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TECHNICAL MEMORANDUM

THE ECOLOGICAL VARIATIONS IN THERMAL INFRARED EMISSIVITY OF VEGETATION

By

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16. Abstract
Thermal emissivity measurements in the 10.5 μm to 12.5 μm spectral region were taken for a variety of native common and dominant plants of southern U.S. and Mexico. Results of these measurements are reported with a statistical analysis that suggests there is a significant difference between the emissivity and hence, the thermal properties of plants from desert, tropical, and temperate regions. A discussion of the significance and interpretation of these results is presented.

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1. INTRODUCTION

The representative thermal emissivity measurements of common and conspicuous plants of the southwestern U.S. and Mexico were part of a project sponsored by the National Aeronautics and Space Administration (NASA) Health Applications Office from 1973 to 1975 for the screwworm eradication project. These data, soil data, and ancillary information were used to compute factors for use in the correction of thermal infrared temperature measurements made by the National Oceanic and Atmospheric Administration (NOAA) satellites. The results of this work were used to obtain accurate ground air temperature estimates twice daily over Mexico and the southwestern U.S. These estimates were applied to the screwworm eradication base and were used in the prediction of the screwworm fly infestation sites. Refer to Barnes and Forsberg[1] for details of this project.

A review of the emissivity values of this project suggests that there are significant differences between values obtained for desert plants and other ecological species. This significance supports preliminary work by Gates[10], who suggested that in very dry areas, plants might alleviate some of their potential heat absorption by efficiently emitting energy in the thermal infrared regions. This feature is especially important in desert regions where large amounts of heat and light are present but mechanisms for heat dispersal are limited due to restricted availability of water needed for cooling in evapotranspiration. To determine the difference in emissivity values between desert plants and other ecological plants, a series of statistical tests was performed on the collected data. In this report, a discussion of emissivity including background is presented prior to documenting the procedures and significant findings of these tests.

1.1 DEFINITION OF EMISSIVITY

The spectral emissivity, ε, of a homogeneous surface is defined by Huschke[13] as the ratio of the radiance of the surface at a specified wavelength and emitting temperature to the radiance of an ideal blackbody at the same wavelength and temperature. The values for emissivity may range from zero to unity.

Planck's law gives the spectral distribution of the radiance from a perfect radiator (blackbody) at temperature T as:

$$B_\lambda = C_1 \lambda^{-5}[\mathrm{EXP}(C_2/\lambda T) - 1]^{-1} \tag{1}$$

where

$C_1 = 3.75 \times 10^{-16} Wm^2$

$C_2 = 1.44 \times 10^{-2} m°K$

λ = wavelength in meters

T = absolute temperature in degrees Kelvin

The spectral radiance emitted by an opaque gray-body may then be written:

$$L_\lambda(T) = \varepsilon(\lambda)B_\lambda(T) \tag{2}$$

Thus, if the actual emissivity of a surface is not considered, the temperature calculated from radiometric data will be lower than the true surface temperature.

For naturally occurring surfaces, emissivity values in the thermal infrared wavelengths have been reported ranging from 0.82 for granite to near 1.0 for water, Buettner and Kern(4). Most surfaces seem to fall within this range. Generally, rock ranges from 0.86 to 0.93, Buettner and Kern(4); soil ranges from 0.90 to 0.97, varying with type and moisture content, Fuchs and Tanner(8). Most vegetative surfaces lie between 0.96 and 0.98.

Equations (1) and (2) may be used to evaluate the magnitude of the error associated with using an incorrect value for emissivity. Figure 1-1 presents this error for the 10.5μm to 12.5μm spectral band which corresponds to the spectral sensitivity of the radiometers carried by the NOAA satellites. The data for this figure was developed for a 300° K surface. Estimated surface temperatures were calculated by numerically inverting equation (1) to satisfy the following relationship:

$$\frac{\hat{\varepsilon}}{\varepsilon} B_\lambda(T) = B_\lambda(\hat{T}) \tag{3}$$

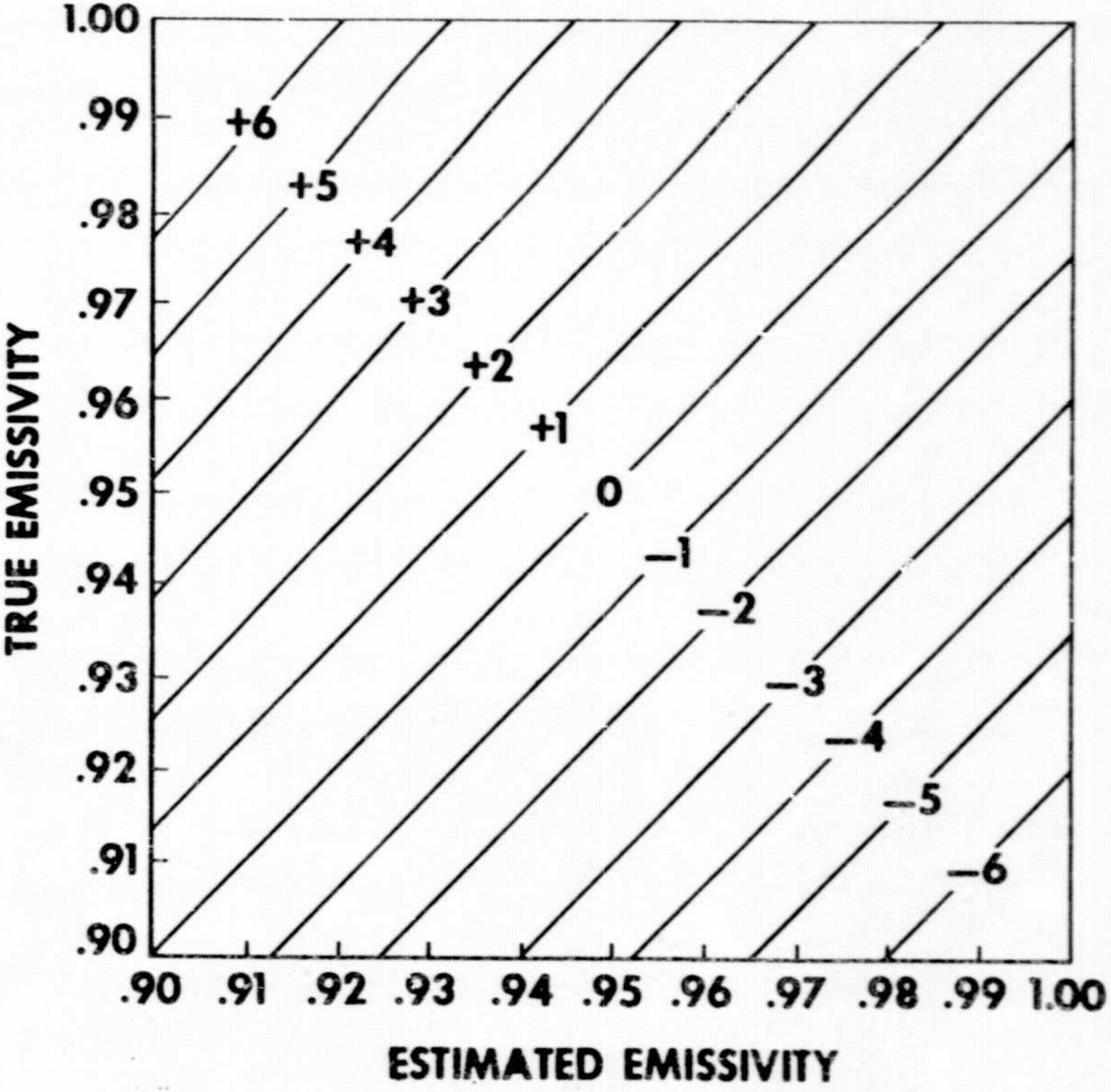

Figure 1-1.— Temperature error (°C) associated with an incorrect assumption of emissivity at 300° K.

where the true emissivity ε and the estimated emissivity $\hat{\varepsilon}$ were varied between 0.9 and 1.0. For simplicity, the emissivity was assumed constant over the spectral region. While this assumption is not strictly valid, particularly for siliceous minerals, an average emissivity can generally be used without serious error in the thermal infrared region.

As can be seen from Figure 1-1, a 0.01 error in emissivity will result in an approximately 0.7° C temperature error. The increasingly sophisticated uses being made of radiometric data can no longer allow errors of several degrees simply due to lack of adequate information on surface emissivity.

1.2 THEORY OF MEASUREMENT OF SURFACE EMISSIVITY

In this report, the radiation terminology proposed by the World Meteorological Organization(16) is used and all radiances are for the entire infrared spectrum.

Consider the longwave radiative balance at the earth's surface which is shown schematically in Figure 1-2. The outgoing spectral radiance, $L\uparrow$, consists of two parts. The largest part, $\varepsilon_s L_b$, is emitted by the surface; the remainder is the portion of the incoming longwave radiation, $L\downarrow$, that is reflected by the surface. Thus, the radiative balance at the surface may be written:

$$L\uparrow = \varepsilon_s L_b + r_s L\downarrow \qquad (4)$$

where r_s, the longwave reflectivity, equals $1 - \varepsilon_s$. Solving equation (4) for emissivity yields the following equation:

$$\varepsilon_s = \frac{L\uparrow - L\downarrow}{L_b - L\downarrow} \qquad (5)$$

Thus, to calculate the infrared emissivity of a surface $L\uparrow$, $L\downarrow$ and L_b must be measured.

In practice, only a portion of the longwave radiance is measured as determined by the spectral sensitivity of the radiometer used. Therefore, care is necessary when comparing emissivities measured with instruments of differing spectral sensitivities. An analysis of the sensitivity of the calculated

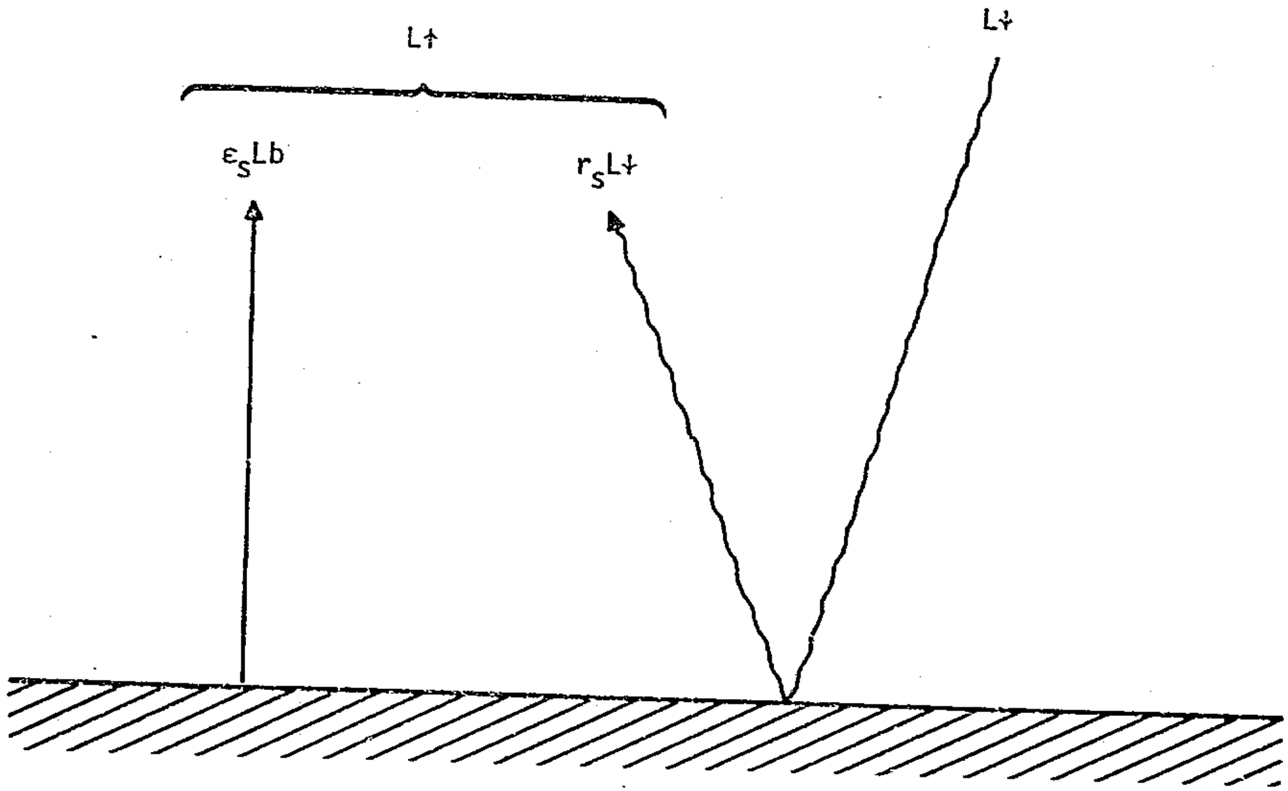

Figure 1-2.— Simplified longwave radiative balance at the earth's surface.

emissivity to measurement errors in the component radiances has been carried out by Davies *et al.*[6]. It was shown that for typical conditions, the sensitivity of ε_s to errors in L↑ was 0.0001 per °K. (The radiance is expressed in terms of equivalent blackbody temperature.) Equivalent sensitivities for L_b and L↑ were -0.026 and -0.028 per °K, respectively. However, under conditions of extremely warm sky, the values for L↓ become significant. Thus, equal care should be taken with all measurements.

2. BACKGROUND

Infrared emissivities have been measured experimentally by a number of researchers using a variety of field and laboratory instrumentation. Before the field trip for plant specimens and emissivity measurements was made, literature on the measurement of infrared emissivities was examined with attention directed toward techniques, instrumentation, and results.

In 1923, Falckenberg[7] measured emissivities at 10μm using a single beam spectrophotometer which ranged from 0.89 for sand to 0.955 for snow.

The first evidence of a systematic variation in components of the radiative heat balance with a change in ecological communities was reported by Billings and Morris[3]. The authors present visible reflectance values for five Great Basin communities ranging from hot desert to cool moist subalpine forests. Their data suggest that communities with hotter, dryer conditions have visible reflectance values higher than values obtained from communities with cooler, wetter conditions. Their results involve the need for corresponding information about components of the infrared energy balance.

Gates and Tantraporn[9] measured the reflectivity of numerous deciduous trees and shrubs using a double-beam Baird spectrophotometer. A systematic variation in emissivity for some species was noted with the upper surface of the leaf higher than the lower, the shade leaf more than the sun, and old leaves more than new. It can be noted in their data that many plants from dry areas had a relatively higher emissivity. This phenomenon was attributed to the presence of a layer of waxy cuticle on the leaf surface.

The work of Buettner and Kern[4] represents a milestone in the measurement of surface emissivities. This and most subsequent work made use of portable infrared radiometers developed by Barnes Engineering Company of Stamford, Connecticut. The technique developed by Buettner and Kern is fairly cumbersome and is more suited to the laboratory than the field. However, the results from their numerous measurements are of high quality and represent a basic reference for the emissivity of a number of minerals.

Buettner and Kern's approach was to create a controlled environment through the use of an emissivity "box". A box with highly reflective sides was constructed such that the top could alternately be a high reflective surface or a temperature controlled pseudo-blackbody. When the highly reflective top was in place, a blackbody cavity (hohlraum) was simulated, and the spectral radiance emitted by the surface was measured through a hole in the top. The high emittance top was maintained at a temperature well below ambient. When the radiance was measured with this top in place, the resultant was the sum of the surface emittance and the reflected portion of the downwelling radiance from the top. If the temperature, the emissivity of the high emittance top, and the radiance of the surface are known when in the hohlraum, the emissivity were easily calculated.

Buettner and Kern used an IT-2 infrared radiometer with a spectral sensitivity from 8 to 12μ. A number of their measurements compared favorably with the integrated readings from a Beckman IR-8 spectrophotometer.

Lorenz[15] studied several surfaces yielding generally good results. However, his results were somewhat erratic probably due to his method of measuring sky radiation. Using an IT-1 infrared radiometer (8 to 14μ), Lorenz measured the surface emittance using an aluminum lined box for a hohlraum. He then measured the combined surface emittance and reflected sky radiation directly by placing the surface under an open sky. The sky radiation was then estimated by integrating several direct readings of sky temperature made at different zenith angles.

Fuchs and Tanner[8] developed their own method of measurement and report experimental data for a few agricultural crops as well as for bare soils. This technique involves using a reference target of known temperature and emissivity to estimate downwelling radiation from the sky. Fuchs and Tanner used an IT-2 and an IT-3 radiometer sensitive to the 8 to 13μ spectral band.

Fuchs and Tanner[9] presented measurements on sand and illustrated the dependence of emissivity on moisture content. Using a sandy soil, Fuchs and Tanner observed variations from 0.90 with 0.7 percent water to 0.94 with 8.4 percent water. At that time they also raised a question as to the relative validity of measurements made with the techniques of Buettner and Kern. Idso and Jackson[14] experimentally examined the rival methods and found them to be equivalent in accuracy with root mean square errors ranging from 0.003 to 0.008.

In contrast with Fuchs and Tanner's work, Hovis[12] reported emissivities of clay and loam soils close to 0.96 with no apparent variation due to soil moisture.

Conaway and Van Bavel[5] reported additional measurements on bare soil using the Buettner and Kern technique. This study examined the use of radiometrically determined surface temperature in calculating evaporation from bare soils.

Davies *et al.*[6] conducted additional measurements of the emissivity of water using a Barnes PRT-5 (8 - 14μ) infrared radiometer. They report a value of 0.972 with no detectable variation due to turbidity. This compares poorly to Buettner and Kern's value of 0.993, perhaps due to the differing spectarl sensitivities of the instruments used in the two studies.

Bartholic *et al.*[2] measured the emissivity of cotton and bare soil in the course of a study to determine the use of thermal infrared in delineating moisture stress and soil moisture conditions.

In general, all of the workers who have developed the techniques for measuring emissivity seem to have reported on a fairly random selection of whatever material was on hand. As a result, persons working on applications which require a knowledge of surface emissivities have been forced to take their own measurements. In addition, with the exception of work by Billings and Morris[3] and Gates *et al.*[10 and 11], little effort has been made to study systematically the collective emissivities of species which occur together in a given ecological situation.

3. METHODS AND MATERIALS

To gather the desired emissivity data, a series of trips were made to eastern and northern Mexico, Texas, New Mexico, and Arizona. Field measurements were made of the important dominant species of each area. The choice of species included only those that formed the exposed overstory in each community as only their radiational surfaces would contribute significantly to the scene emissivity as perceived by the NOAA satellite.

When first entering a study area, the scientist determined the kind and number of dominant plant communities. The use of botanical literature and available aerial photographs greatly simplified the problems associated with determining the distribution of the key Mexican and U.S. communities. After a general survey, representative communities were selected for detailed analyses. Quadrats were used to determine plant cover and dominance. At each site, representative localities were chosen, quadrats 50 m on a side were marked off, and the vegetation measured and mapped. Based upon a plant's relative occurrence within a community, the conspicuously dominant, common, and occasional plants were listed for each community.

After an area had been surveyed and the candidates for measurements were known, the instruments were set up in a clear area with no overhead trees or other radiational obstructions in the immediate area. The measurement site was away from cars and the accessory instruments to ensure that radiation from cars, people, and accessory instruments did not affect the field measurements. While the instruments were being assembled and warmed up, specimens, representing all desired material, were gathered quickly. Time is a critical factor in all phases of emissivity measurements because temperatures and sky radiation can fluctuate rapidly within a few minutes and specimens can wilt, often quickly.

Only leafy branch tips from the exposed upper surfaces of the plant were clipped for emissivity measurements. Branches from the lateral but exposed portions are best because the leaf orientation with respect to the sun will remain approximately the same when measured by the radiometer. Several branches 8 to 10 inches long were selected and laid one upon the other with upper leaf surfaces facing upward and correctly aligned so that the leaf sample orientation was as nearly normal as possible. Careful attention made sure that enough layers of leaves were placed together so that none of the underlying surface showed through. Usually, a dense bundle of leaves 10 inches in diameter was created. If botanical reference specimens were needed, it was useful and sometimes critical to collect samples of fruit, flowers, and/or seeds for use in species identification. These latter portions were not included in the emissivity sample unless they formed a conspicuous portion of the canopy. A bundle for each species was made and laid in order of collection number on the ground at the measurement site. For woody species or those that habitually show dead or bare branches in the canopy, bare twigs were included in the bundle. For such cases, it was frequently difficult to create a representative mass of vegetation and branches.

Each specimen was given a collection number and reference name (or botanical name if known). In the field notebook, the collection number was recorded with data or local distribution and relative dominance. Once the collection numbers were assigned, measurements were made, alleviating the potential for wilting which can be a serious problem in dry or windy areas. Afterwards, further notes were recorded. Upon completion of the critical measurements, portions of each specimen sample were placed in the plant press as needed for later use in specimen identification and verification. If fruits, flowers, or seeds were previously collected, these were included plus enough vegetative material to make two herbarium sheets of voucher material.

The field readings were screened on the spot with complete reduction occuring at a later date in the laboratory. Generally, it is a good practice to evaluate at least a part of the data in the field to eliminate spurious readings.

The calibration curves for the Barnes PRT-5 were used to convert the readings from the digital voltmeter to temperature. The temperatures were then converted to radiances.

The magnitude of the downwelling sky radiation was calculated from the measurements made upon the reference target. Using equation (4) and solving for $L\downarrow$ yields:

$$L\downarrow = \frac{L\uparrow - \varepsilon_r L_b}{1 - \varepsilon_r} \qquad (6)$$

Thus, by measuring L directly over the reference's target and measuring L_b using the emissivity box, $L\downarrow$ can be calculated when the emissivity of the reference target, ε_r, is known.

The emissivity of the surface (over the spectral range of the radiometer) may then be calculated. After examining equation (5), it is seen that the thermal infrared emissivity can be calculated directly from $L\downarrow$ and the measurements of L_b and $L\uparrow$ taken over the unknown. The emissivity values for various Mexican and southwestern U.S. plants that were measured as part of this study are presented in Table 3-1.

The equipment used for conducting these measurements consisted of a modified Barnes PRT-5 with spectral sensitivity from 10.5μm to 12.5μm and a digital voltmeter for the radiometric measurements, an aluminum lined emissivity box for measurement of surface radiance, and a brass reference target used to calculate downwelling sky radiation. All radiance values used hereafter are for the 10.5μm to 12.5μm spectral region.

The measurement sequence for each surface is conducted as follows:

1. Measure $L\uparrow$ of the reference target

2. Measure L_s of the reference target using the emissivity box

3. Measure $L\uparrow$ of the unknown

4. Measure L_s of the unknown

The ideal conditions for measurement are low winds with a cold clear sky. Often, early morning and late afternoon produce the best results as the changes

TABLE 3-1.— EMISSIVITY VALUES FOR VARIOUS MEXICAN AND SOUTHWESTERN U.S. PLANTS

Habitat/niche	Measurement site	Botanical name	Common name	Collection number	Emissivity	Native or cultivated	Date	Number of replications
			Chaparral					
Chaparral component	Marathon, TX	*Acacia constricta* Gray	Acacia	4633	0.974	Native	10/75	3
Chaparral component	Chiati Mountains, TX	*Acacia neovernicosa* *Isely*	Acacia	4618	.982	Native	10/75	2
Ground cover; invader	Laredo, TX	*Boraginaceae family*		4283	.991	Native	11/74	1
Introduced range grass	Lardeo/Del Rio, TX	*Cenchrus ciliaris* L.	Buffelgrass	4286	.976	Cultivated	11/74	2
Chaparral	Chiati Mountains, TX	*Condalia viridis* I. M. Johnston		4619	.963	Native	10/75	3
Chaparral component	Starr County, TX	*Helietta parvifolia* (Gray) Benth.	Barreta	4260	.987	Native	11/74	1
Chaparral component	Starr County, TX	*Karwinskia Humboldtiana* (R.S.) Zucc.	Coyotillo	4261	.945	Native	11/74	1
Chaparral component	Starr County, TX	*Leucophyllum frutescens* (Berl.) I.M. Johnston	Chenizo	4258	.958	Native	11/74	1
Chaparral component	Laredo, TX	*Leucophyllum frutescens* (Berg.) I.M. Johnston	Chenizo	4287	.989 .984	Native	11/74	2
Chaparral component	Laredo, TX	*Porlieria angustifolia* (Engelm.) Gray	Guayacán	4288	.950	Native	11/74	2
Dominant shrub	Laredo, TX	*Prosopis glandulosa* Torr.	Mesquite	4284	.987	Native	11/74	2
Dominant tall brush	Lower Valley, TX	*Prosopis glandulosa* Torr.	Mesquite	SN	.988	Native	11/74	1
			Cloud forest					
High elevation shrub	Mirador near Esperanza, Puebla	*Baccharis conifera* H.B.K.	Encino	4528	.978	Native	1/75	2
High elevation mesophytic pine	Mirador near Esperanza, Puebla	*Pinus leiophylla* Schlecht. and Cham.	Pine	4529	.958	Native	1/75	2
Temperate tree	Coscomatepec, Veracruz	*Platanus lindeniana* Mart. and Gal.	Sycamore	4548	.966	Native	1/75	3
High elevation tree	Mirador near Esperanza, Puebla	*Quercus candicans* Nee	Encino	4531	.969	Native	1/75	3
High elevation tree	Mirador near Esperanza, Puebla	*Quercus crassifolia* Humb. and Bonpl.	Encino	4530	.973	Native	1/75	2
High elevation shrub	Mirador near Esperanza, Puebla	*Solanum cervantesii* Lag.	Nightshade	4532	.958	Native	1/75	4
			Desert					
Desert shrub	Laredo, TX	*Acacia farnesiana* (L.) Willd.	Huisache	4282	.989	Native	11/74	1
Common in rosette form deserts	Hot Springs, TX	*Agave lecheguilla* Torr.	Lecheguilla	4606	.997	Native	10/75	3
Desert grassland	Marathon, TX	*Agrostis sp.*		4626	.961	Native	10/75	3
Common in washes	Ft. Stockton, TX	*Aloysia gratissima* (Gill. & Hook.) Troncoso.	White brush	4311	.988	Native	11/74	2

TABLE 3-1.— Continued.

Habitat/niche	Measurement site	Botanical name	Common name	Collection number	Emissivity	Native or cultivated	Date	Number of replications
				Desert				
Desert grass	Laredo, TX	*Aristida glauca* (Nees.) Walp.	Three-awn	4285	0.983 .982	Native	11/74	2
Limestone hills	Sanderson Canyon, TX	*Aristida sp.*	Three-awn	4655	.972	Native	10/75	4
Winter annual understory	Ft. Stockton, TX	*Astragalus sp.*	Milk-vetch	4323	.993	Native	11/74	3
Alkali desert shrub	Marathon, TX	*Atriplex canescens* (Pursh) Nutt.	Four-wing salt bush	4628	.966	Native	10/75	3
Desert grass-land	Marathon, TX	*Bouteloua curtipendula* (Michx.) Torr.	Side-oats grama	4630	.987	Native	10/75	4
Desert grass	Van Horn, TX	*Bouteloua eriopoda* (Torr.) Torr.	Black grama	4327	.990	Native	11/74	2
Desert grass-land	Marathon, TX	*Bouteloua hirsuta* Lag. Hairy Grama	Grama	4627	.969	Native	10/75	3
Ground cover	Ft. Stockton, TX	*Boraginaceae family*		4259	.988	Native	11/74	1
Rosette form desert	Hot Springs, TX	*Boraginaceae family*		4601	.983	Native	10/75	2
Desert grass	Hot Springs, TX	*Buchloe dactyloides* (Nutt.) Engelm.	Buffalo grass	4604	.978	Native	10/75	3
Creosote bush hills	Plata, TX	*Chrysothamnus sp.*	Rabbit-brush	4610	.985	Native	10/75	4
Rosette form desert	Hot Springs, TX	*Compositae*		4603	.975	Native	10/75	3
Desert shrub	Van Horn, TX	*Condalia ericoides* (Gray) M.C. Johnson	Havelina bush	4326	.988	Native	11/74	2
Roadside weed	Chiati Mountains, TX	*Croton pottsii* (Kl.) Muell. Arg.	Leather weed	4620	.955	Native	10/75	3
Desert grass	Van Horn, TX	*Erioneuron pulchellum* (H.B.K.) Tateoka	Fluffgrass	4331	.978	Native	11/74	2
Desert cactus	Tehuacan, Puebla	*Escontria chiotilla* (Web.) Rose	Chiotilla	4534	.960	Native	1/75	2
Desert shrub	Ft. Stockton, TX	*Flourensia cernua* D.C.	Tarbush	4312	.993	Native	11/74	2
Desert shrub	Van Horn, TX	*Flourensia cernua* D.C.	Tarbush	4328	.993	Native	11/74	2
Creosote bush	Plata, TX	*Flourensia cernua* D.C.	Tarbush	4609	.993	Native	10/75	3
Desert grass	Ft. Stockton, TX	*Hilaria mutica* (Buckl.) Benth.	Tobosa	4310	.982	Native	11/74	3
Desert mountain	Ft. Stockton, TX	*Juniperus Ashei* Buchh.	Rock cedar	4304	.993	Native	11/74	2
Limestone desert	Sanderson Canyon, TX	*Juniperus Deppeana* Steud.	Alligator juniper	4658	.994	Native	10/75	5
Desert shrub	Ft. Stockton, TX	*Koeberlinia spinosa* Zucc.	Allthorn	4317	.982	Native	11/74	2
Desert grass-land	Marathon, TX	*Labiatae*		4632	.986	Native	10/75	2
Desert shrub	Ft. Stockton, TX	*Larrea tridentata* (D.C.) Cov.	Creosote bush	4313	.981	Native	11/74	3
Desert shrub	Van Horn, TX	*Larrea tridentata* (D.C.) Cov.	Creosote bush	4325	.981	Native	11/74	3

TABLE 3-1.— Continued.

Habitat/niche	Measurement site	Botanical name	Common name	Collection number	Emissivity	Native or cultivated	Date	Number of replications
				Desert				
Desert shrub	Hot Springs, TX	*Larrea tridentata* (D.C.) Cov.	Creosote bush	4602	0.986	Native	10/75	2
Desert shrub	Plata, TX	*Larrea tridentata* (D.C.) Cov.	Creosote bush	4608	.995	Native	10/75	3
Hot desert cactus	Tehuacan Valley, Puebla	*Lemaireocereus stellatus* (Pfeiffer) Br. & Rose	Organ pipe	4533	.969	Native	1/75	3
Hot desert cactus	Tehuacan Valley, Puebla	*Lemaireocereus weberi* (Cault.) Br. & Rose	Cardon	4536	.996	Native	1/75	2
Limestone hills	Sanderson Canyon, TX	*Leucophyllum candidum* I.M. Johnston	Chenizo	4659	.977	Native	10/75	4
Desert shrub, xerophytic	Ft. Stockton, TX	*Lycium Torreyi* Gray	Wolf berry	4316	.991	Native	11/74	2
Limestone hills	Sanderson Canyon, TX	*Mahonia trifoliata* (Moric.) Fedde	Agarito	4656	.984	Native	10/75	3
Desert grass	Ft. Stockton, TX	*Muhlenbergia Porteri* Scribn.	Bush muhly	4322	.979	Native	11/74	2
Desert grass	Van Horn, TX	*Muhlenbergia Porteri* Scribn.	Bush muhly	4329	.979	Native	11/74	3
Limestone hills	Sanderson, TX	*Nolina erumpens* (Torr.)	Bear-grass	4654	.979	Native	10/75	5
Desert grass-land	Marathon, TX	*Nolina texana* Wats.	Bunch-grass	4631	.985	Native	10/75	5
Prominent exposed cactus	Ft. Stockton, TX	*Opuntia phaeacantha* Engelm.	Prickly pear	4318	.977	Native	11/74	3
Desert grass-land	Chiati Mountains, TX	*Opuntia phaeacantha* Engelm.	Prickly pear	4616	.953	Native	10/75	3
Creosote hills	Plata, TX	*Opuntia violacea* Engelm.	Purple prickly pear	4612	.964	Native	10/75	2
Desert	Tehuacan Valley, Puebla	*Opuntia sp.*	Prickly pear	4535	.982	Native	1/75	2
Desert shrub often near water courses	Ft. Stockton, TX	*Prosopis glandulosa* Torr.	Mesquite	4315	.989	Native	11/74	3
Creosote hills	Plata, TX	*Prosopis glandulosa* Torr.	Mesquite	4611	.981	Native	10/75	3
Desert washes	Marathon, TX	*Prosopis glandulosa* Torr.	Mesquite	4629	.987	Native	10/75	5
High desert shrub	Canada Morelos, Puebla	*Quercus c.f. depressipes* Trel.	Encino	4539	.982	Native	1/75	2
Hot, seasonally dry low hills of Veracruz	Mirador near Huatusco, Veracruz	*Quercus oleoides* Schlect. & Cham.	Encino tesmole	4519	.979	Native	1/75	3
Hot, seasonally dry low hills of Veracruz	Mirador near Huatusco, Veracruz	*Quercus peduncularis* Nee	Encino	4527	.989	Native	1/75	2
Limestone hills	Sanderson Canyon, TX	*Rhus virens* Gray	Evergreen sumac	4660	.988	Native	10/75	4
Aggressive weed	Marathon, TX	*Salsola Kali* L.	Russian-thistle	4634	.995	Introduced	10/75	3
High desert tree	Canada Morelos, Puebla	*Schinus molle* L.	Pirul	4538	.965	Introduced	1/75	2

TABLE 3-1.— Continued.

Habitat/niche	Measurement site	Botanical name	Common name	Collection number	Emissivity	Native or cultivated	Date	Number of replications
				Desert				
Desert grass	Ft. Stockton, TX	*Scleropogon brevifolius* Phil.	Burro grass	4314	0.977	Native	11/74	3
Desert grass-land	Marathon, TX	*Setaria sp.*		4625	.980	Native	10/75	4
Agressive weddy herb	Fortin, Veracruz	*Sida rhombifolia* L.		4513	.988	Native	1/75	2
Roadside weed	Chiati Mountains, TX	*Sida sp.*		4617	.985	Native	10/75	3
Roadside weed	Chiati Mountains, TX	*Verbenaceae family*		4621	.971	Native	10/75	3
Agressive weed	Forin, Veracruz	*Verbesina turbacensis* H.B.K.		4512	.989	Native	1/75	2
Limestone hills	Sanderson Canyon, TX	*Yucca Thompsoniana* Trel.	Yucca	4657	.958	Native	10/75	3
Rosette form desert	Hot Springs, TX	*Yucca Torreyi* Shafer	Yucca	4605	.988	Native	10/75	3
				Pinon-Juniper				
Pinon-Juniper belt	Davis Mountains, TX	*Juniperus scopulorum* Sarg.	Rocky mountain juniper	4673	.991	Native	10/75	5
Pinon-Juniper belt	Davis Mountains, TX	*Pinus cembroides* Zuil.	Mexicon Pinon	4674	.986	Native	10/75	5
Pinon-Juniper belt	Davis Mountains, TX	*Pinus ponderosa* Laws.	Ponderosa pine	4675	.978	Native	10/75	5
Pinon-Juniper belt	Davis Mountains, TX	*Quercus arizonica* Sarg.	Arizona oak	4672	.977	Native	10/75	4
Pinon-Juniper belt	Davis Mountains, TX	*Quercus turbinella* Greene	Scrub oak	4676	.982	Native	1/75	2
				Mangrove				
Coastal estuaries	Coast of Veracruz	*Laguncularia racemosa* (L.) Gaetn. f.	Black-mangrove	4553	.962	Native	1/75	3
Coastal estuaries	Coast of Veracruz	*Rhizophora Mangle* L.	Red-mangrove	4552	.960	Native	1/75	2
				Montane rain forest				
Secondary succession in disturbed areas	Fortin, Veracruz	*Acacia sp.*	acacia	4506	.952	Native	1/75	3
Secondary succession in disturbed areas	Fortin, Veracruz	*Cecropia obtusifolia*	Cecropia	4509	.955	Native	1/75	2
Coffee cover crop	Mirador near Huatusco, Veracruz	*Inga sp.*	Inga	4507	.970	Cultivated	1/75	3
Coffee cover crop	Mirador near Hua-tusco, Veracruz	*Inga sp.*	Inga	4516	.943	Cultivated	1/75	2
Montane rain forest tree	Fortin, Veracruz	*Persea schiedeana* Nees		4511	.901	Native	1/75	3
Secondary growth shruby herb	Coscomatepec, Veracruz	*Pluchea odorata* (L.) Cass.		4547	.990	Native	1/75	2
Montane rain forest	Fortin, Veracruz	*Pothomorphe umbellata* (L.) Mig.		4510	.943	Native	1/75	2

TABLE 3-1.— Concluded.

Habitat/niche	Measurement site	Botanical name.	Common name	Collection number	Emissivity	Native or cultivated	Date	Number of replications
Temperate forest								
Mesophyte	Galveston County, TX	*Ilex vomitoria* Ait.	Yaupon	4335	0.981 .982	Native	12/74	2 1
Old field invador	League City, TX	*Juniperus virginiana* L.	Eastern red cedar	4336	.996	Native	12/74	4
Agressive understory	League City, TX	*Lonicera japonica* Thunb.	Japanese honeysuckle	4334	.981	Introduced	12/74	2
Wetland tree	Galveston County, TX	*Quercus nigra* L.	Water oak	4338	.987 .993	Native	12/74	2 1
Mesophytic tree, central and coastal TX	Galveston County, TX	*Quercus virginiana* Mill.	Live oak, upper area; Live oak, lower area	4333	.988	Native	12/74	3
Epiphyte	Galveston County, TX	*Tillandsia usneoides* (L.) L.	Spanish-moss	4337	.985	Native	12/74	2
Tropical deciduous forest								
Agressive weedy herb	Mirador near Hau-tusco, Veracruz	*Mangifera indica* L.	Mango	4518	.960	Cultivated	1/75	2
Fruit tree	Playa Carino, Veracruz	*Mangifera indica* L.	Mango	4557	.960	Cultivated	1/75	2
Palmar	Piedras Negras, Veracruz	*Sabal mexicana* Mart.	Sabal palm	4550	.962	Native	1/75	3
Woodland savanna								
Woodland savanna	Playa Carino, Veracruz	*Acacia sp.*	acacia	4551	.952	Native	1/75	2
Widespread in woodland savanna	Playa Carino, Veracruz	*Ceiba pentandra*	Kapok	4556	.966	Native	1/75	2
Hot, low wood-land savanna	Playa Carino, Veracruz	*Tabebuia rosea* (Bert.) D.C.	Tabebuia	4555	.942	Native	1/75	2

in temperature produced by shading the surface from the sun are smallest at these times. A high overcast also produces favorable conditions. Broken or low warm cloud conditions should be avoided whenever possible. However, rapid measurements and frequent replications generally produce usable results even under difficult conditions.

4. DISCUSSION

4.1 ANALYSIS OF DATA

The variability of the measured emissivity values was examined using analysis of variance techniques. Through a series of contrasts, the statistical significance of differences in emissivity between broad ecological groups was determined. The group studied and the number of observations available are given in Table 4-1. The difference between desert vegetation and all other types was clear. The hypothesis stating that the means of each ecological group were equal was strongly rejected. No significant differences were found between the two types of desert vegetation or among the four types of non-desert vegetation. However, it was found that the rain forest vegetation was significantly different from that of the temperate region. These comparisons may be seen in Table 4-2 along with a comparison of desert, rain forest, and temperate regions. This comparison showed significant differences among the group means. The means and standard deviations of each group may be seen in Table 4-3.

4.2 INTERPRETATION OF RESULTS

The results of the statistical analysis suggest the following ecologically important ideas.

As a means of avoiding excessive and possibly fatal absorption and retention of heat in the desert, desert plants reemit virtually all incoming radiation. This aids in keeping plant temperature at a viable level without benefit of the common evapotranspiration mechanisms available to more mesic plants.

Temperate region plants face less of a heat stress problem than desert plants, yet their leaf temperatures must be kept within a range consistent with their metabolic requirements. In the temperate areas of the U.S. where these plants were studied, a moisture stress develops in the late summer when temperatures are highest but soil moisture levels are low. An adaptive advantage can be speculated for plants that can increase their heat reduction during warm dry periods without increasing their evapotranspirational losses.

TABLE 4-1.— MAJOR ECOLOGICAL GROUPS EXAMINED FOR VARIATION IN EMISSIVITY

Group	Number of observations
Dry desert	61
Humid desert	15
Montane rain forest	11
Salt water aquatic	2
Deciduous rain forest	10
Temperate region	11

TABLE 4-2.— PRINCIPAL CONTRASTS OF THE ECOLOGICAL GROUPS

Contrast	F-test	Degrees of freedom	Significance
Desert versus all others	21.7	1,108	Highly significant
Dry versus humid desert	.4	1,74	Not significant
Montane rain forest versus aquatic versus deciduous rain forest versus temperate region	1.7	3,30	Not significant
Deciduous rain forest versus temperate region	5.3	1,30	Significant at the 5-percent level
Desert versus rain forest versus temperate region	16.1	2,105	Significant at the 1-percent level

TABLE 4-3.— MEANS AND STANDARD DEVIATIONS OF EMISSIVITY FOR THREE VEGETATIONAL GROUPS

Group	Emissivity	Standard deviation
Desert	0.981	0.011
Rain forest	.962	.020
Temperate region	.977	.012

In the two tropical groups studied, the montane rain forest and tropical deciduous forest, abundant moisture occurs during the growing season. There is no shortage of moisture needed in cooling. In the cooler dry season, the deciduous forest is dormant and leafless while the montane rain forest has a lesser but still sufficient amount of moisture to meet its needs.

4.3 CONCLUSIONS

It appears from this work that there is some physiological adaptation in plants to their radiational environment. The data and analyses presented suggest that on a community-wide level, plants of the desert, tropics, and temperate regions have each adapted to deal with specific and characteristic radiation levels found in each area.

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