Estimation of Potential Evapotranspiration from NOAA-AVHRR Satellite

B. Narasimhan, R. Srinivasan, A. D. Whittaker

Abstract

Potential evapotranspiration is widely used by farmers and hydrologists as a measure for determining actual evapotranspiration for irrigation scheduling, drought monitoring, hydrologic modeling and regional water balance studies. In the present study a comprehensive methodology has been developed for estimating reference crop (Grass) ET using Penman-Monteith combination equation from Advanced Very High Resolution Radiometer (AVHRR) for Texas at a spatial resolution of 1km^2. As part of this study 282 NOAA-14, AVHRR satellite images acquired between May 1999 to August 2000 and weather data measured at several weather stations across Texas were analyzed. Regression relationships were developed to calculate the weather parameters maximum air temperature and vapour pressure deficit from satellite's infrared surface temperature. The regression relationships were validated using independent weather station observations. The root mean square error (RMSE) of daily ET calculated using these weather parameter estimates was within ±1.1 mm day^{-1} when compared to ET derived from ground based weather station measurements of climatic variables.

Keywords. Evapotranspiration, AVHRR, Remote sensing, Penman-Monteith, Energy balance, Surface temperature.

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Introduction

Evapotranspiration (ET) is defined as the combined loss of water by evaporation from soil and transpiration from plants. Depending on the geographic location, 60-80% of total annual precipitation is lost in the form of evapotranspiration. Since ET accounts for a major portion of water lost to the atmosphere, accurate estimation of ET is essential for the success of hydrologic modeling studies, water resources planning and drought monitoring. Potential evapotranspiration is widely used as a reference level from which actual evapotranspiration is determined using soil and other crop specific coefficients. Penman-Monteith Combination equation is universally accepted as an accurate method to estimate potential ET (or reference crop ET) (Allen et al., 1998). Potential ET by Penman-Monteith method is estimated using climatic data such as net radiation, air temperature, wind velocity, vapor pressure deficit and relative humidity obtained from the nearest weather stations. However, few weather stations measure all the parameters needed for estimating ET by Penman-Monteith method. In the absence of a dense network of weather stations, interpolating weather data to determine ET across a large area spanning different climatic divisions could introduce errors of large magnitude.

During the last two decades, Geographical Information System (GIS) and Remote Sensing have evolved as an indispensable tool for monitoring natural resources. Due to the availability of spatially distributed data from satellites, and adopting GIS principles, accurate determination of regional ET is possible. The present study aims at deriving reference crop ET across Texas using data obtained from NOAA-AVHRR satellite. Advanced Very High Resolution Radiometer (AVHRR) is a sensor aboard NOAA series of Polar Operational Environmental Satellites (POES), sensing in the visible (Channel 1), near-infrared (Channel 2) and thermal infrared portions (Channel 3, Channel 4 and Channel 5) of the electromagnetic spectrum. The main purpose of NOAA-AVHRR satellite is to forecast weather and monitor regional climatic conditions. As part of this study 282 NOAA-14, AVHRR satellite images acquired between May 1999 to August 2000 and weather data measured at several weather stations across Texas were analyzed for developing a comprehensive methodology for estimating reference crop ET across Texas using Penman-Monteith model.

Vertical Energy Budget Model

During the past decade, the estimation of ET from satellite data has been widely studied by researchers across the globe (Price 1982; Moran and Jackson 1991; Seguin et al. 1994; Granger 1995; Tan and Shih 1997; Bastiaanssen et al. 1998). The conventional vertical energy balance model involving sensible heat flux, latent heat flux and soil heat flux is used for estimating ET from satellite. The vertical energy budget equation can be written as (Jensen et al., 1990):

$$R_n = \lambda ET + H + G \tag{1}$$

Where:

R_n - net radiation flux at the surface [MJ m^{-2} day^{-1}],

λET - latent heat flux [MJ m^{-2} day^{-1}],

λ - latent heat of vaporization [MJ kg^{-1}],

ET - evapotranspiration [mm day^{-1}],

H - sensible heat flux to the air [MJ m^{-2} day^{-1}],

G - soil heat flux to the soil [MJ m^{-2} day^{-1}].

The sensible heat flux to the air is given by (Jensen et al., 1990):

$$H = \frac{\rho_a C_p}{r_a} U_2 (T_s - T_a) \tag{2}$$

Where:

ρ_a - density of the air [kg m^{-3}],

C_p - specific heat of the air at constant pressure [MJ kg^{-1} $°C^{-1}$],

r_a - aerodynamic resistance [s m^{-1}],

U_2 - wind speed at a height 2m [m s^{-1}],

T_s - surface temperature [°C],

T_a - mean air Temperature [°C].

Seguin et al. (1994) conducted field experiments in France, the Sahel and North Africa and found that ($ET - R_n$) and ($T_s - T_a$) are linearly related. Hence, Seguin et al. (1994) proposed a regression methodology to estimate ET from this linear relationship. Tan and Shih (1997) also adopted a similar procedure for estimating ET in South Florida. The main drawback of this approach is that it does not account for the wind velocity and hence it is applicable only to humid regions characterized by less sensible heat flux (less wind speed) than the latent heat flux. Texas is characterized by a humid climatic zone in the east, sub-humid/arid climatic zone at the center and a dry arid zone in the west (Fig. 1). Hence a different approach that can better quantify the sensible heat flux needs to be developed.

Bastiaannssen et al. (1998) developed the Surface Energy Balance Algorithm (SEBAL) for estimating evapotranspiration across composite terrain. SEBAL uses the surface albedo, vegetation index, and infrared surface temperature (T_s) to parameterize the land surface for surface energy balance calculations. The model is based on the assumption that the satellite measured infrared surface temperature (T_s) is equal to the true aerodynamic surface temperature (T_0). Hence, the accuracy of this energy balance approach relies on how closely the satellite derived infrared surface temperature (T_s) approximates the true aerodynamic surface temperature (T_0). A field scale study by Alves et al. (2000) showed that for dry arid conditions, the infrared surface temperature T_s can greatly depart from the true aerodynamic temperature (T_0), due to which, stability corrections cannot be performed accurately on the aerodynamic resistance. This could introduce considerable errors in estimating sensible heat flux.

Further, even though the satellite data provide a distributed spatial coverage over several land use/land cover types, only certain crop specific parameters can be estimated from the satellite data (e.g. Albedo used for estimating net radiation). However, parameters like aerodynamic resistance and the surface resistance that depend on crop height, growth cycle and the stomatal characteristics cannot be estimated from satellite data for all land-use/land-cover types. Although some exponential type relationship between Normalized Difference Vegetation Index (NDVI) versus roughness length (aerodynamic resistance) (Moran and Jackson, 1991) and T_s/NDVI Vs surface resistance (Nemani and Running, 1989) have been suggested for few land cover types, without further field scale studies the results cannot be applied for wide variety of land cover classes for deriving regional ET. Due to difficulty in obtaining crop specific parameters for various land-use/land-cover types on a regional scale, there is a need to develop a methodology to determine reference crop ET from the satellite data. Hence, the objective of the present study is:

1. To develop a methodology to determine the reference crop ET (Grass) using Penman-Monteith model in all regions and climates of Texas with minimal ground based weather data inputs.

2. To develop a relationship between the satellite data and the weather parameters needed in the calculation of reference crop ET by Penman-Monteith model.

Penman-Monteith Model

Penman (1948) proposed that for continued evaporation two conditions must be met:

1. an energy source to sustain evaporation and
2. a mechanism to remove the water vapor (sink strength or mass transfer).

Based on these conditions Penman (1948) derived a combination equation (Energy balance and mass transfer) for estimating evapotranspiration. Later, Monteith (1981) included a surface resistance function in addition to the aerodynamic resistance function in the original Penman combination equation. Penman-Monteith combination equation describes adequately the evapotranspiration process from a vegetated surface. Jensen et al. (1990) compared 20 different methods of estimating ET and found that Penman-monteith combination equation provided the most accurate estimate of reference crop ET. The Penman-Monteith combination equation is given by (Allen et al., 1998):

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \tag{3}$$

where:

r_a - aerodynamic resistance [s m^{-1}],

r_s - surface resistance [s m^{-1}],

e_s - saturation vapour pressure [kPa],

e_a - actual vapour pressure [kPa],

e_s-e_a - vapour pressure deficit [kPa],

Δ - slope of vapour pressure curve [kPa $°C^{-1}$],

γ - psychrometric constant [kPa °C^{-1}].

The concept of reference crop evapotranspiration was introduced because of the lack of appropriate measures of parameters (mainly surface resistance and aerodynamic resistance) for various crop types and for different growth stages of the crop (Allen et al., 1998). Crop coefficients derived from field measurements and lysimeter measurement for specific crops at different growth stages are then used to convert the reference crop ET into a crop specific ET. More field scale experiments are needed at this stage to derive all these crop specific parameters from the satellite data. Hence, in this study the grass reference ET will be derived using parameters specific to a well watered grass covered surface. For deriving grass reference ET, the characteristics suggested by Allen et al. (1998) are, a crop height of 0.12m to derive aerodynamic resistance ($r_a = 208/U_2$), a fixed surface resistance (r_s) of 70 s m^{-1}and an albedo of 0.23 to derive net radiation. After substituting the above parameter values for grass reference in eq.3, the Penman-Monteith combination equation for grass reference ET can be written as (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{(T_a + 273)} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (4)$$

where:

ET_0 - grass reference evapotranspiration [mm day^{-1}],

T_a - air temperature [°C],

U_2 - wind speed at 2m height [m s^{-1}].

The weather parameters like air temperature and vapour pressure deficit cannot be readily derived from the satellite data. Hence these weather parameters needed to be estimated by developing relationships between satellite data and weather station observations. In this study, data from 282 satellite images from NOAA-14 satellite were acquired between May 1999 and August 2000 and pre-processed using the algorithm developed by Chen et al (2001). During the same time period data from 57 ground based weather stations that measures air temperatures and 16 weather stations that measures the parameters needed for estimating ET by Penman-Monteith were acquired (Fig.1). The methodology developed to estimate weather parameters from the satellite data is described in the following section.

Methodology for estimating weather parameters

Infrared Surface Temperature (T_s)

Infrared surface temperature is measured by AVHRR satellites in two channels, channel 4 (10.3 – 11.3 μm) and channel 5 (11.5 – 12.5 μm). Infrared radiation sensed by AVHRR satellites is influenced by atmospheric absorption by water vapor and other gases (principally CO_2). These make it difficult to accurately predict the surface temperature. Split window algorithms take advantage of the differential absorption in two close infrared bands to account for the effects of absorption by atmospheric gases. Several split window algorithms are currently available to derive infrared surface temperature (T_s) from brightness temperature [Becker and Li (1990); Kerr et al. (1992); and Price (1984); Ulivieri et al. (1992)]. A study conducted by Vázquez et al. (1997) showed that the split widow algorithm developed by Ulivieri et al. (1992) performed better than other split window algorithms. The split window algorithm developed by Ulivieri et al. (1992) is given by:

$$T_S = T_4 + 3.33(T_4 - T_5) + 48(1-\varepsilon) - 75\Delta\varepsilon \qquad (5)$$

where:

T_s = Infrared Surface Temperature [°C],

T_4 = Brightness temperature obtained from Channel 4 [°C],

T_5 = Brightness temperature obtained from Channel 5 [°C],

ϵ_4 = Surface emissivity in AVHRR channel 4,

ϵ_5 = Surface emissivity in AVHRR channel 5.

ϵ = $(\epsilon_4 + \epsilon_5)/2$

$\Delta\varepsilon$ = $\epsilon_4 - \epsilon_5$.

Subsequently, infrared surface temperature derived by using the split window algorithm (eq.5) is used in this study to derive other weather parameters needed for the estimating ET by Penman-Monteith method.

Air Temperature (T_a)

Air temperature is one of the important parameters for estimating ET by Penman-Monteith equation. Analysis of infrared surface temperature data and the maximum air temperature measured at 57 weather stations across Texas showed that there is a strong linear relationship between T_s and the maximum air temperature. This is because the satellites afternoon overpass time between 3:00 - 5:00 PM coincides with the occurrence of the maximum air temperature of the day. Hence, a simple linear regression approach has been adopted for deriving T_a from T_s. However, this linear relationship varied spatially among weather stations located across the ten climatic divisions of Texas. Fig.2 shows such a variation between climatic divisions 4 and 5. Hence long-term monthly maximum air temperature (T_{lm}) obtained from 30 years of historical weather data was incorporated into the regression model to account for spatial variation in the relationship among weather stations. Incorporation of T_{lm} in the regression model reduced the spatial variation in the relationship among weather stations within a given climatic division. Since there are ten climatic divisions in Texas, one such regression model has been developed for each of the ten climatic divisions. The regression model adopted in the study is of the form:

$$\hat{T}_a(i) = m(i)\sqrt{T_s \times T_{lm}} + C(i) \qquad (7)$$

Where:

$\hat{T}_a(i)$ - estimated daily maximum air temperature for climatic division i,

T_s - infrared surface temperature [°C],

T_{lm} - long-term monthly maximum air temperature [°C],

m(i) and C(i) are regression constants for climatic division i (where i = 1,.....10).

In this study the daily maximum air temperature (September, 1999 to August, 2000) from 57 weather stations (Fig.1) distributed across Texas were available for model development and validation. Daily maximum air temperature from 27 weather stations were used for model development and data from 30 weather stations were used for model validation. The regression coefficients used in eq. 7 to derive T_a from T_s for each of the 10 climatic divisions of Texas are given in Table 1. Comparison of model estimated $\hat{T}_a$ with that of the measured T_a (Fig. 3) show that the model estimated air temperatures are in good agreement with the measured air temperature (r^2 = 0.79). Since T_s is just a one time measurement in a day taken during the afternoon overpass, the air temperature derived from it is used as an estimate of mean air temperature in eq.4 for deriving ET.

Vapour Pressure Deficit (e_s - e_a)

The mean daily vapour pressure deficit is calculated as a difference between the mean saturated vapour pressure (e_s) and the mean actual vapor pressure (e_a). Granger (1995) through field scale experiments demonstrated the existence of a linear relationship between vapour pressure deficit and the saturated vapour pressure at surface temperature T_s. In the present study comparison of saturated vapour pressure at T_s from satellite data with that of vapour pressure deficit measured at weather stations across Texas also showed a strong linear correlation. The vapour pressure deficit measured at 16 weather stations (Fig.1) across Texas between (May 1999 to April 2000) were available for model development and validation. Daily vapour pressure deficit measured at 7 of those weather stations was used for model development (Fig. 4). The saturated vapour pressure at surface temperature (T_s) is calculated as (Allen et al., 1998):

$$e_S(T_S) = 0.6108 \exp\left[\frac{17.27 T_S}{T_S + 273}\right] \tag{8}$$

Where:

$e_s(T_s)$ - saturated vapour pressure [kpa] at the infrared surface temperature T_s [°C]

The regression relationship developed to estimate mean daily vapour pressure deficit from saturated vapour pressure at surface temperature T_s is given in Fig.4:

$$e_S - e_a = 0.2264 e_S(T_S) + 0.2579 \tag{9}$$

The mean daily vapour pressure deficit measured at the 9 other weather stations were used for model validation. The saturated vapour pressure deficits estimated from AVHRR satellite compared reasonably well with the measured vapour pressure deficits (Fig.5).

Net Radiation (R_n)

The net radiation is the amount of energy available in a given day after accounting for the energy absorbed, reflected and emitted by the earth surface, calculated as a difference between the net short wave radiation and the net long wave radiation and is given by:

$$R_n = R_S(1-\alpha) + \varepsilon(R_l - \sigma T_S{}^4) \tag{10}$$

where:

R_s - incoming shortwave radiation [MJ m^{-2} day^{-1}],

α - albedo (0.23 for grass),

ϵ - surface emissivity (0.97 for grass),

R_l - incoming long-wave radiation [MJ m^{-2} day^{-1}],

σ - Stefan-Boltzmann constant [4.90×10^{-9} MJ m^{-2} d^{-1} K^{-4}],

T_s - surface temperature in [K].

Incoming short wave radiation for a clear sky is estimated using the equations suggested by Allen et al. (1998). Cloud cover is assumed to be zero when there is a valid satellite. The algorithm developed by Swinbank (1963) was used to calculate the incoming long-wave radiation from the air temperature. Net radiation calculated from the satellite's surface temperature and the maximum air temperature compared well with the estimates from 16 ground based weather stations (Fig.6).

Wind Velocity (U_2)

Wind velocity is one of the important and a highly variable parameter that drives the sensible heat flux component of the evapotranspiration process, especially in the arid and the semiarid regions more than in the humid regions. At present no technique exists to estimate wind velocity from the satellite data. Hence, in the present study, the daily mean wind velocity measured at 16 weather stations across Texas was interpolated using a spline interpolator for calculating ET from the satellite data. Spline interpolator fits a minimum-curvature surface through the input points.

Results and Discussion

The methodologies described in the previous sections were adopted in this study for deriving various weather parameters needed for calculating grass-reference ET by Penman-Monteith method (eq.4). In order to test the applicability of the developed methodology all throughout the year, 282 NOAA-14 satellite images acquired between May 1999 to August 2000 were used for estimating daily crop reference ET across Texas (Fig.7). For this study, all the weather parameters needed to estimate daily crop reference ET were obtained from 16 ground based weather stations located across Texas (Fig.1). The daily ET estimated from ground based weather stations were compared with the daily ET calculated from the AVHRR satellite data (Fig.8). The statistical analysis showed, that the developed methodology was able to estimate crop reference ET with a RMSE of ±1.1mm day^{-1} (R^2 = 0.64). This is sufficient to give reliable information regarding the condition of regional water stress on the crops and the amount of moisture needed to meet this stress. When the daily ET values where accumulated over larger time steps of 10 days and 30 days, the variability in the ET values reduced and the performance of the methodology considerably improved with an R^2 = 0.68 and 0.74 respectively (Fig. 9 and 10).

There are several reasons that can be attributed to the variability observed in the results.

1. The ET values derived from satellite are based on just one time of the day observation obtained from the satellite's afternoon over pass. However, the ET values, obtained from ground stations are based on mean values of weather observations taken through out the day. This will be an inherent limitation if one uses any POES (Polar Operational Environmental Satellites) for deriving ET. This problem can be overcome by the use of data from GOES (Geostationary Operational Environmental Satellites) which looks at a portion of earth constantly. However, there is a trade-off in the spatial resolution of the data one can obtain from GOES ($\approx 4km^2$) when compared to POES ($\approx 1km^2$).

2. The ET values obtained from weather stations are point observations. However, the ET values obtained from satellite are based on the data collected by the satellite from a $1km^2$ area. Hence, the variability in ET could be caused partially by the difference in the spatial scale at which the observations are made.

3. Cloud cover during part of the day is another major factor that could contribute to the variability in ET estimates. Net radiation is an important climatic factor that is affected by the

cloud cover. However, it is not possible to account for cloud cover condition from satellite data based on only one observation in a day.

Conclusions

Potential ET is an important parameter in hydrological modeling studies and serves as a reference tool to estimate actual evaporation. Penman-Monteith combination equation takes into account important physiological variables that affect crop evapotranspiration and provides a comprehensive frame work to compute potential ET. Hence a comprehensive approach adopting the Penman-Monteith combination equation has been developed in this study to estimate grass reference ET. By adopting the proposed methodology daily reference crop ET was calculated within an average error range of ±1.1mm day^{-1} at a spatial resolution of $1km^2$.

Even though there are several factors, that need detailed study, the estimation of ET from satellite data across varying climatic zones is promising. However, more field scale studies need to be conducted before the results can be applied at a smaller scale. The future studies should be backed by field scale experiments, on deriving aerodynamic resistance and stomatal resistance factors for major landuse/landcover types from satellite observation like T_s and NDVI. Once such relationships are established for major crops and land cover types, then the satellite data can be used to derive crop specific ET.

The ET estimates obtained from the satellite data could be used on a near real-time basis for irrigation scheduling, water resources planning and allocation, and drought monitoring. With the help of potential end users like irrigation districts and state agencies, projects are underway at the Rio Grande river basin to demonstrate the use of remotely sensed evapotranspiration data with the hydrologic model Soil and Water Assessment Tools (SWAT) (Arnold et al. 1998; Srinivasan et al. 1998) for managing agricultural systems and water resources planning.

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References

Allen R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. *Crop Evapotranspiration: Guidelines for computing crop water requirements.* FAO Irrigation and Drainage Paper No.56. FAO, Rome, Italy. 300pp.

Alves, I., J. C. Fontes, and L. S. Pereira. 2000. Evapotranspiration estimation from infrared surface temperature. I: The performance of the flux equation. *Transactions of the ASAE* 43(3): 591-598.

Arnold, J.G., R. Srinivasan, T.S. Ramanarayanan, J. Williams. 1998. Large area hydrologic modeling and assessment: Part I - model development. *Journal of the American Water Resources Association.* Vol. 34(1), pp. 73-90.

Bastiaanssen, W. G. M., M. Menenti, R. A. Feddes, and A. A. M. Holtslag. 1998. A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. *Journal of Hydrology* 212-213: 198-212.

Becker, F., and Z. L. Li. 1990. Towards a local split window method over land surface. *International Journal of Remote Sensing* 3:369-393.

Chen, P. Y., R. Srinivasan, G. Fedosejevs, and B. Narasimhan. 2001 (Accepted). An automated cloud detection method for daily NOAA-14 AVHRR data for Texas, U.S.A. *International Journal of Remote Sensing.*

Granger, R.J. 1995. A feedback Approach for the estimate of evapotranspiration using remotely-sensed data. In *Application of Remote Sensing in Hydrology*, 211-222. G. W. Kite, A. Pietroniro and T. J. Pultz, eds. Proceedings of the Second International Workshop, NHRI Symposium No. 14, Saskatoon, October 18-20,1994.

Jensen, M. E., R. D. Bruman, and R. G. Allen. 1990. Evapotranspiration and Irrigation Water Requirements. ASCE manuals and Reports on Engineering Practice No. 70. ASCE, New York, 332pp.

Kerr, Y. H., J. P. Lagouarde, and J. Imbernon. 1992. Accurate land surface temperature retrieval from AVHRR data with use of an improved split window. *Remote Sensing and Environment.* 41: 197-209.

Monteith, J. L. 1981. Evaporation and surface temperature. *Quarterly Journal of Royal Meteorological Society* 107: 1-27.

Moran, M.S., and R. D. Jackson. 1991. Assessing the spatial distribution of evapotranspiration using remotely sensed inputs. *Journal of Environmental Quality* 20(4):725-737.

Nemani, R. R., and S. W. Running. 1989. Estimation of regional surface resistance to evapotranspiration from NDVI and thermal-IR AVHRR data. *Journal of applied meteorology* 29: 276-284.

Penman, H. L. 1948. Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc. London,* A 193: 120-146.

Price, J. C. 1982. Estimation of regional scale evapotranspiration through analysis of satellite thermal-infrared data. *IEEE Transactions on Geoscience and Remote Sensing* GE-20(3):286-292.

Price, J. C. 1984. Land Surface Temperature measurements from the split window channels of the NOAA 7 Advanced Very High Resolution Radiometer. *Journal of Geophysical Research.* 89: 7231 – 7237.

Seguin.B, D. Courault, and M.Guérif. 1994. Surface Temperature and Evapotranspiration: Application of Local Scale Methods to Regional Scales Using Satellite Date. *Remote Sensing and Environment.* 49(3):287-295.

Srinivasan, R., T.S. Ramanarayanan, J.G. Arnold, and S.T. Bednarz. 1998. Large area hydrologic modeling and assessment: Part II - model application. *Journal of the American Water Resources Association.*Vol. 34(1), pp. 91-102.

Swinbank, W. C. 1963. Long-wave radiation from clear skies. *Quarterly Journal of Royal Meteorological Society.* 89:339-348.

Tan, C. H. and S. F. Shih. 1997. Using NOAA Satellite Thermal Infrared Data for Evapotranspiration Estimation in South Florida. *Soil Crop Science Society, Florida Proceedings,* 56: 109 – 113.

Ulivieri, C., M. M. Castronouvo, R. Francioni, and A. Cardillo. 1992. A Split-window algorithm for estimating land surface temperature from Satellites. *Advances in Space Research.* 14(3): 59-65.

Vázquez, D. P., F. J. Olmo Reyes and L. A. Arboledas. 1997. A comparative study of algorithms for estimating land surface temperature from AVHRR data. *Remote sensing and Environment.* 62: 215-222.

Table 1. Regression coefficients used for deriving T_a from T_s[1]

Climatic division	m(i)	C(i)	R^2
1	0.78	5.04	0.74
2	0.88	3.46	0.80
3	0.86	4.73	0.81
4	0.9	4.82	0.83
5	0.82	2.72	0.75
6	0.86	4.12	0.78
7	0.75	7.47	0.72
8	0.86	5.31	0.78
9	0.81	5.99	0.71
10	0.81	6.55	0.75

[1] $\hat{T}_a(i) = m(i)\sqrt{T_S \times T_{lm}} + C(i)$

Where:

$\hat{T}_a(i)$ - estimated daily maximum air temperature for climatic zone i,

T_s - infrared surface temperature [°C],

T_{lm} - long-term monthly maximum air temperature [°C],

m(i) and C(i) are regression constants for climatic division i (where i = 1,.....10).

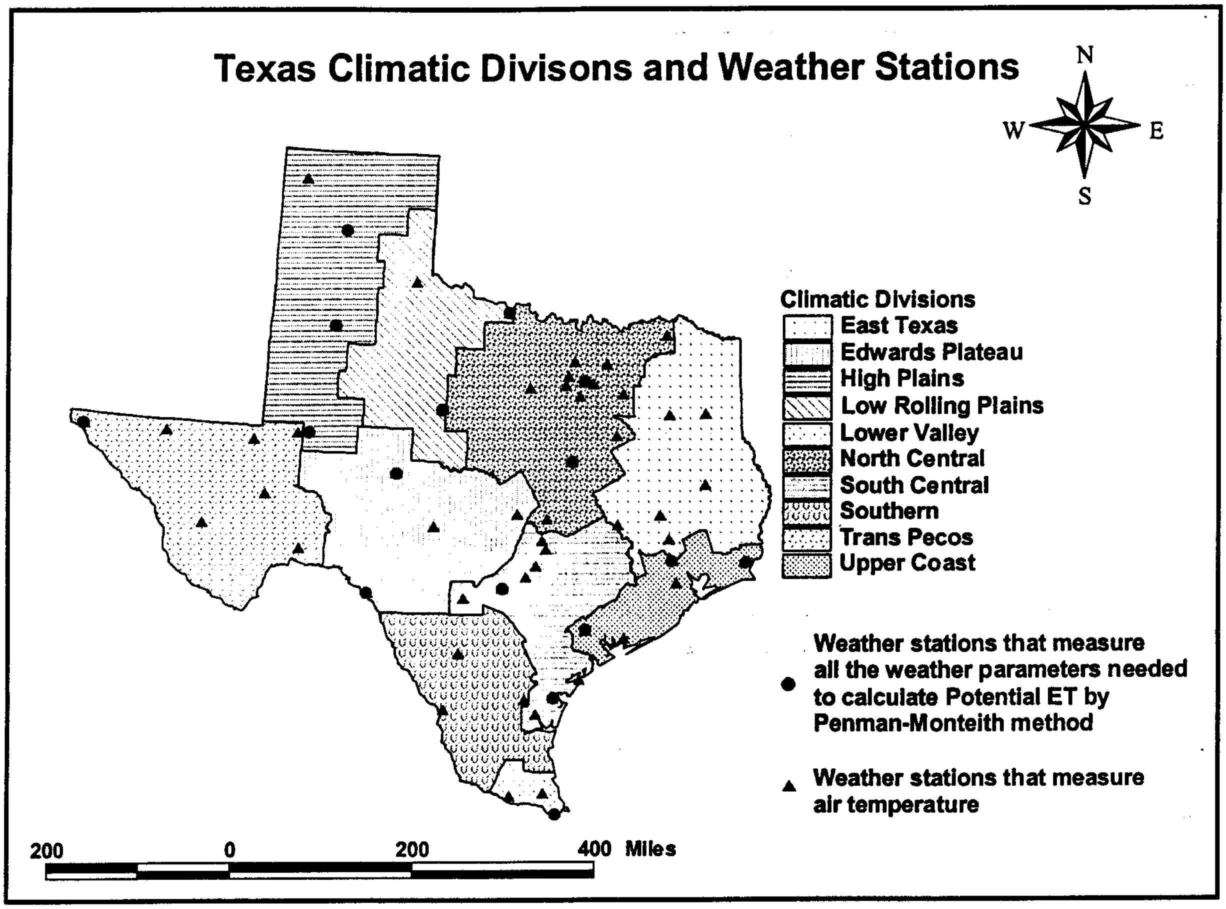

Figure 1. Climatic divisions of Texas and the weather stations used for model development and validation.

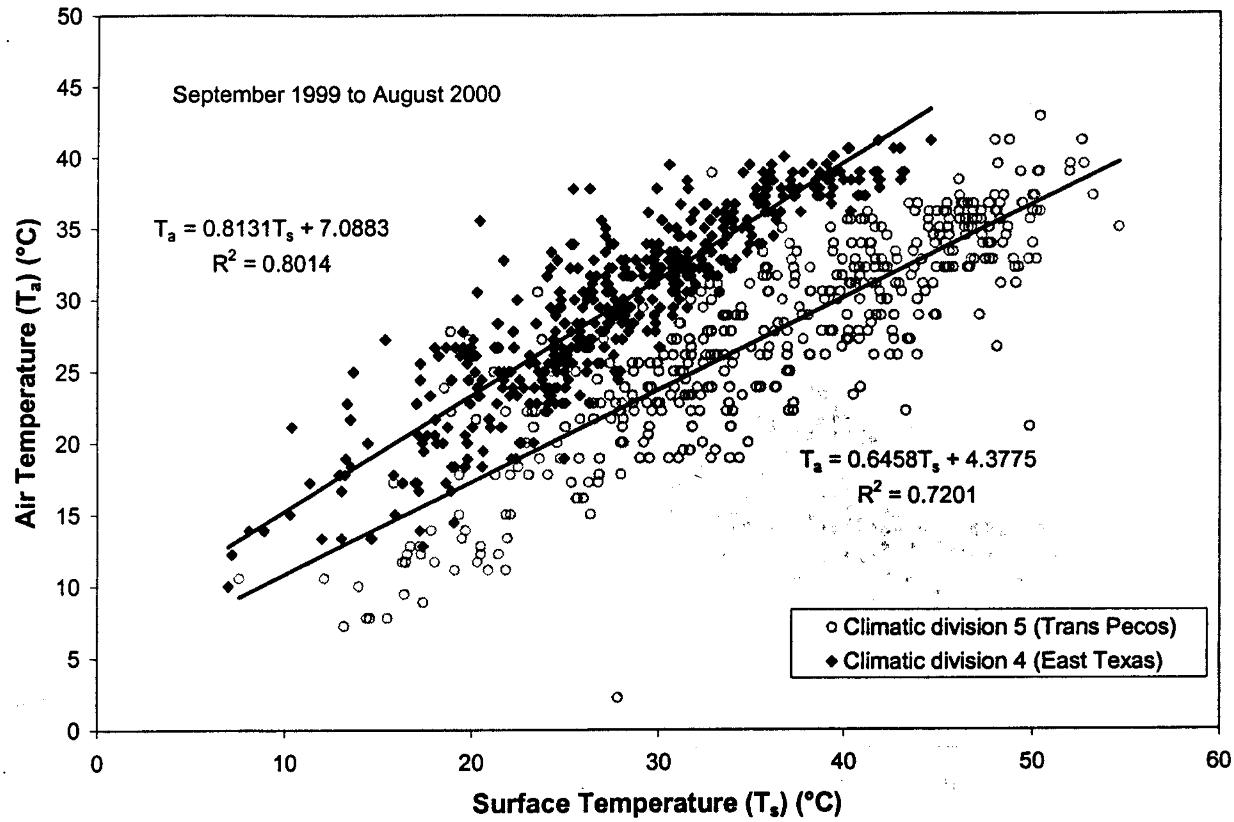

Figure 2. Difference in linear relationship between T_s and T_a among weather stations located in two climatic divisions (4 & 5) in east and west Texas.

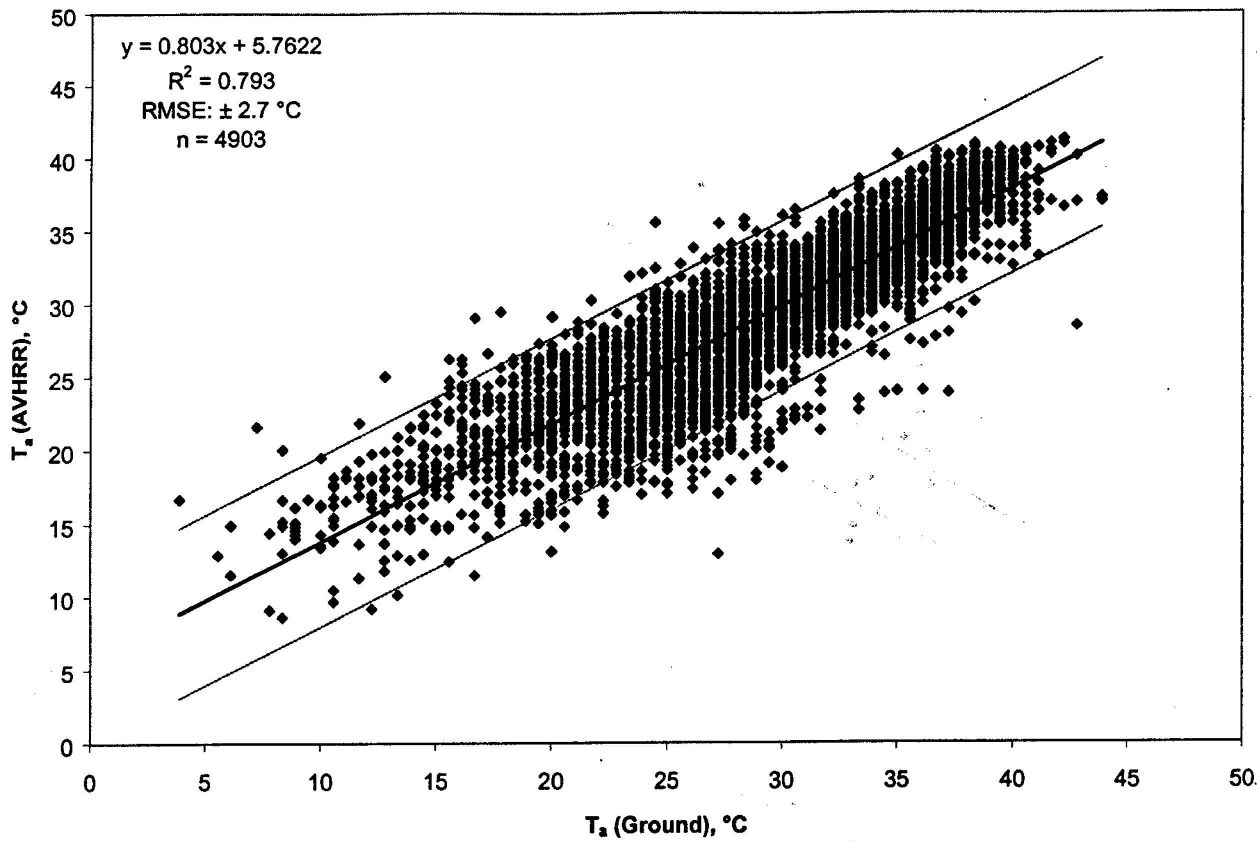

Figure 3. Validation of maximum air temperature estimated from AVHRR using the regression model (eq. 7) with the air temperature measured from 30 weather stations along with the 95% confidence limits.

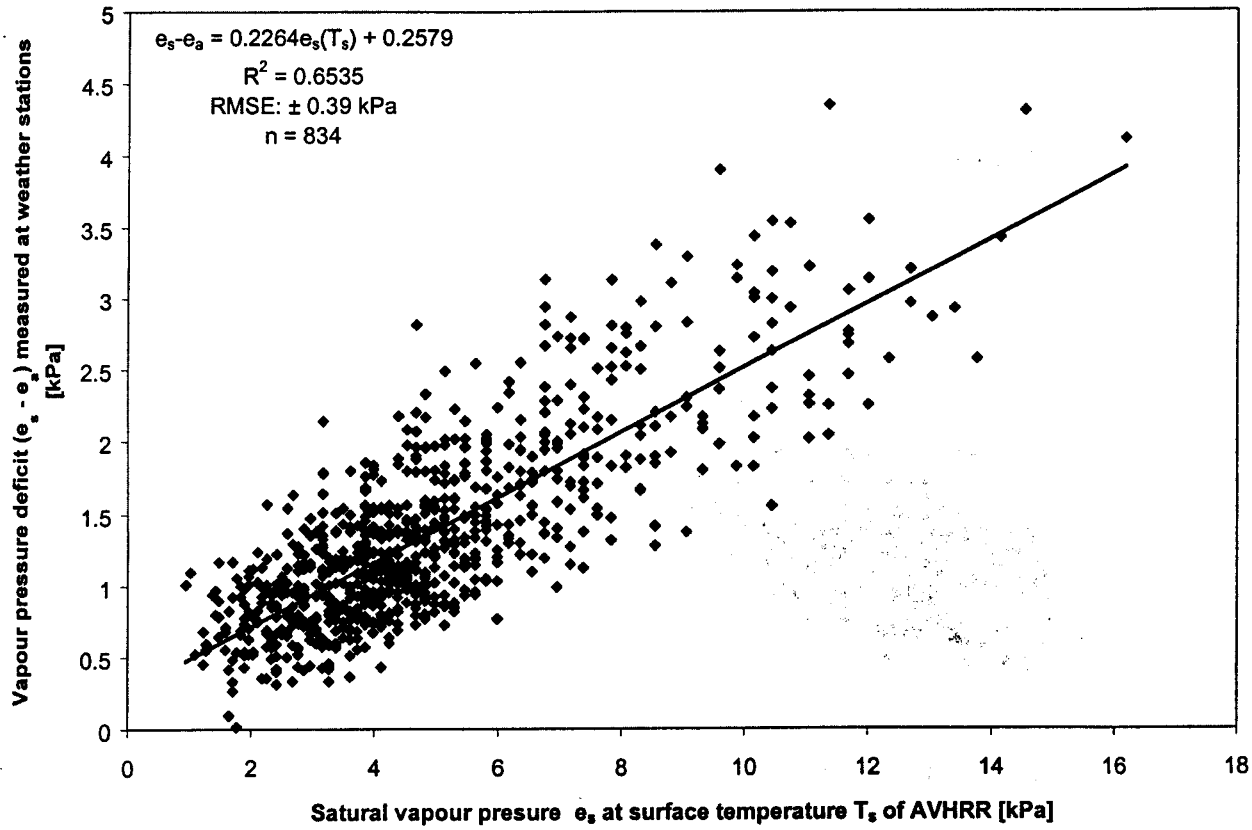

Figure 4. Linear regression relationship between saturated vapour pressure estimated at T_s and measured vapour pressure deficit at 6 weather stations.

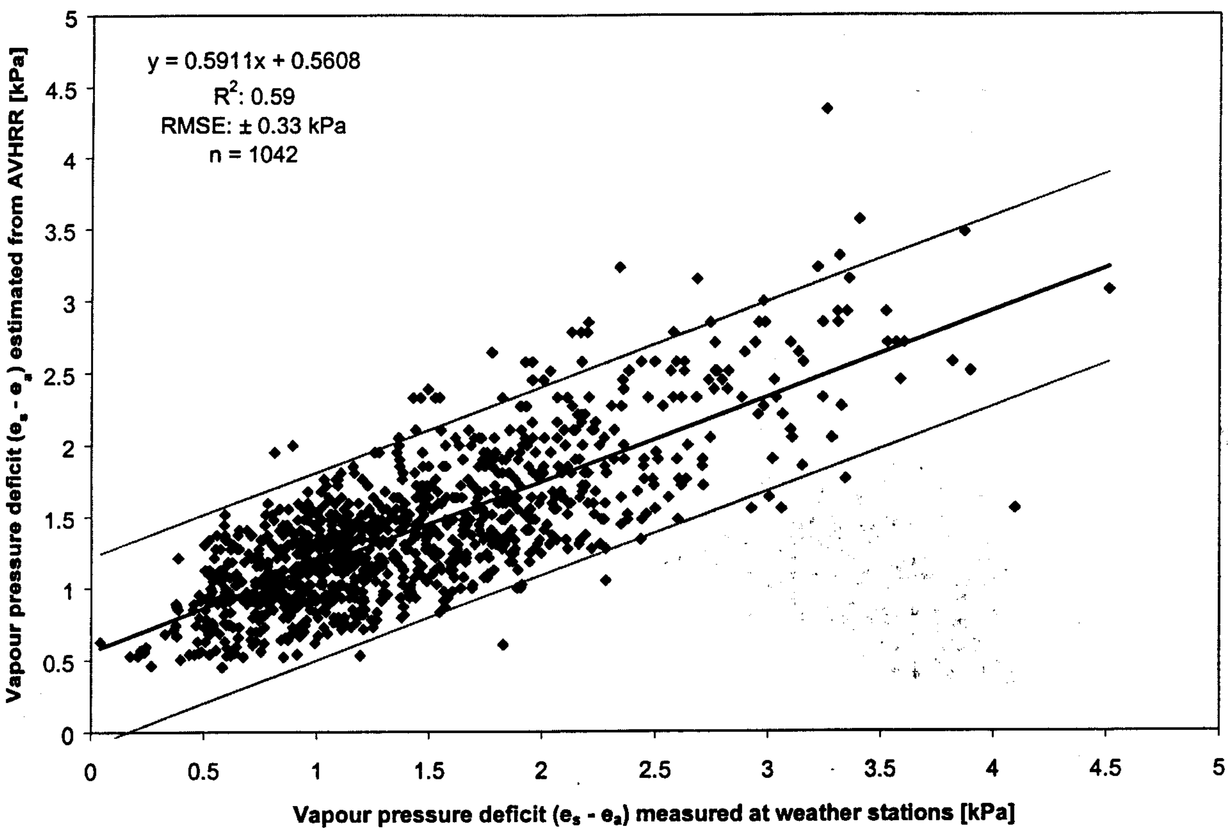

Figure 5. Validation of vapour pressure deficit estimated from AVHRR using the regression model (eq. 9) with the vapour pressure deficit measured at 9 weather stations along with the 95% confidence limits.

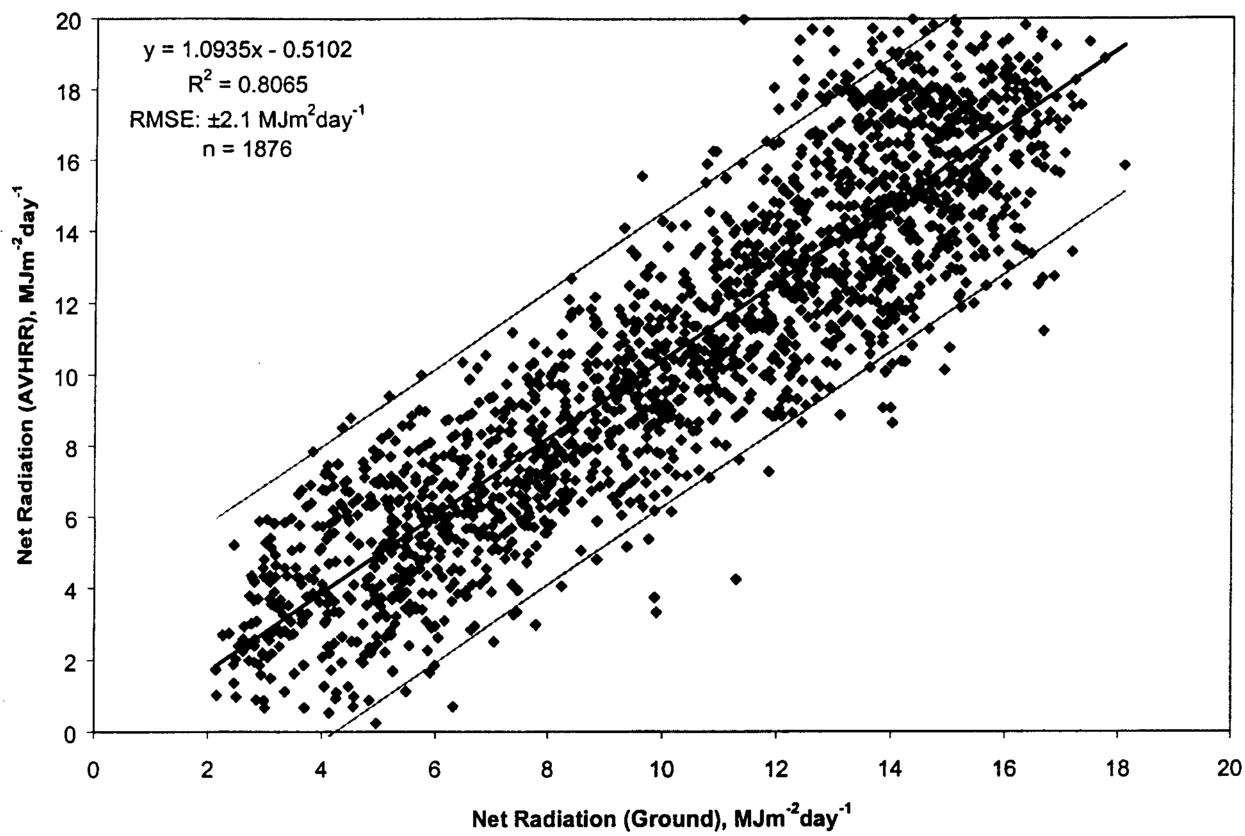

Figure 6. Net radiation measured in ground at 16 weather stations with that of net radiation estimated from AVHRR along with the 95% confidence limits.

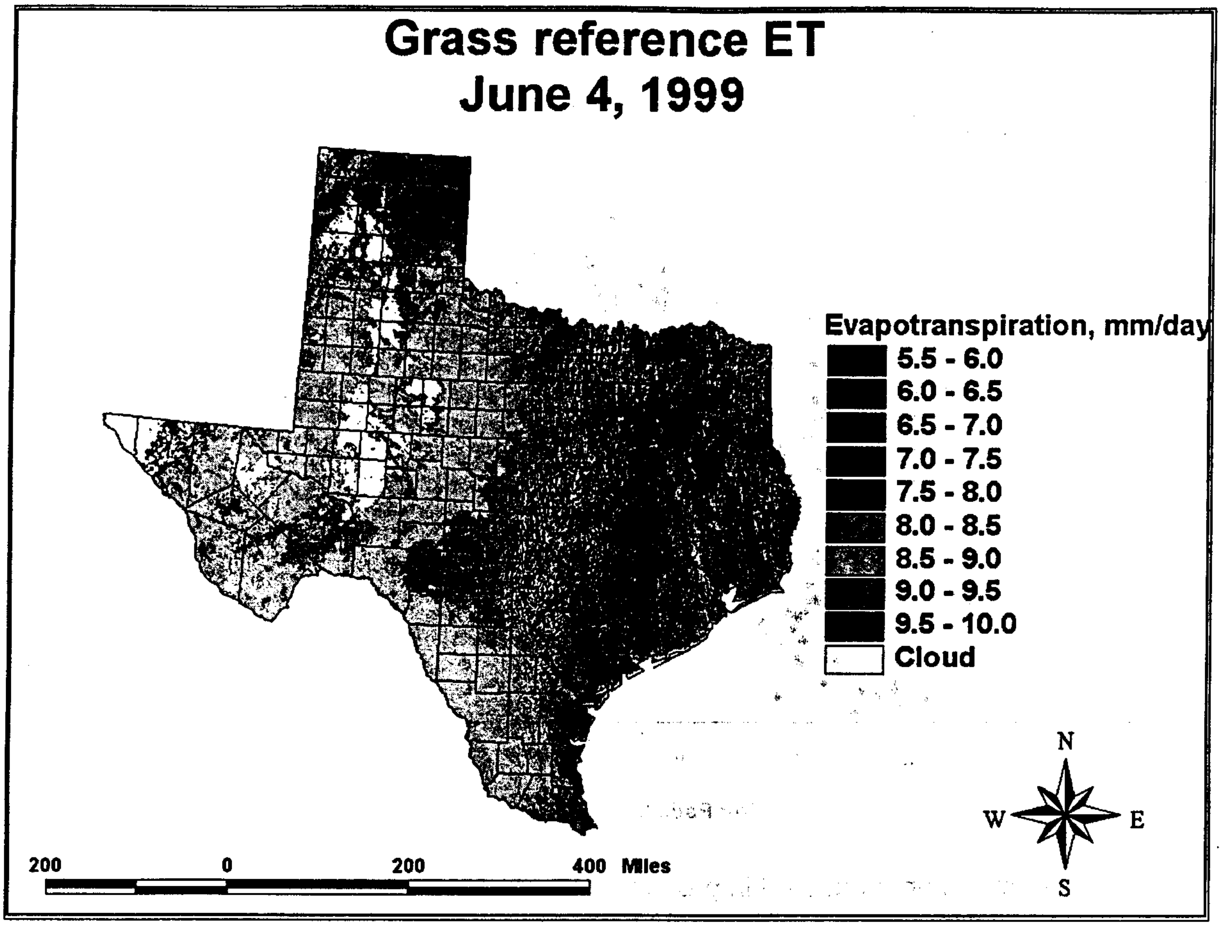

Figure 7. Grass reference ET derived from AVHRR satellite on June 4, 1999.

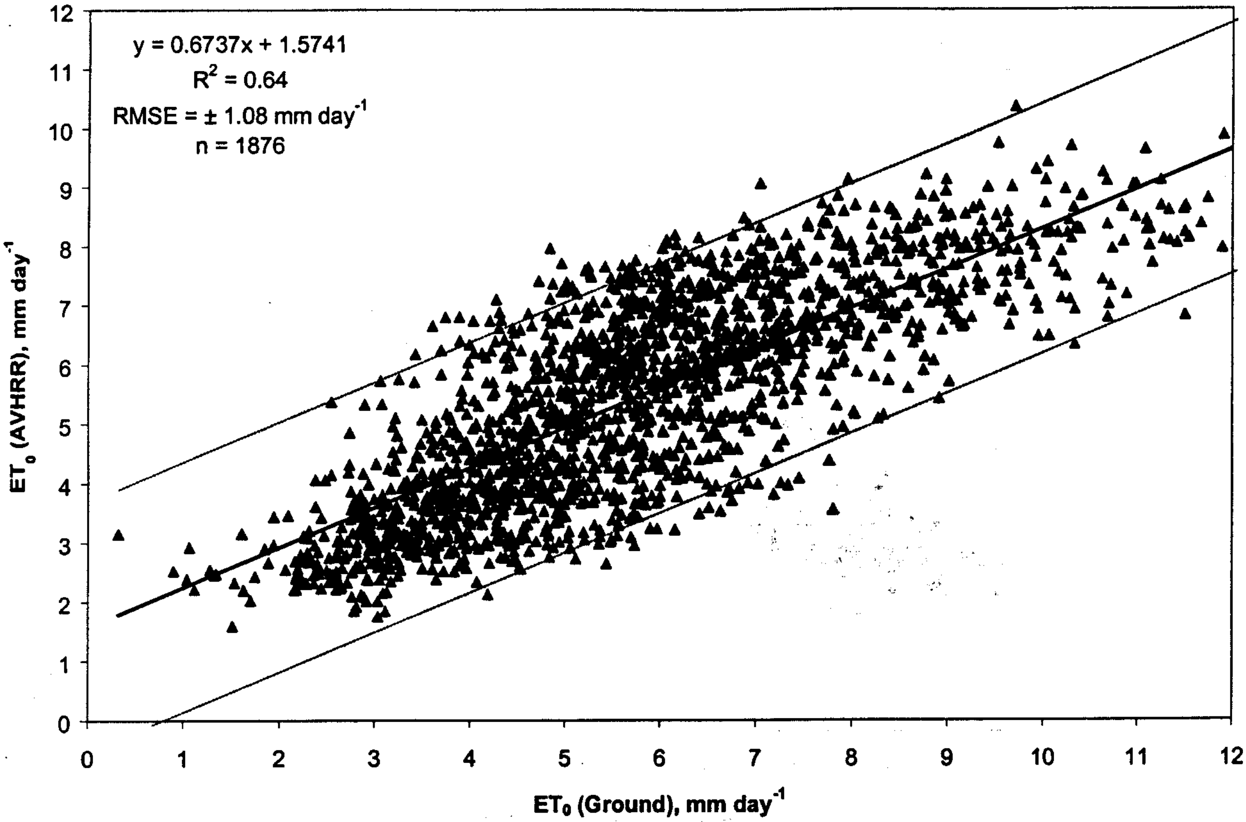

Figure 8. Daily grass reference ET estimated from AVHRR with that of ET estimated from 16 weather stations along with the 95% confidence limits.

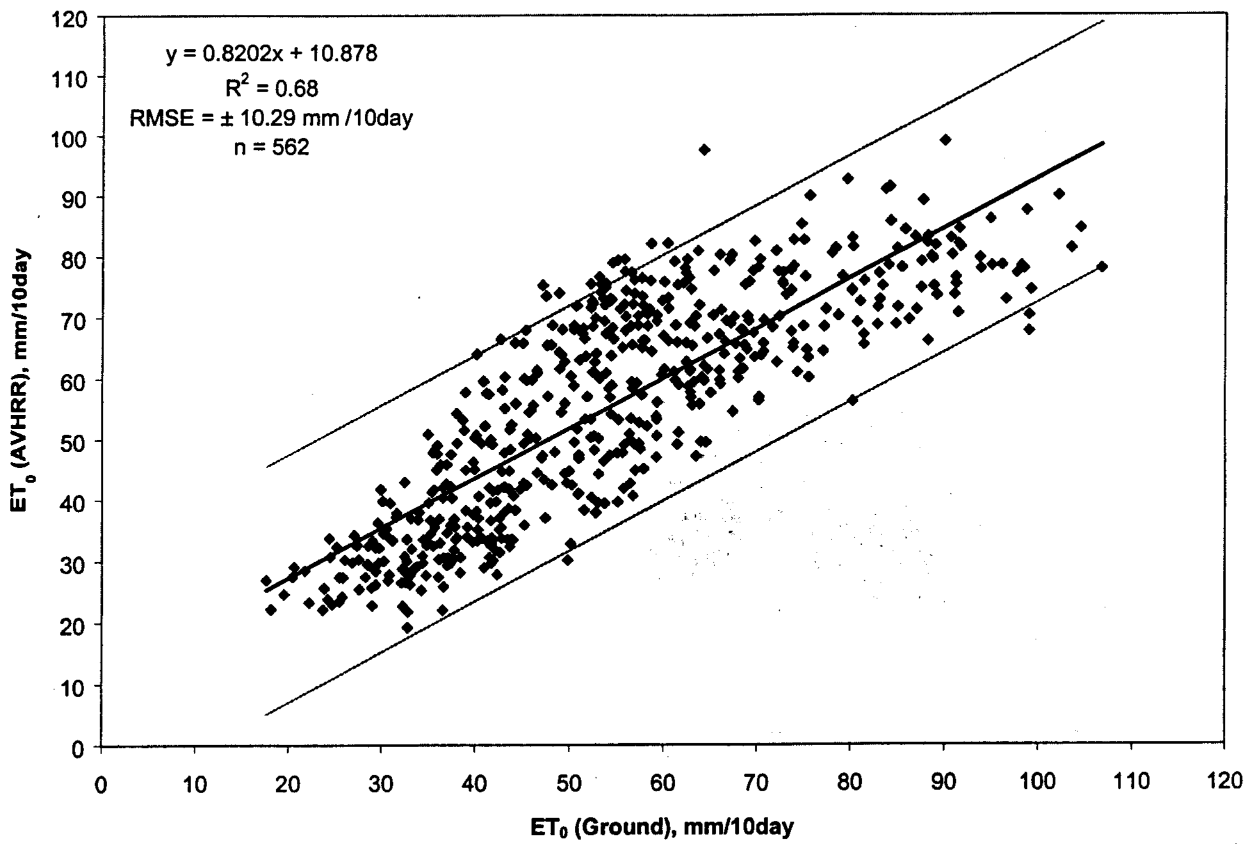

Figure 9. Cumulative 10day grass reference ET estimated from 16 weather stations with that of ET estimated from AVHRR along with the 95% confidence limits.

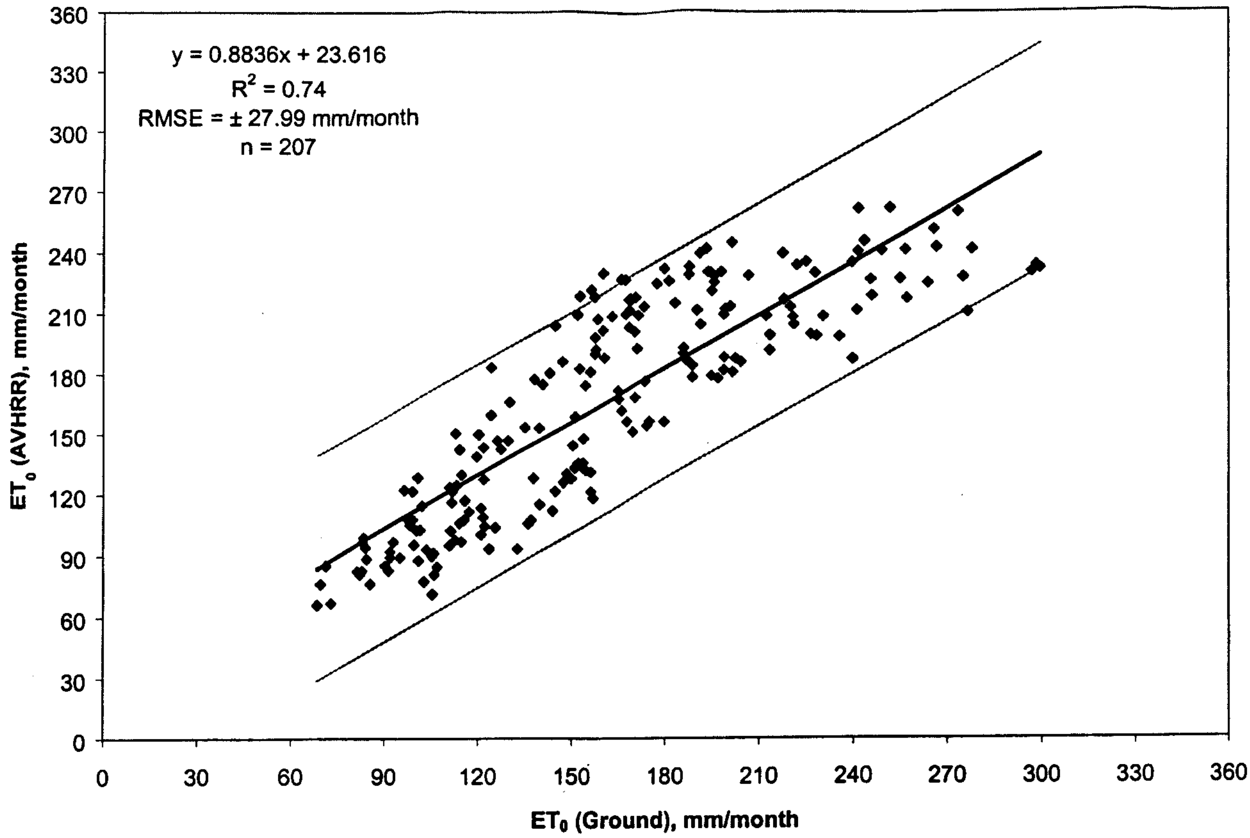

Figure 10. Cumulative monthly grass reference ET estimated from 16 weather stations with that of ET estimated from AVHRR with the 95% confidence limits.