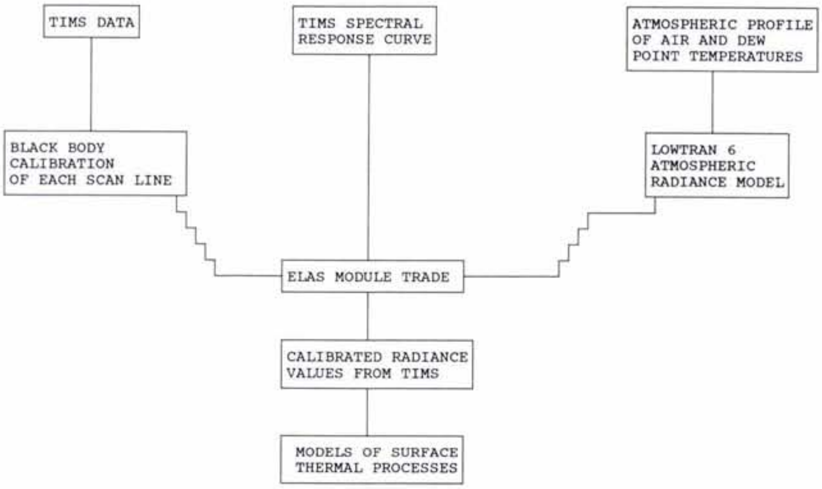

Fig. 3. The steps involved in obtaining calibrated surface temperatures from the TIMS using the ELAS TRADE module.

Therefore, the net allwave radiation, Q^*, can be given as

$$Q^* = K^* + L^*. \quad (5)$$

Net radiation is a particularly critical term because, under most conditions, it represents the total amount of energy available to the forest canopy for partitioning into non-radiative processes at the surface. The amount of net radiation (Q^*) is dependent upon forest type and varies with canopy leaf area and structure: i.e.,

$$Q^* = LE + H + G \quad (6)$$

where

H = the sensible heat flux,
LE = the latent heat flux (evapotranspiration), and
G = energy flux in or out of storage.

The partitioning of LE, H, and G is also canopy dependent. Both the physiological control of moisture loss (stomatal resistance) and the amount of canopy leaf area determines how Q^* is partitioned among LE, H, and G.

Thermal Response Number

Tropical rain forests include a large amount of canopy biomass. The change in heat storage can be a significant component in the energy budget. Most micrometeorological studies on tropical forest energy budgets have not attempted to estimate canopy heat storage (Shuttleworth *et al.*, 1984). In an Amazon primary tropical rain forest canopy, heat storage accounted for 80 Wm^{-2} of the total energy budget during certain periods of the day and could be a significant part of the hourly budget (Moore and Fisch, 1986).

A change in forest canopy temperature can be used as an aggregate expression of both surface properties (canopy structure and biomass, age, and physiological condition) and environmental energy fluxes ($K\downarrow$, $L\downarrow$, Q^*, LE, H, and G). A time interval of 15 to 30 minutes between flight passes usually reveals a measurable change in forest canopy temperature due to the change in incoming solar radiation ($K\downarrow$). Surface net radiation integrates the effects of the non–radiative fluxes, and the rate of change in forest canopy temperature reveals how non–radiative fluxes are reacting to radiant energy inputs. The ratio of net radiation to change in temperature can be used to define a surface property which Luvall and Holbo (1989) refer to as a Thermal Response Number (TRN).

Thermal Response Number ($J\ m^{-2}{}^{\circ}C^{-1}$):

$$\mathrm{TRN} = \frac{\sum_{t1}^{t2} [(Q^*)(\Delta t)]}{\Delta T} \quad (7)$$

where

$\sum_{t1}^{t2} [(Q^*(\Delta t)]$ = total net radiation (Q^*) over the time period between flights (Δt), and
ΔT = change in mean temperature for each site.

From Equation 7 it can been seen that Q^* expresses the combined energies of the non–radiative surface processes, making it the appropriate reference value for ΔT in the TRN.

Estimating Evapotranspiration

Remotely sensed forest canopy temperatures were used to determine evapotranspiration (Jarvis 1981): i.e.,

$$LE = (\rho C_p/c)\,(VD_a - VD_s)/(Rs) \quad (8)$$

where

ρ = density of air,
C_p = specific heat of air,
VD_a = water vapor density of the air,
VD_s = saturated water vapor density of the air at the forest canopy, temperature measured from TIMS channel 4,
c = psychrometric constant, and
Rs = stomatal resistance.

The Penman–Monteith equation (Monteith, 1973) was used to estimate evapotranspiration from the meteorological data collected from towers 1 and 2: i.e.,

$$LE = \frac{s\,(Q^* - G) + \frac{(\rho C_p)(V)}{Ra}}{s + c\,(1 + Rc/Ra)} \quad (9)$$

where

L = the latent heat of vaporization of water,
E = transpiration flux,
s = slope of the saturation vapor pressure relationship,
Q^* = net radiation flux,
G = energy flux, to the ground or canopy,
V = vapor density deficit of the air,
Ra = aerodynamic resistance of the canopy, and
Rc = (stomata resistance/ leaf area index).

Additional information was needed from the forest canopy in order to determine canopy resistance. Diurnal stomata resistance measurements (LiCor 1600 porometer) were taken over an approximately two week period for each tower from the forest canopy leaves within reach of the towers (Sanders and Luvall, unpublished). Aerodynamic resistance was estimated from wind speed (μ) at the top of the canopy from Shuttleworth *et al.* (1984) relationship developed from an Amazon tropical rain forest: i.e.,

$$R_a = 33/\mu \quad (10)$$

Leaf area estimates were taken by using six vertical lines samples from the top of canopy and counting the resulting leaf intercepts.

RESULTS AND DISCUSSION

TIMS Forest Canopy Temperature Spatial Variability

The temperature frequency distributions for each forest inventory plot were different (Figure 4). It appeared that the canopy of the 100-m plot was the most variable, with several distinct classes of canopy temperatures. The canopy temperatures for the 1500-m plot were the most narrowly defined, only covering a 3.3°C temperature range.

One can examine two traditional measurements used in forest community analyses, basal area (m^2ha^{-1}) and density (number of stems per hectare) of trees, in an attempt to explain the differences among the plots in their temperature frequency distribution curves (Figures 5a and 5b). It appears that using measurements of basal area and density contribute little to our understanding of canopy temperature variability. The complex structure of these canopies including a multi-layered canopy, emergent tree crowns, and the presence of epihytes are difficult to quantify especially over a large area. Also tree fall gaps are common and can be 1/4 hectare in size, adding to canopy heterogeneity.

The effect of forest canopies on the spatial differences in surface temperature can readily be quantified using TIMS data (Holbo and Luvall, 1989; Luvall and Holbo, 1990). Figure 6 shows a calibrated thermal image produced from TIMS in the area of La Selva Biological Station. TIMS temperature transects of 5-m pixels taken from the image are shown in Figure 7, moving from pasture

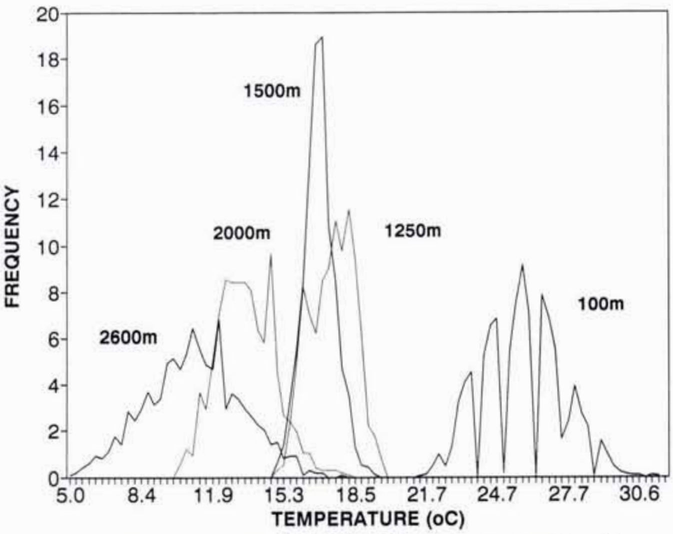

FIG. 4. Temperature frequency distributions from the five forest inventory plots.

through a burn (one month old) and a small tree island and back to pasture. The two lines represent duplicate TIMS flights taken at 0730 hours and repeated approximately 17 minutes later.

There is a large temperature range among the various surfaces. The comparatively cool tree island is about 29°C, and the warmest burn area is about 38°C. The transitions between the burn area and tree island are quite abrupt, spanning only about 3 pixels or 15 metres. Forest edges generate steep, complex microclimate gradients, and support a dynamic assemblage of woody and herbaceous plant species (Ranney *et al.*, 1981). Intensive microclimate measurements across forest edges have seldom been undertaken to quantify spatial variability in forest microclimate, because conventional micrometeorological techniques for studying forest energy budgets demand a large, uniform canopy. However, it is evident that TIMS canopy temperatures can provide information on the microclimate of forest edges.

The second TIMS flight ($\approx$ 17 minutes later) showed the same relative temperature differences, but temperatures were shifted upward with increased input of solar radiation. The TIMS image is an instantaneous "look" at the surface. It is important that the relative temperature differences were maintained through time because the temperature relationships among the surfaces obtained are not unique to that time. Luvall and Holbo (1990) found similar patterns from temperature transects in a douglas-fir forest and clearcut for daytime flights and an inverse relationship shortly after sundown when the surface was cooling.

The difference in air temperature and surface temperature is not surprising. The air temperature represents the 1/2-hour average ending 0800 hours taken at 2-m height at one location and thus not spatially averaged. Also, during the same time period solar radiation was quickly increasing and warming the surface. From Equations 6 and 8 it can readily be seen that air temperatures would be a poor predictor of canopy temperatures.

THERMAL RESPONSE NUMBER (TRN) AS AN EXPRESSION OF G

The estimation of canopy heat storage (G) is important in the determination of sensible and latent heat fluxes for forests (McCaughey, 1985). However, published estimates of G for tropical rain forests are limited (McCaughey, 1985; Aston, 1985; Moore and Fisch, 1986). An approach by Aston (1985) for a young Eucalypt forest to estimate G involved direct measurement

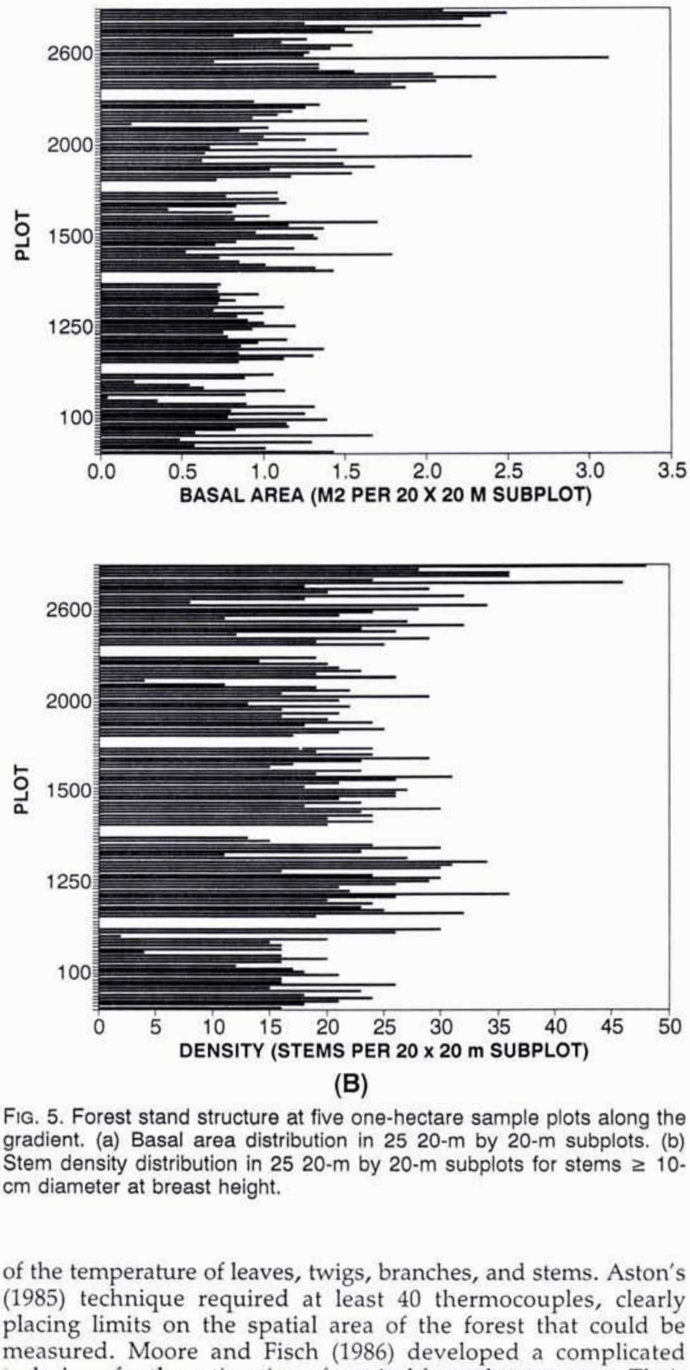

FIG. 5. Forest stand structure at five one-hectare sample plots along the gradient. (a) Basal area distribution in 25 20-m by 20-m subplots. (b) Stem density distribution in 25 20-m by 20-m subplots for stems $\geq$ 10-cm diameter at breast height.

of the temperature of leaves, twigs, branches, and stems. Aston's (1985) technique required at least 40 thermocouples, clearly placing limits on the spatial area of the forest that could be measured. Moore and Fisch (1986) developed a complicated technique for the estimation of tropical forest heat storage. Their complicated technique required the measurement of stem temperatures, tree diameters, surface area, and volume, and estimates of canopy biomass, specific heat capacity of wood, and many other terms. Again the technique is limited to specific, well instrumented sites.

The TRN for the forest inventory plots differed markedly (Figure 8). The TRN values range from 25 KJ $m^{-2}{}^{\circ}C^{-1}$ for the 2600 m plot to 192 KJ $m^{-2}{}^{\circ}C^{-1}$ for the 100-m plot. These differences in TRN among the various plots do not appear to be related to basal area or stem density. However, there are qualitative visual differences in canopy structure and leaf morphology among the plots. These visual differences can be readily seen in the temperature frequency distributions taken from the forest canopy around the towers (Figure 9). The canopy around tower 2 (2600-m elevation) is not as rough, with few if any emergent tree

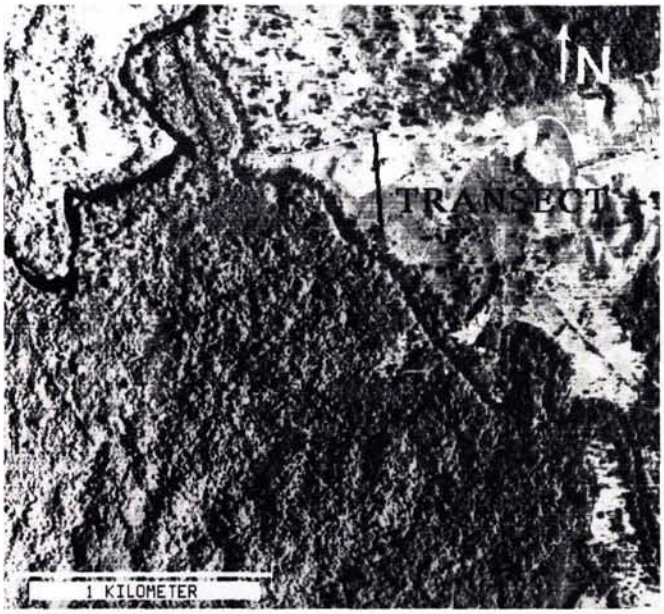

FIG. 6. A 5-metre resolution TIMS image, channel 4, (9.4 to 10.4 mμ) of La Selva Biological Station taken at 0730 hours. The 315-m temperature transect from which pixels were extracted for Figure 6 are shown. Notice that individual tree crowns can be recognized.

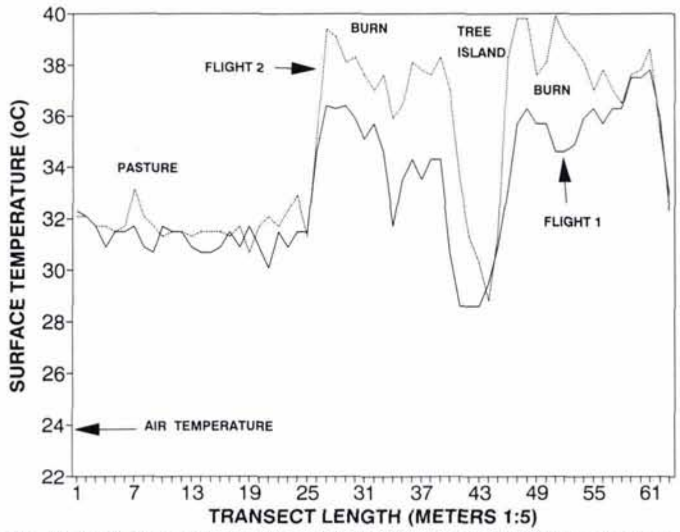

FIG. 7. TIMS surface temperature transects of 5-m pixels from pasture through a burn (one month old) and a small tree island and back to pasture. The two lines represent duplicate TIMS flights taken at 07:30 (TIMS filght 1) and repeated approximately 17 minutes later (TIMS flight 2).

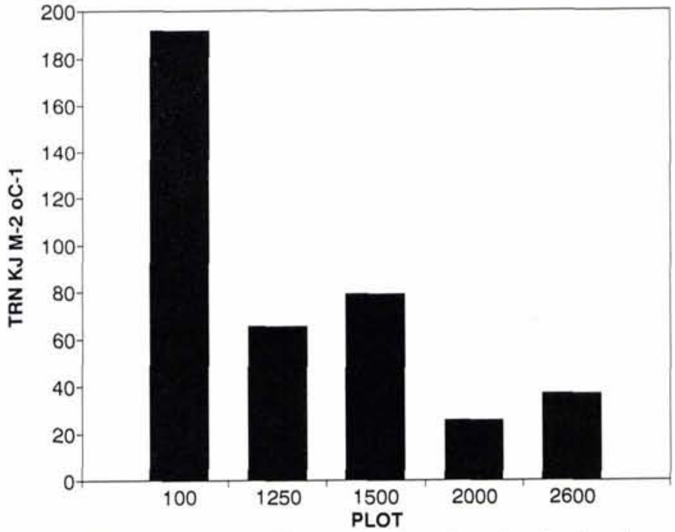

FIG. 8. The TRN from several forest canopies along the elevational gradient.

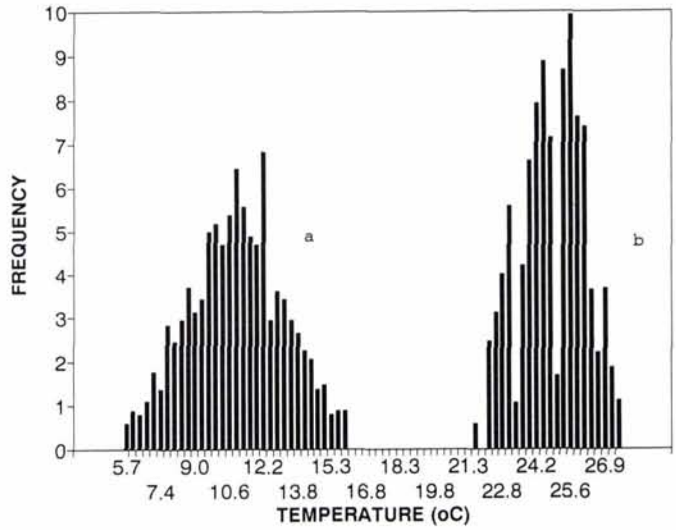

FIG. 9. Temperature frequency distributions for one hectare of forest canopy around tower 2 (a) and tower 1 (b).

crowns, and the temperature frequency distributions appear normally distributed. However, the temperature frequency distributions for the canopy around tower 1 (200-m elevation) are broken down into several groups, reflecting the presence of a rough canopy with emergents. The techniques for quantifying the various components of a tropical forest canopy (leaf, epiphyte, and stem biomass; leaf area index) have yet to be validated over large spatial scales, making direct comparisons among the plot canopies difficult.

The (TRN) has been used previously in temperate coniferous forests to assess differences in canopy structure/biomass due to stand age (Luvall and Holbo, 1989). Large differences were found among the forest types, where the TRN ranged from 406 KJ m^{-2} for a two-year-old replanted clear-cut to 1631 KJ m^{-2} for a 30-year-old Douglas fir plantation forest. It is not surprising that there is considerable differences in the TRN between the Douglas-fir forests and the tropical forests given the differences in leaf and canopy morphology and in the environment to which the forest canopy is responding.

EVAPOTRANSPIRATION

It is interesting to compare the temperature obtained from leaf thermocouples to that obtained from TIMS canopy temperatures (Table 1). The temperature obtained from the TIMS was slightly higher, but the maximum and minimum bracketed the thermocouple value. Of course, we are dealing with a limited leaf temperature sample size, but Luvall (1988) found similar close agreement with white pine needle temperatures and pixel-averaged TIMS canopy temperature.

The estimates obtained for evapotranspiration for the Penman-

TABLE 1. COMPARISON OF LEAF THERMOCOUPLE TEMPERATURES WITH TIMS PIXEL TEMPERATURES FROM TOWER 1.

	Tower 1[a]	TIMS[b]
Air temperature	25.3	
Mean leaf temperature	23.7	24.8
Maximum leaf temperature	26.2	28.8
Minimum leaf temperature	22.4	21.4

[a]Leaf temperatures were obtained from four thermocouples from upper canopy leaves adjacent to the tower.
[b]A polygon (2102 pixels, 5-m resolution) centered at tower 1 was extracted from the TIMS data and used for average canopy temperatures.

TABLE 2. COMPARISON OF EVAPOTRANSPIRATION ESTIMATED FROM THE PENMAN-MONTEITH EQUATION AND TIMS ESTIMATED FOREST CANOPY TEMPERATURES.

	EVAPOTRANSPIRATION Wm^{-2}	
	Tower 1	Tower 2
Penman–Monteith[a]	286.9	286.7
TIMS[b]	188.8	177.4

[a]Penman–Monteith estimates were determined from one–half hour averages ending at 0800 hours for tower 1 and 0730 hours for tower 2.
[b]Tims evapotranspiration estimates were determined for tower 1 at 0745 hours and tower 2 at 0719 hours.

Monteith equation were greater for both canopies (Table 2). It is difficult to directly compare the evapotranspiration estimated from the Penman-Monteith and the TIMS. First, one is dealing with different time resolutions. The Penman-Monteith estimates were based on the average energy fluxes for an entire 1/2-hour period, a time which the solar and net radiation fluxes were rapidly changing (Figure 10). The TIMS image represents the canopy temperature at a single point in time. Second, the canopy temperatures are spatially variable, which represent spatial differences in the forest canopy energy budget. The estimates of evapotranspiration from the Penman-Monteith equation would depend on the placement of the tower and instruments.

Evapotranspiration rates varied markedly among forests plots (Figure 11). The largest evapotranspiration estimates were from the 1250-m and 1500-m plots. There was no definite relationship between the evapotranspiration estimates and basal area or stem density of the plots. However, over a large elevational gradient the microclimate changes and differences in evapotranspiration could be related more to environmental conditions than to changes in the forest structure. It is not possible to separate the contribution of forest structure and microclimate to changes in evapotranspiration from our data.

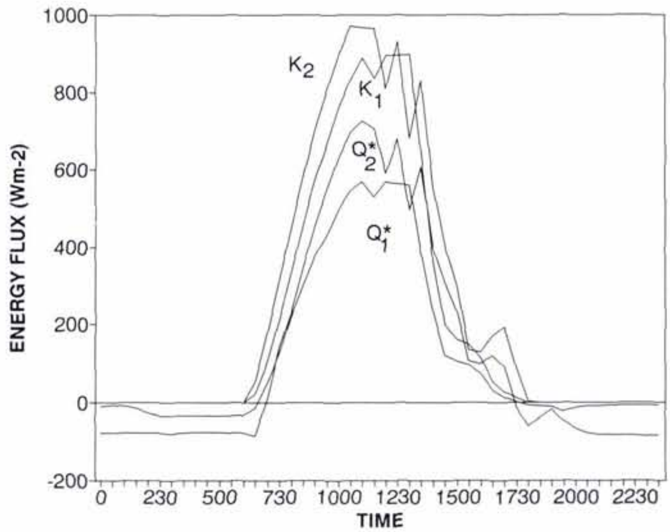

FIG. 10. Solar and net radiation fluxes during the day of the TIMS overflights.

CONCLUSIONS

Analysis of TIMS data revealed considerable variation in forest canopy temperatures in the study area, both within and between forest types. Several factors may contribute to these differences, including changes in microclimate, forest canopy structure, and species composition, although it is difficult at present to separate the relative effects of these factors.

Because of the high spatial resolution of the TIMS, detailed studies of forest edges or other ecotones are possible. Use of canopy temperature transects may be an effective tool for determining edges and minimum patch size and shape needed to minimize the effect of edge on interior forest habitats.

Thermal remote sensing is a potentially powerful tool for examining forest canopy thermal responses on a landscape scale, and is particularly suited for use in tropical forest where access is difficult. Clearly, knowledge of the spatial distribution pattern of significant aspects of forest energy budgets will contribute to our understanding of the determinants of these processes, and will enhance our ability to model such processes over landscape scales.

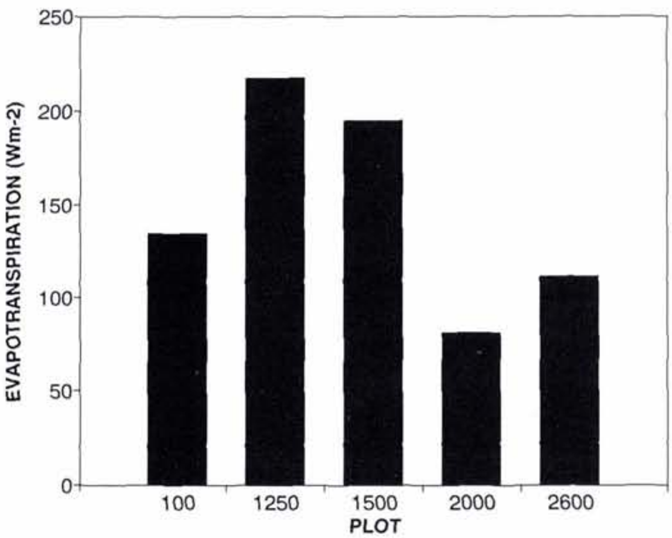

FIG. 11. Evapotranspiration from several forest canopies along the elevational gradient.

ACKNOWLEDGMENTS

We are grateful to the Costa Rican National Parks Service and the Organization for Tropical Studies for access to the study areas and logistical support. We also thank Victor Robles and Rodney Villegas for assistance in the field and Joe Sanders (University of Georgia) for technical assistance. This work was funded by NASA's Terrestrial Ecosystems program through RTOP # 677–21–33 and grant NAGW–1033.

REFERENCES

Anderson, J. E., 1985. *Thermal Infrared Data: Its Characteristics and Use.* American Society for Photogrammetry and Remote Sensing Technical Paper 1:43-155.

Aston, A. R., 1985. Heat storage in a young eucalypt forest. *Agriculture and Forest Meteorology* 35:281-297.

Garnier, B. J., and A. Ohmura, 1968. A method of calculating the direct shortwave radiation income of slopes. *Journal Applied Meteorology* 7:796-800.

Graham, M. H., B. G. Junkin, M. T. Kalcic, R. W. Pearson, and B. R. Seyfarth, 1986. *ELAS — Earth Resources Laboratory Applications Software*. Revised Jan 1986, NASA/NSTL/ERL Report No. 183.

Gramzow, R. H., and W. K. Henry, 1972. The rainy pentads of Central America. *Journal Applied Meteorology* 11:637-642.

Hartshorn, G., and R. Peralta, 1988. Preliminary description of primary forests along the La Selva-Volcan Barva altitudinal transect, Costa Rica. *Tropical Rainforests: Diversity and Conservation* (F. Almeda and C. M. Pringle, editors). California Academy of Sciences, San Francisco, California.

Heilman, J. L., and E. T. Kanemasu, 1976. An evaluation of a resistance form of the energy balance to estimate evapotranspiration. *Agronomy Journal*. 68:607-611.

Holbo, H. R., and J. C. Luvall, 1989. Modeling surface temperature distributions in forest landscapes. *Remote Sensing of Environment* 27:11-24.

Holdridge, L. R., 1967. *Life Zone Ecology*. Revised edition. Tropical Science Center, San Jose, Costa Rica.

Jarvis, P. G., 1981. Stomatal conductance, gaseous exchange and transpiration. *Plants and their Atmospheric Environment* (J. Grace, E. D. Ford, and P. G. Jarvis, editors). Blackwell, Oxford, U. K. pp. 175-204.

Kneizys, F. X., E. P. Settle, W. O. Gallery, J. H. Chetwynd, Jr., L. W. Abreu, J. E. A. Selby, R. W. Fenn, and R. A. McClatchey, 1983. *Atmospheric Transmittance/Radiance: Computer Code Lowtran-6*. Air Force Geophysics Laboratory Report AFGL-TR83-0187. Optical Physics Division, Hanscom Air Force Base, MA 01731. 200 p.

Luvall, J. C., 1988. Using the TIMS to estimate evapotranspiration from a white pine forest. *Remote Sensing for Resource Inventory, Planning and Monitoring* (J. D. Greer, editor), American Society of Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 90-98.

Luvall,. J. C., and H. R. Holbo, 1989. Measurement of short-term thermal responses of coniferous forest canopies using thermal scanner data. *Remote Sensing of Environment* 27:1-10.

———, 1990. Modeling forest canopy thermal response on a landscape scale using remotely sensed data. *Quantitative Methods in Landscape Ecology* (Monica G. Turner and Robert H. Gardner, editors). Springer-Verlag, New York, N.Y. (in press).

McCaughey, J. L., 1985. Energy balance storage terms in a mature mixed forest at Petawawa, Ontario— a case study. *Boundary-Layer Meteorology*. 31:89-101.

McNaughton, K. G., and T. A. Black, 1973. Evapotranspiration from a forest: a micrometeorological study. *Water Resource Research* 9:1579-1590.

Monteith, J. L., 1973. *Principles of Environmental Physics*. Edward Arnold, London, 241 p.

Moore, C. J., and G. Fisch, 1986. Estimating heat storage in Amazonian tropical forest. *Agriculture and Forest Meteorology* 38:147-169.

Norman, C., 1985. Virgin rain forest reprieved. *Science* 227:273.

Oke, T. R., 1987. *Boundary Layer Climates*. John Wiley & Sons, New York, N.Y., 372 p.

Palluconi, F. D., and G. R. Meeks, 1985. *Thermal Infrared Multispectral Scanner (TIMS): An Investigator's Guide to TIMS Data*. JPL publication 85-32, 14 p.

Peralta, R., 1985. *Mapificacion detallada de zonas de vida y descripcion general de unidades homogeneas en el area de estudio en Costa Rica. La Dinamica de Bosques Tropicales por Medio de Sensores Remotos de la NASA*. Tropical Science Center, San Jose, Costa Rica.

Pierce, L. L., and R. G. Congalton, 1988. A methodology for mapping forest latent heat flux densities using remote sensing. *Remote Sensing of Environment* 24:405-418.

Portig, W. H., 1976. The climate of Central America. *Climates of Central and South America. World Survey of Climatology*, Vol. 12 (W. Schwerdtfeger, editor), Elsevier Scientific Publ. Co., New York, N.Y., pp. 405-478.

Ranney, J. W., M. C. Bruner, and J. B. Levenson, 1981. The importance of edge in the structure and dynamics of forest islands. *Forest Island Dynamics in Man-Dominated Landscapes* (R. L. Burgess and D. M. Sharpe, editors), Springer-Verlag, New York, N.Y. pp. 67-95.

Sader, S. A., 1986. Analysis of effective radiant temperatures in a Pacific Northwest forest using Thermal Infrared Multispectral Scanner data. *Remote Sensing of Environment* 19:105-115.

Sader, S. A., and A. T. Joyce, 1988. Deforestation rates and trends in Costa Rica —1940 to 1983. *Biotropica* 20:11-19.

Seguin, B., and B. Itier, 1983. Using midday surface temperature to estimate daily evaporation from satellite thermal IR data. *International Journal of Remote Sensing*, 4(2):371-383.

Shuttleworth, W., J. H. C. Gash, C. R. Lloyd, C. J. Moore, J. Roberts, A. O. M. Filho, G. Fisch, V. P. S. Filho, M. N. G. Ribeiro, L. B. Molion, L. D. A. Sa, C. A. Nobre, O. M. R. Cabral, S. R. Patel, and J. C. Moraes, 1984. Eddy correlation measurements of energy partition for Amazonian forest. *Quarterly Journal Royal Meteorological Society*. 110:1143-1162.

Sweat, M. E., and J. Carroll, 1983. On the use of spectral radiance models to obtain irradiances on surfaces of arbitrary orientation. *Solar Energy* 30:373-377.

Swift, L. W., Jr., 1976. Algorithm for solar radiation on mountain slopes. *Water Resource Research* 12(1): 108-112.

Swift, L. W., and K. R. Knoerr, 1973. Estimating solar radiation on mountain slopes. *Agriculture Meteorology* 12:329-336.

Swift, L. W., Jr., W. T. Swank, J. B. Mankin, R. J. Luxmoore, and R. A. Goldstein, 1975. Simulation of evapotranspiration and drainage from mature and clear-cut deciduous forests and young pine plantation. *Water Resource Research* 11(5):667-673.

Wilson, S. B., and J. M. Anderson, 1986. The applicability of LOWTRAN 5 computer code to aerial thermographic data correction. *International Journal Remote Sensing* 7:379-388.

(Accepted 12 June 1990)