Determination of Regional Scale Evapotranspiration of Texas from NOAA – AVHRR satellite

Principle Investigators: -

Balaji Narasimhan
Graduate Student
Department of Agricultural Engineering
201 Scoates Hall,
Texas A&M University,
College Station, TX – 77843 – 2117.
Phone: (979) 845 – 3600
Fax   : (979) 845 – 3932
E-mail: balaji@tamu.edu

Dr. Raghavan Srinivasan
Director and Associate Professor
Spatial Sciences Laboratory
Department of Forest Science
Spatial Sciences Laboratory
700 University Drive, Suit # 104
College Station, TX – 77840 – 2120.
Phone: (979) 845 - 5069
Fax   : (979) 845 - 2273
E-mail: srin@brc.tamus.edu

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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 is essential for the success of hydrologic modeling studies. ET is estimated using climatic data like net radiation, air temperature, wind velocity, vapor pressure deficit and relative humidity obtained from the nearest weather stations. However, interpolating ET using data obtained from a point data source to derive regional ET could introduce errors of large magnitude. During the last two decades, 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 ET is possible. The present study aims at deriving spatially distributed ET using NOAA-AVHRR satellite data.

Advanced Very High Resolution Radiometer (AVHRR) is a sensor aboard NOAA series of polar orbiting earth satellites that are in operation for more than three decades. The main purpose of these satellites is to forecast weather and monitor regional climatic conditions. However, its potential for monitoring crop growth, assessing crop yield and monitoring forest cover has been realized only during the past decade. AVHRR is a broadband scanner, 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. Currently NOAA-14 and NOAA-15 satellites are in orbit. The spectral ranges of different channels are given in Table 1.

Table.1 Spectral range of AVHRR

Channel	**Wavelength (μm)**
1	0.58 – 0.68
2	0.73 – 1.10
3	3.55 – 3.93
4	10.3 – 11.3
5	11.5 – 12.5

Data from Channel 1 and Channel 2 are used extensively for Land Use/Land Cover monitoring. However data obtained from thermal channels have been put to very little use. In this research project, data obtained from thermal channels 4 and 5 have been used in addition to the use of channel 1 and 2 in the estimation of ET.

PREVIOUS STUDIES

Few studies have been done in the past for the estimation of regional scale evapotranspiration from satellites. Seguin et al. (1994) conducted field experiments in France, the Sahel and North Africa and demonstrated the existence of a linear relationship between ($ET – R_n$) and ($T_s – T_a$) and the potential to derive ET from AVHRR satellite where, ET – Evapotranspiration, R_n – net radiation, T_s – Surface temperature and T_a – Air temperature. The disadvantage of this method is that the coefficients in this equation are site specific and separate equations have to be derived for different sites. Granger (1995) developed a feedback algorithm for the estimation of ET from AVHRR thermal channels. This study established a relationship between saturated vapor pressure at surface temperature T_s and vapor pressure deficit. The vapor pressure deficit estimated from surface temperature measurements is used to estimate evapotranspiration. Granger (1995) suggested that the equation developed could be applied for wide range of surface cover types. However, comparison of the model estimates with the field observations of vapor pressure deficit for Panhandle, Texas showed poor correlation. Tan and Shih (1997) adopted a similar approach suggested by Seguin et al (1994) for South Florida. Jiang and Islam (1999) adopted an approach similar to that of Priestly-Taylor method (ASCE, 1990) for estimation of ET. However, the values of _ are derived from inverse relationship between NDVI (Normalized difference Vegetation Index and T_s). This equation doesn't take into account the advective flux and hence can be useful only for regions with low advective flux.

The objectives of this study are:

1. to develop a relationship between satellite surface temperature T_s and maximum air temperature T_a
2. to use minimal ground based inputs for deriving potential ET

METHODOLOGY

There are several methods available for estimating ET. The level of accuracy needed, quality and availability of weather parameters determine the adoption of a particular method for estimating ET. Penman-Monteith method is widely adopted because of its applicability to wide range of climatic conditions. Accurate estimates of ET could also be obtained using the energy budget method. This method is not widely adopted because of the non-availability of surface temperature (T_s) estimates from weather stations. With the help of AVHRR channel 4 and channel 5, surface temperature could be accurately estimated by using a split window algorithm developed by Price (1984). In the present study, ET is estimated using Energy Budget Method. Air temperature is one of the important input in the estimation of ET. In the following section a procedure to estimate air temperature from surface temperature and to ultimately estimate ET has been described

Estimation of Maximum Air temperature from Surface Temperature:

Surface Temperature:

Land Surface Temperature (LST) is the temperature measured just few inches above the surface of the land or the vegetation sensed by the thermal bands of AVHRR satellite. Infrared radiation sensed by AVHRR satellites is influenced due to atmospheric absorption by water vapor and other gases (principally CO_2). These make it difficult to accurately predict the surface temperature. This is further complicated because the land surface does not behave as a perfect emitter of infrared radiation and presents a high variability.

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 algorithm are currently available to derive LST from brightness temperature [Becker and Li (1990); Keer 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 Price (1984) performed better over other split window algorithms. Hence the algorithm developed by Price (1984) has been used to derive the Land Surface Temperature, which is given by:

$$LST = T_4 + 3.3 \cdot (T_4 - T_5) \cdot \frac{5.5 - \varepsilon_4}{4.5} + 0.75 \cdot T_5 \cdot \Delta\varepsilon \qquad (1)$$

Where:

LST = Land Surface Temperature [° C],

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

T_5 = Brightness temperature obtained from Channel 4 [° C],

$\Delta\varepsilon$ = $\varepsilon_4 - \varepsilon_5$,

ε_4 = Surface emissivity in AVHRR channel 4,

ε_5 = Surface emissivity in AVHRR channel 5.

Cihlar et al. (1997) developed an algorithm to calculate the surface emissivities ε_4 and ε_5 from NDVI (Normalized Difference Vegetation Index):

$$\varepsilon_4 = 0.9897 + 0.029 \cdot \ln(NDVI) \qquad (2)$$

$$\Delta\varepsilon = \varepsilon_4 - \varepsilon_5 = 0.01019 + 0.01344 \cdot \ln(NDVI) \qquad (3)$$

Relationship between T_s and T_a:

Comparison of surface temperature obtained from the satellite and the maximum air temperature measured at weather stations across Texas show that there is a strong linear relationship between T_s and T_a. This is because the overpass time of the satellite coincides with the occurrence of the maximum air temperature during noon. Hence a simple regression approach has been adopted for deriving T_a from T_s. However this linear relationship varied spatially among weather stations across Texas even within the same climatic division [Texas is divided into ten climatic divisions (Fig. 1) by NWS based on the climatological parameters like temperature, precipitation, etc.,]. Hence long-term 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 climatic division. The regression model adopted in the study is of the form:

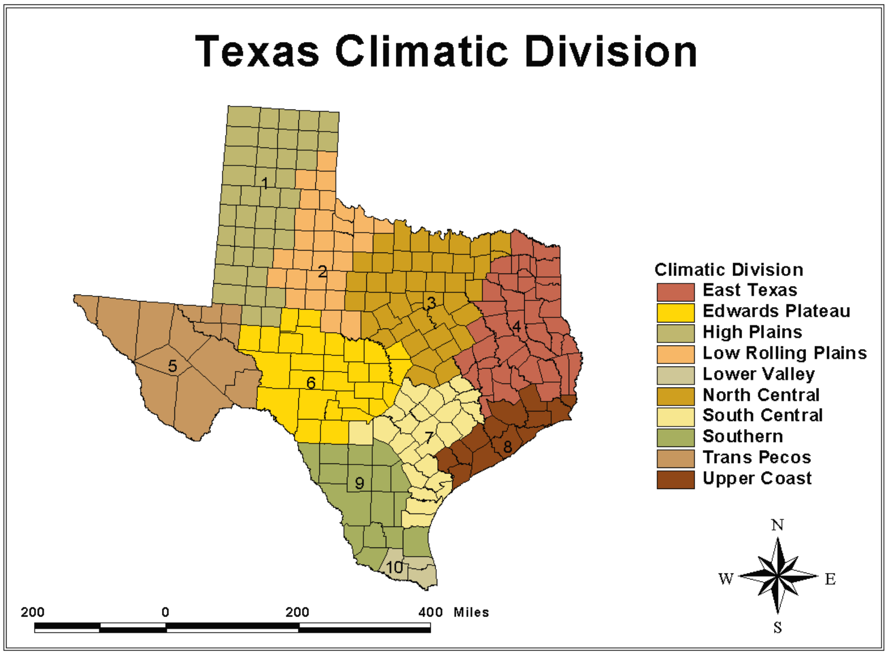

Figure 1. Climatic Divisions of Texas.

$$\hat{T}_a(i) = m(i)\sqrt{T_s \leftrightarrow T_{lm}} + C(i) \qquad (4)$$

Where:

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

T_s - land surface temperature (˚F)

T_{lm} - long-term monthly maximum air temperature (˚F) m(i) and C(i) are regression constants for climatic zone I (where i = 1,…..10). In this study daily weather data (September, 1999 to August, 2000) from 57 weather stations distributed across Texas were available for model development and validation (Fig.2).

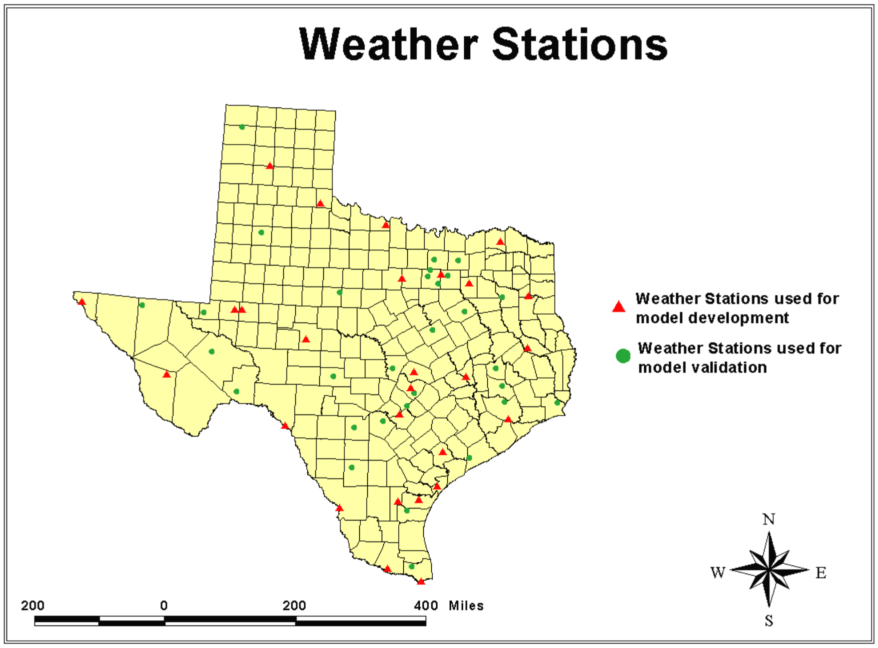

Figure 2. NWS weather stations used for model development and validation.

Daily weather data from 27 weather stations were used for model development and data from 30 weather stations were used for model validation. 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 ($r^2 = 0.79$ and slope ≈ 1).

Table 2. Regression coefficients used for deriving T_a from T_s

Climatic Division	m(i)	c(i)	R^2
1	0.78	15.60	0.74
2	0.89	9.29	0.8
3	0.87	12.10	0.82
4	0.91	11.21	0.84
5	0.83	9.98	0.76
6	0.87	11.05	0.78
7	0.78	18.45	0.74
8	0.86	13.46	0.79
9	0.82	16.24	0.72
10	0.81	17.35	0.75

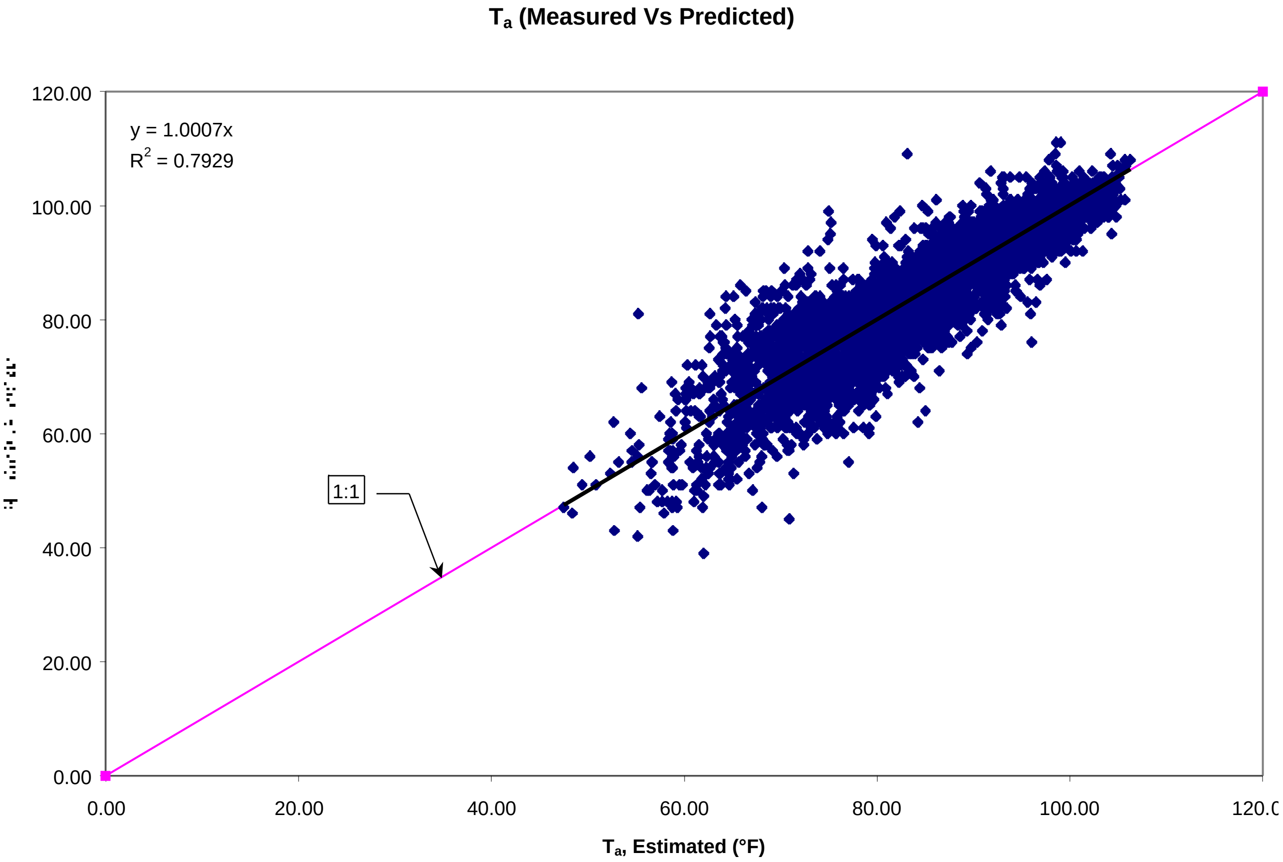

Figure 3. Comparison of model estimated air temperature with air temperature measured at NWS weather stations.

Estimation of potential ET:

The procedure for estimating ET on the vertical energy budget of a vegetated surface has been described in this section. The Energy Balance Equation is given by (ASCE 1990):

$$R_n = \lambda E + H + G \tag{5}$$

Where:

R_n - net radiation flux at the surface [MJ m^{-2} day^{-1}],
_E - latent heat flux [MJ m^{-2} day^{-1}],
H - sensible heat flux to the air [MJ m^{-2} day^{-1}],
G - sensible heat flux to the soil [MJ m^{-2} day^{-1}].

The sensible heat flux to the air is given by (ASCE 1990):

$$H = \frac{\rho_a C_p}{r_a} U_2 (T_s - T_a) \qquad (6)$$

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 - air Temperature [°C].

The roughness coefficient is given by (FAO 1998):

$$r_a = \frac{\ln\frac{z-d}{z_{om}} \quad \ln\frac{z-d}{z_{ov}}}{k^2 U_2} \qquad (7)$$

Where:

k - Von Karman constant [0.41],

d - zero-plan displacement parameter [m],

Z_{om} - roughness parameter for momentum [m],

Z_{ov} - roughness parameter for head and vapor transfer [m].

Adopting coefficients for a grass reference crop suggested by FAO (FAO 1998) and substituting in eq. 3, eq.2 becomes:

$$H = \gamma \frac{900}{T_a + 273} \lambda U_2 (T_s - T_a) \qquad (8)$$

Where:

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

Assuming sensible heat flux to the soil (G) as negligible, ET can be found by:

$$E = \frac{R_n - H}{\lambda} \qquad (9)$$

where:

E - Evapotranspiration in [mm day^{-1}],

λ - Latent heat of vaporization at 20 °C [2.45 MJ kg^{-1}].

Net radiation (R_n):

Net radiation is the amount of radiation absorbed by the land surface from the incoming solar radiation:

$$R_n = (1-\alpha)R_s + \varepsilon R_l - \varepsilon\sigma(T_s + 273.16)^4 \qquad (10)$$

where:

R_n - net radiation [MJ m^{-2} d^{-1}],

R_s - incoming short wave radiation [MJ m^{-2} d^{-1}],

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

α - surface albedo,

T_s - Surface temperature [°C],

ε - emissivity,

_ - Stefan-Boltzman constant (4.90 X 10-9 MJ m^{-2} d^{-1} K^{-4}).

Incoming short wave radiation is estimated using empirical relationship suggested by FAO (FAO 1998). Surface albedo was calculated from the channel 1 and channel 2 of AVHRR, by adopting the method proposed by Gutman (1988). The algorithm developed by SwinBank (1963) was used to calculate the incoming long-wave radiation.

Psychrometric Constant (γ):

The psychrometric constant is given by (FAO 1998):

$$\gamma = \frac{C_p P}{\varepsilon\lambda} = 0.665 \times 10^{-3} P \qquad (11)$$

where:

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

P - atmospheric pressure [kPa],

λ - Latent heat of vaporization, 2.45 [MJ kg^{-1}],

C_p - Specific heat at constant pressure, 1.013×10^{-3} [MJ kg^{-1} $°C^{-1}$],

ε - ratio of molecular weight of water vapor/dry air = 0.622.

The atmospheric pressure varies with elevation. A 1km resolution DEM (Digital Elevation Model) is used in the calculation of atmospheric pressure (FAO 1998):

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \qquad (12)$$

where:

P - atmospheric pressure [kPa],

z - elevation above sea level [m].

Wind Velocity:

A constant wind velocity of 2m/s was assumed for estimation of grass reference ET since it cannot be derived from the satellite.

RESULTS AND DISCUSSION

By adopting the methodology outlined in this report, potential ET was calculated for cloud free days between May 1999 to April 2000 satellite images. Arc/Info 8.1 was used for processing the satellite images. During the same days potential ET was calculated for 16 FAA weather stations (Fig.4) from its ground based weather observations.

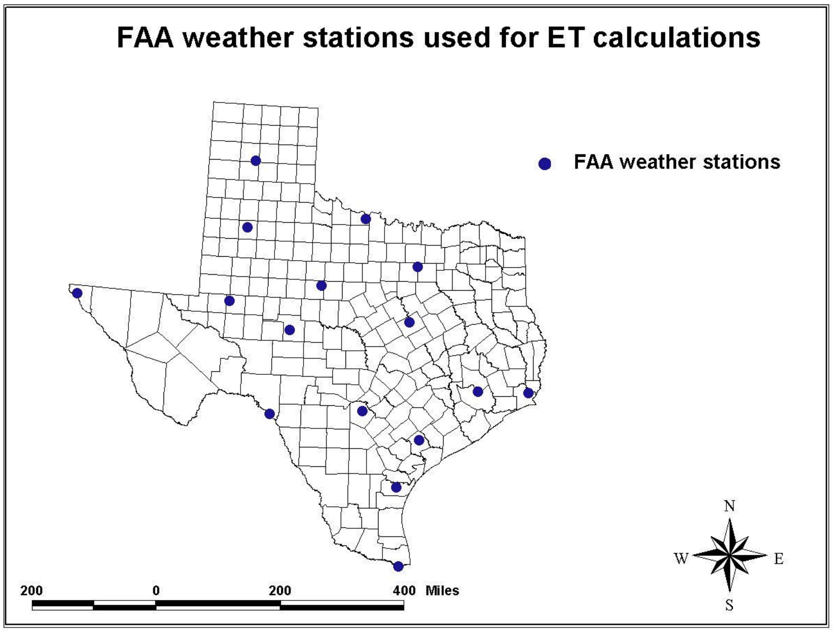

Figure 4. FAA weather stations used for calculated potential ET.

Ta, Rn, and ET0 (Potential ET) calculated for cloud free days from satellite were compared with the FAA weather station estimates (Figs. 5, 6, and 7).

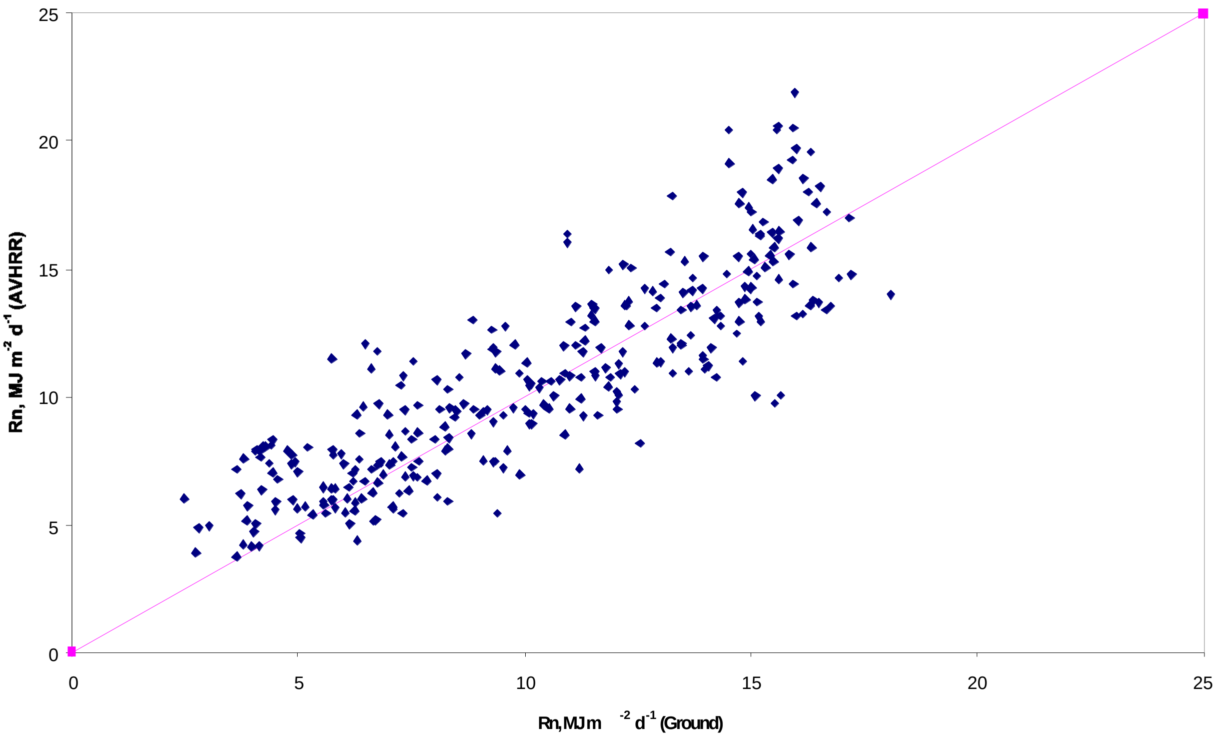

Figure 5. Comparison of net radiation derived from FAA stations and AVHRR

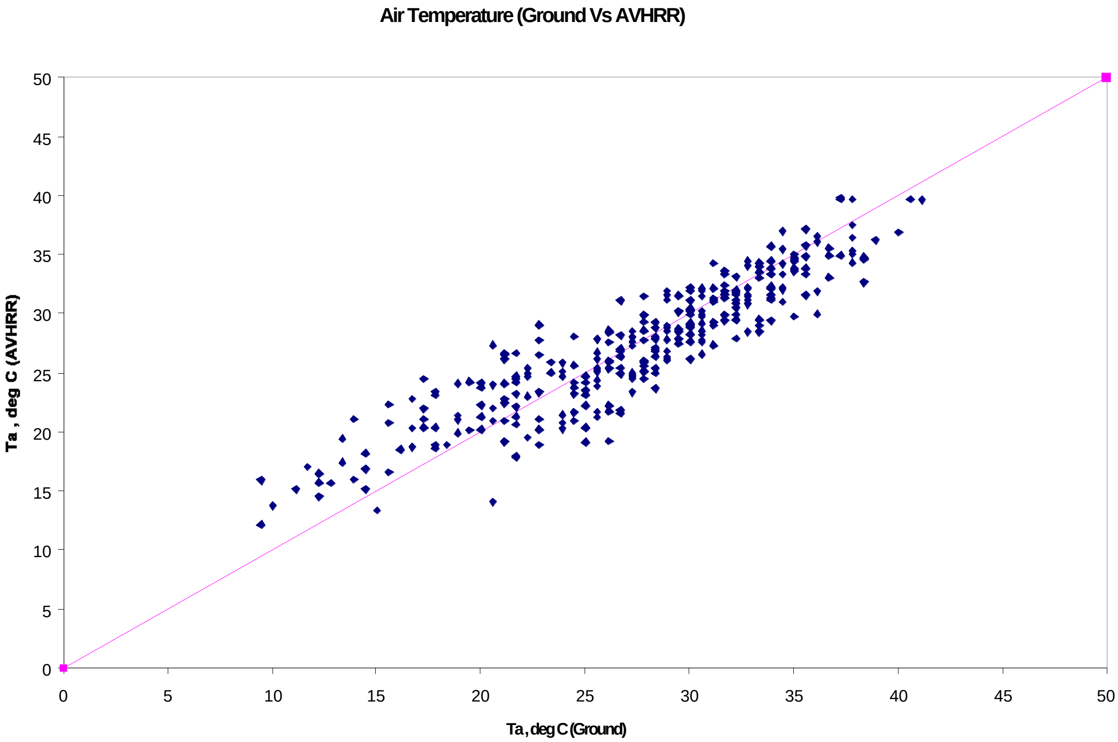

Figure 6. Comparison of maximum air temperature derived from FAA stations and AVHRR

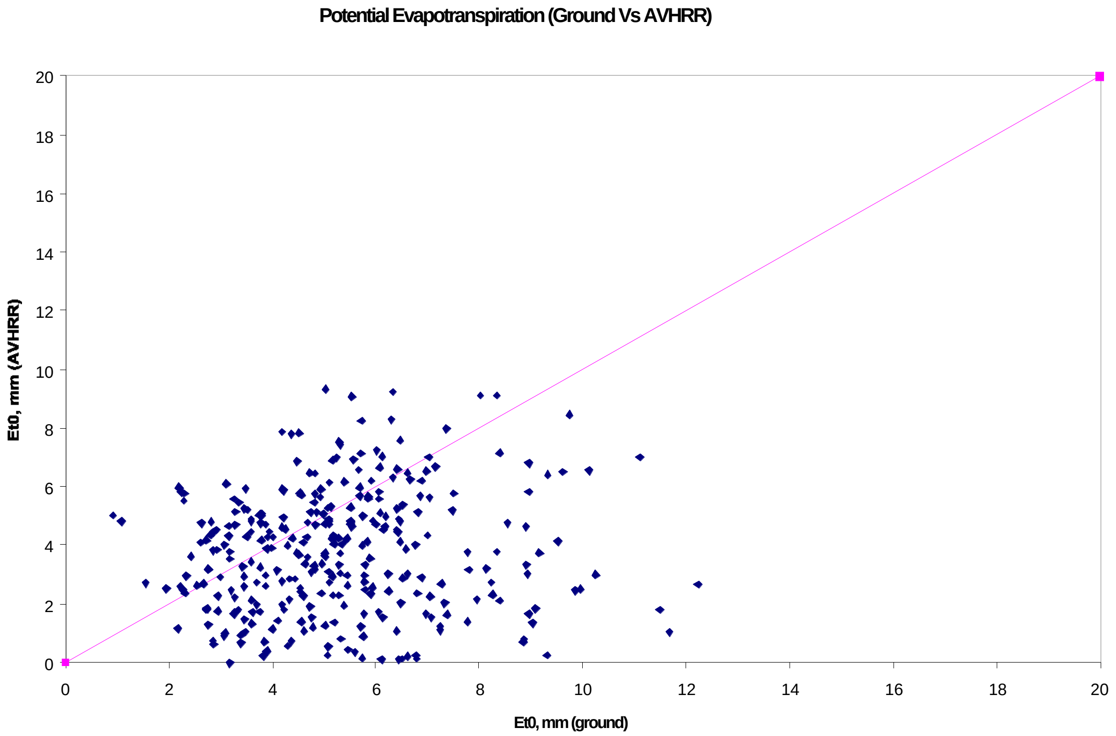

Figure 7. Comparison of potential ET derived from FAA stations and AVHRR

Comparison of Figs. 5, 6, 7 show that the air temperature and net radiation derived from AVHRR satellite compare well with the ground based estimates. However, the potential ET derived from ground based observations didn't match well with the ET derived from AVHRR. There are several reasons for this:

1. Penman-Monteith combination equation has been used to derive ET from ground based estimates. But an energy balance approach has been used to derive ET from AVHRR satellites. Because all the parameters needed for the estimation of ET using Penman-Monteith method cannot be derived from AVHRR satellite.
2. A constant wind velocity of 2m/s was used for the calculation of ET from AVHRR satellite; however, measured wind velocity was used for calculating ET from FAA weather stations.
3. The ET derived from FAA stations is derived from point observations. However, ET derived from AVHRR satellite is obtained by using parameters measure over an area of 1 km X 1km.

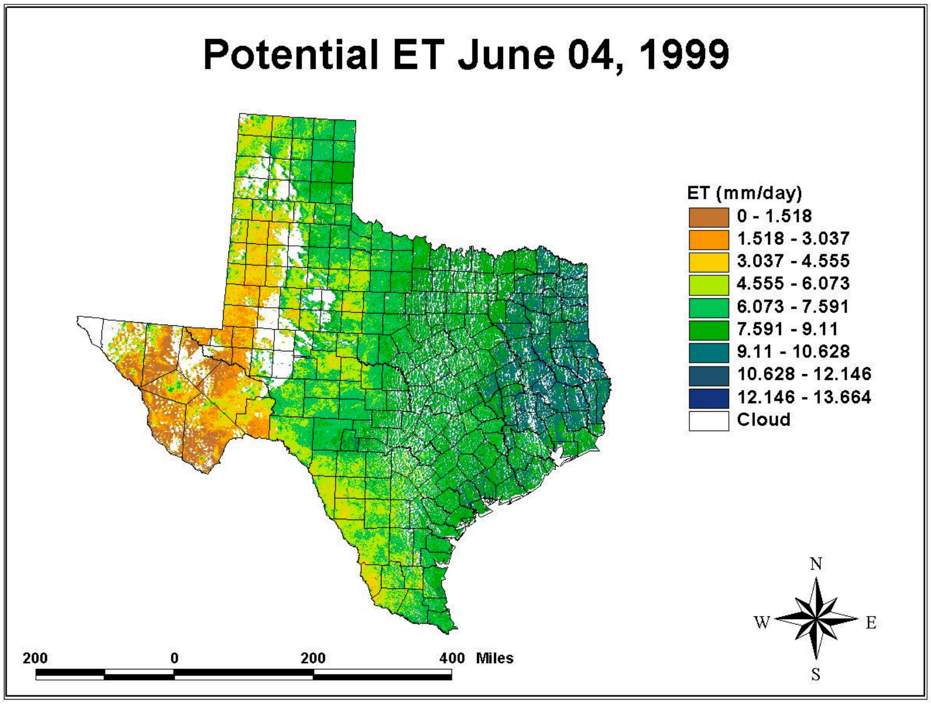

Figure 8. Potential ET derived from AVHRR satellite on June 4, 1999.

CONCLUSION

This research study developed a good understanding of the basic processes involved in the derivation of potential ET from AVHRR satellite. Preliminary results show that AVHRR satellite could be used for deriving potential ET. However some more research needs to be done to improve the accuracy of the ET estimates from AVHRR satellite. Research is in progress at the Spatial Sciences Laboratory to improve the methodology involved in the calculation of potential ET from AVHRR satellite.

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