3.3 ESTIMATION OF EVAPORATIVE FRACTION AND EVAPOTRANSPIRATION FROM REMOTELY SENSED DATA USING COMPLEMENTARY RELATIONSHIP

Virginia Venturini[(1,*)], Shafiqul Islam[(2)], Gautam Bisht[(3)], and Leticia Rodriguez[(1)]

[(1)] Facultad de Ingeniería y Ciencias Hídricas, Universidad Nacional del Litoral, C.C. 217, Santa Fe, 3000. Argentina.
[(2)] Department of Civil and Environmental Engineering, Tufts University, 113 Anderson Hall, Medford, MA 02155.
[(3)] Department of Civil & Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139.

ABSTRACT

We present a new formulation to derive evaporative fraction (EF) and evapotranspiration (ET) maps from remotely sensed data without auxiliary relationships such as those relating a vegetation index and land surface temperature or site-specific relationships. The new equation is based on Grager and Gray's complementary relationship and Priestley-Taylor's equation. The proposed model with a relative evaporation (ET/Epot) parameter eliminates the use of wind functions and associated resistance parameterizations commonly applied for ET calculation. By combining this relative evaporation parameter, Grager and Gray complementary relationship and Priestley-Taylor equation we obtain a simple model to estimate ET. This proposed formulation was applied and validated over the Southern Great Plains (SGP) region of the United States for several clear sky days with MODIS Atmospheric and Land products. The overall RMSE and bias are 31.68 and -5.11 Wm^{-2} respectively. Our results suggest that the proposed approach is robust and valid for a wide range of atmospheric and surface conditions.

1-INTRODUCTION

The evapotranspiration (ET) and evaporative fraction (EF) are needed for many hydrologic models as well as for water and agricultural management applications. In the last two decades many models have been developed to estimate ET for a wide range of spatial and temporal scales, and surface conditions. Most of these models are variations of Penman's equation (Monteith and Unsworth 1990) and Priestley-Taylor's equation (Priestley and Taylor 1972). Some of these models have been taken advantage of complementary relationships proposed by Bouchet (1963). These ET models have been widely applied with varying results (e.g., Jackson et al. 1977, Seguin et al. 1989; Grager and Gray 1989, Holwill and Stewart 1992, Bastiaanssen et al. 1996, Carlson and Ripley 1997, Jiang and Islam 2001, Norman et al. 2003, Nishida et al. 2003, Rivas and Caselles 2004).

Complementary relationships allow the estimation of regional ET as complementary function of potential evapotranspiration (Epot), for a wide range of available energy and moisture conditions. Examples of successful complementary models are those developed by Brutsaert and Stricker, (1979), Morton, (1983) and Hobbins et al., (2001). All of them applied Bouchet (1963) heuristic complementary relationship.

In many current approaches to estimate ET, air temperature is only available from ancillary sources (Price 1990, Gillies et al. 1997, Jiang and Islam 1999, Nishida et al. 2000). One of the most relevant advances introduced by Earth Observing System (EOS) satellites is the Atmospheric Profiles Product derived from MODIS sensors onboard EOS-Terra and EOS-Aqua satellites. MODIS's Atmospheric profile product (MOD07 and MYD07) provides several atmospheric parameters, such as air and dew point temperature profiles. This product is available on a daily base, at 20 vertical atmospheric pressure levels and at 5x5km spatial resolution (Menzel et al. 2002*)*.

This new remote source of atmospheric data as well as the already widely used Ts maps, obtained from different sensors, opens a new opportunity to revise the complementary relationship concepts that relate the actual rate of evapotranspiration (ET) and the potential rate of evapotranspiration (Epot), (Crago and Crowley 2005, Ramirez et al. 2005).

We present a new method to derive EF and ET maps from remotely sensed data without auxiliary relationships such as those relating a vegetation index (VI) and the land surface temperature (Ts), common in contextual approaches, or site-specific relationships. This new equation to compute ET,

[*]*Corresponding author address:* Virginia Venturini,
Fac. de Ing. y Ccs Hídricas - C.C. 217,
Santa Fe- S3000ADQ .
Argentina. vventurini@gigared.com

is based on Grager and Gray's complementary relationship and Priestley-Taylor's equation. Hence spatially distributed maps of EF and ET can be easily obtained from a simple and scalable equation that is applicable to any surface wetness.

2- REVIEW OF COMPLEMENTARY MODELS.

Bouchet (1963) postulated that as a well-watered surface dries, the decrease in ET is equal to an increase in Epot. Thus, the following relationship applies.

$$ET + Epot = 2\ Ew \tag{1}$$

where Ew is referred to as wet-environment evapotranspiration, defined as the evaporation which occurs when ET=Epot. This relationship assumes that as ET increases, Epot decreases with the same magnitude i.e., δET=-δEpot. Bouchet's equation has been widely used in conjunction with Penman's equation and Priestley-Taylor's equation (Brutsaert and Stricker 1979, Morton 1983, Hobbins et al. 2001).

Grager and Gray (1989) argued that the above relationship lacks a theoretical background, mainly due to Bouchet's assumption of δET=-δEpot. In order to derive a physically based complementary relationship between ET, Ew and Epot, Grager and Gray (1989) proposed the inequality Epot ≥ Ew ≥ ET and demonstrated the following complementary relationship:

$$\mathrm{ET} + \mathrm{Epot}\frac{\gamma}{\Delta} = \mathrm{Ew}\left(\frac{\Delta + \gamma}{\Delta}\right) \tag{2}$$

It can be easily verified that equation (2) is equivalent to equation (1) when $\gamma=\Delta$. Nevertheless, the condition of $\gamma=\Delta$, holds true when the slope of the saturation vapor pressure (SVP) curve equates with the psychrometric constant. This is true only at Ts near to 6 °C (Grager, 1989), where the SVP curve changes smoothly.

Grager and Gray (1989) pointed out that as ET increases, vapor pressure of the air also increases, then they assumed that the drying power of air, Ea, reflects the drying process of the surface; thus ET, for a nonsaturated surface is a function of Ea. These authors established a coefficient G*= ET/Epot, to simplify equation (2). The ratio ET/Epot was empirically related to D= Ea/(Ea+Q), where Q=Rn-G is the energy available from net radiation (Rn) and soil heat flux (G) and Ea is the drying power of the air. The expression of G* is complex and may require site-specific calibration, since it was obtained with relatively few measurements (Grager and Gray 1989). At that time, only the relationship between the relative evaporation (ET/Epot) and coefficient D was derived. It was not until recently that Crago and Crowley (2005) applied equation (2) to a large data set of ground measurements and found promising results.

3- PROPOSED METHOD

The advantage of using a simple equation with a relative ET/Epot parameter (see equation 3), as proposed by Granger and Gray to abridge equation (2), relies on the elimination of wind functions and resistant factor estimations that introduce uncertainties and complexity to the ET calculation.

$$\frac{\mathrm{ET}}{\mathrm{Epot}} = \frac{f_u\,(e_s - e_a)}{f_u\,(e_s^* - e_a)} \tag{3}$$

Temperatures have been used as surrogates for vapor pressures in many studies (Monteith and Unsworth 1990, Nishida et al. 2003). Although the relationship between vapor pressure and temperatures is not a linear one, it is commonly linearized for small temperature differences.

The main difficulty in equation (3) is how to estimate (e_s-e_a), since there is no simple way to relate e_s to any known surface temperature. Figure 1 shows the relationship between e_s, e^*_s and e_a and their corresponding temperatures; where e_w^* is the SVP at an unknown surface temperature Tw. An analogy to the dew temperature concept suggests that Tw would be the temperature of the surface if it is brought to saturation without changing the actual surface vapor pressure. Thus Tw must be lower than Ts if the surface is not saturated and close to Ts if surface is saturated. Hence, e_s could be derived from this unknown surface temperature, Tw. Although, it cannot possibly be measured in the field, due to the process complexity and the intricate soil-vegetation-atmosphere feedback, it can be derived from the slope of the exponential SVP curve, as a function of Ts and Td. This calculation is further discussed in section 5. Thus, the saturation surface vapor pressure at Tw would be the actual soil vapor pressure; therefore ET/Epot can be written as follow,

$$F = \left(\frac{fu}{fu}\right)\frac{(Tw - Td)}{(Ts - Td)}\left(\frac{\Delta_1}{\Delta_2}\right) \quad (4)$$

where f_u is a function of the wind speed. This function depends on vegetation height and wind speed and it is independent of surface and air moisture. In other words the wind function affects

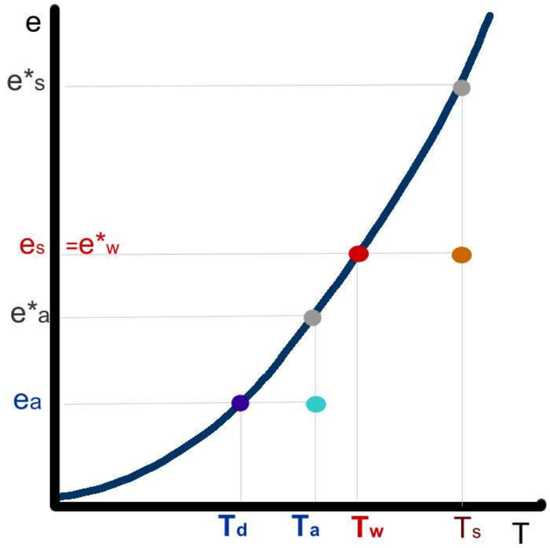

Figure 1: Relationship among Tw, Ts, e_s and e^*_w.

ET and Epot in the same manner (Grager 1989). The slopes of the SVP curve, Δ_1 and Δ_2 are assumed equal since they may be approximated at Ta; although their estimation at Td and Ts would not add further complexity to this computation, thus:

$$F = \frac{ET}{Epot} = \frac{(Tw - Td)}{(Ts - Td)} \quad (5)$$

The new coefficient F is the fraction of the actual water vapor deficit over the potential water vapor deficit. Since Epot is larger than or equal to ET, F ranges from 0 to 1. For a dry surface with Ts >> Tw, Ts-Td is larger than Tw-Td and ET/Epot tends to 0. In the case of a saturated surface with Ts close to Tw, the difference Ts-Td is similar to Tw-Td and ET/Epot tends to 1. Spatially distributed temperature values to estimate F (in Equation 6) can be obtained from MODIS-Terra and MODIS-Aqua data products (http://modis-atmos.gsfc.nasa.gov).

In order to estimate ET with Equation (2), one needs to compute Ew. Grager and Gray's equation was derived using Penman's concept, which they interpreted as Ew. In this new proposed method, Priestley and Taylor's equation is used to approximate Ew, while Epot remains the same, i.e. Dalton-type equation. Hence, the inequity Epot>Ew>ET holds true. The actual ET for any surface condition is obtained combining equations (2), (5) and Priestley-Taylor's equation, thus

$$ET = \alpha\left(\frac{F\Delta}{F\Delta + \gamma}\right)(R_n - G) \quad (6)$$

Equation (6) inherits Priestley and Taylor's assumption that the main driving force for ET is the available radiant energy. This new equation is alike the equation derived by Barton (1979), who extended Priestley-Taylor's approach for unsaturated surfaces.

The key advantage of this simple formulation is that it is physically based and is expected to hold true for a range of atmospheric and surface conditions. This new model considers the actual air and surface vapor pressure, what make it applicable to any surface cover and moisture under varying air conditions (as shown in section 5). The advection factor, represented by the wind function f_u, is considered in F as it would affect ET as well Epot; and there is no need to approximate it for Ew estimation. Equation 6 is likely to be applicable for a wide range of spatial scales, i.e. from local to meso scales.

4- STUDY AREA AND MODIS PRODUCTS

4.1. *Study Region*

The Southern Great Plains (SGP) region of US is a flat terrain, heterogeneous land cover and seasonal variation in temperature and humidity. It broadens over the State of Oklahoma and southern part of Kansas, extending in longitude from 95.3º W to 99.5º W and in latitude from 34.5º N to 38.5º N. The pre-defined projection grid of this domain is divided into 467 columns by 444 rows, in pixels of resolution of approximately 1.0 km.

This region has relatively extensive and well distributed coverage of surface flux and meteorological observation stations. In this study, Energy Balance Bowen Ratio stations (E), maintained by the Atmospheric Radiation Measurement (ARM) program are used for the validation of surface fluxes. The stations are widely distributed over the whole domain as shown in Figure 2: E8, E9, E13, E15 are located in crops and mixed farming region; E19 and E24 in short grass region; E7 and E12 in tall grass region while E20 is in interrupted forest region.

4.2. *MODIS Products*

The MODIS geolocation dataset, called MOD03, comprises of latitude, longitude, ground elevation, solar zenith angle, satellite zenith angle and azimuth angle for each MODIS 1km pixel. MOD11 contains Ts and band emissivities (for band 31 and 32) at a spatial resolution of 1km and 5km for clear sky days. The generalized split window is used to calculate Ts for those pixels, whose emissivities are known in band 31 and 32 (Wan and Dozier 1996). The MODIS Atmospheric profile product (MOD07) provides several parameters, of which air and dew point temperature profiles were used in the current study. The spatial resolution of this product is 5x5km, at 20 vertical atmospheric pressure levels and it is produced daily, (Menzel et al. 2002).

In the present study, air temperature and dew point temperature at vertical pressure level of 1000hPa, are taken as surrogate for the temperatures at screen level height. Also the temperatures are assumed homogenous over the 5x5km grid.

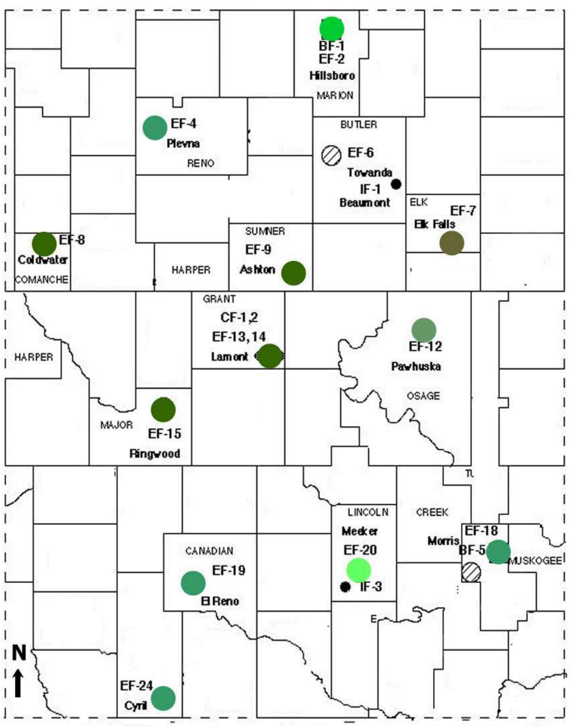

Figure 2: Overview of the Southern Great Plains and the ground station locations.(source: http://www.arm.gov/sites/sgp.stm)

4.3 *Clear sky day selection*

Daytime images for five days in year 2003 with at least 80% of the study area free of clouds were selected. Table 1 summarizes the image information (date, Julian day, satellite overpass time and image quality).

Date in 2003	Julian Day	Overpass time (UTC)	Image Quality (% clouds)
23rd March	82	17:05	18
1st April	91	17:00	18
19th September	262	16:40	23
12th October	285	16:45	9
19th October	292	16:50	6

Table 1: Day of the year, Julian day, overpass time and image quality of the five study days.

5- RESULTS

In order to apply equation (6) to obtain ET estimates, we need to calculate net radiation (R_n). In this work, R_n has been estimated with Bisht et al. (2005) methodology, which provides a spatially consistent and distributed R_n map over a large domain for clear sky days. With this method, R_n can be evaluated in terms of its components of downward and upward short wave radiation fluxes and downward and upward long wave radiation fluxes. Several of MODIS data products are utilized to estimate every component. Details of this calculation and further description of the MODIS products for the case days presented in this work can also be found in Bisht et al. (2005).

Soil heat fluxes have been calculated using Moran et al. (1989) with daily NDVI maps, calculated with MOD021KM products and Δ, the slope of the SVP calculated at Ta have been obtained with Buck's equation (Buck 1981) and MODIS Ta product.

5.1 *Results of Tw calculation*

We propose to estimate the key variable Tw from the SVP curve. It can be assumed that e_s is larger or equal to e_a and lower or equal to e^*_s, thus Tw must be in between Ts and Td. We recognize that this assumption may not be always true; indeed, a coefficient should be applied when the surface is not saturated. In fact, the slope of the SVP curve can be calculated from the first derivative at Ts and at Td, and it can also be computed from linearized curve between the intervals [Tw,Ts] and [Td,Tw], which are symbolized as Δ_1 and Δ_2, respectively . Thus, Tw expression is derived from a simple system of two equations with two unknown,

$$T_w = \frac{\left(e_s^* - e_a\right) - \Delta_1 T_s + \Delta_2 Td}{\Delta_2 - \Delta_1} \quad (7)$$

We compare several equations that relate SVP and temperature, i.e. Murray (1967), Bolton (1980) and Buck (1981), all of them are exponential function, concluding that any of these parameterizations will be applicable for this study. Buck's equation (1981) is chosen for its simple form and simple first derivative,

Julian Day	Observed ET (Wm^{-2})		Model ET (Wm^{-2})	
	Mean	σ	Mean	σ
JD82	191.79	34.22	181.34	14.84
JD91	232.55	41.58	234.20	17.59
JD262	242.07	40.74	197.1	13.06
JD285	203.97	33.38	214.57	16.265
JD292	212.20	46.10	231.24	17.78

Table 2: ET (Wm^{-2}) means and standard deviations (σ)

In order to apply equation (7), the first derivative of Buck' is obtained, then the slopes $\Delta 1$ is estimated at Td and $\Delta 2$ is estimated at Ts; with this two values we calculated a first estimated of Tw. In this first calculation we linearize a large segment of the SVP curve; we iterate the process by re-calculating $\Delta 2$ at this first value of Tw and compute a new Tw which is the presented in Figure 3. In Figure 3 (note the air SVP curves are at 2°K off set) can be seen how the air and surface actual vapor pressures relate to the corresponding temperatures in October 19th; in this day the e_a and e_s curves present little superposition, suggesting large e_s-e_a differences. The air seems to be dry in the whole region, while the surface seems to have few wet pixels.

Tw estimation can be improved by introducing another surface variable, such as soil moisture. In order to demonstrate the strength of this methodology, Tw calculation is kept simple, with minimum data requirements.

5.2 *Compare with ground measurements*

We must mention that there are no generally accepted methodologies to validate distributed ET values from our proposed model to point flux station observations, and hence it is difficult to evaluate the reliability of model outputs for the remaining pixels in an image. Besides, the measurement errors should also be kept in mind while doing such comparisons.

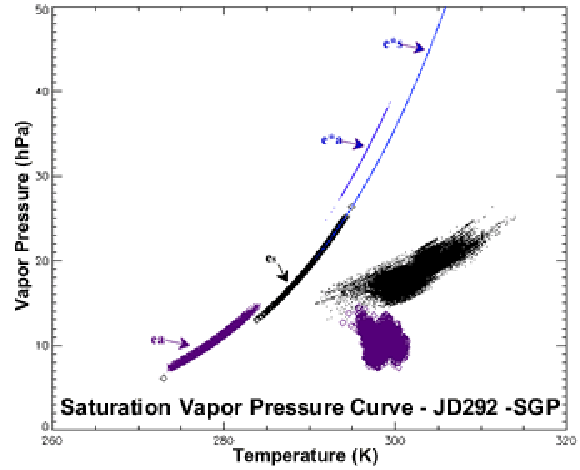

Figure 3: Buck's saturation vapor pressure curve. e_a was obtained with Td, e_s with Tw, e^*_a with Ta and e^*_s with Ts. Ta vs. e_a are shown with violet diamonds and Ts vs. e_s with black dots.

First, we compare several descriptive statistics for observed and model estimated ET for several days, as shown in Table 2. There are good agreements between mean ET values in every day, with differences ranging from ±1 to ±44 Wm^{-2}. The standard deviation (σ), seems to be systematically lower for ET estimated with the proposed method. Similar results were reported from earlier studies as well (Jiang and Islam 1999 and 2001, Kustas et al. 2003).

The comparison between ground measurements and corresponding ET estimates is shown in Figure 4 and Table 3. In general, the root mean square errors (RMSE) are less than 18% of the mean values for each day and the biases also tend to be low. The correlation coefficient, R^2, indicates the ET estimates correlate well with the measurements. Even though, the biases are low and do not exceed ± 7% of the mean observations and the RMSE are low, we acknowledge Tw estimates may not completely represent the surface characteristics.

The overall root mean square error (RMSE) and bias (Observed – Derived) are 31.68 and -5.11 Wm^{-2} respectively, with R^2 of about 0.58. Batra et al. (2005) reported RMSE of abut 50 Wm^{-2} for the same region and days. Batra et al. (2005) applied Jiang-Islam methodology which is simpler and do not account for atmospheric variables (Jiang and Islam 2001). Crago and Crowley (2005) published similar RMSE with more complex

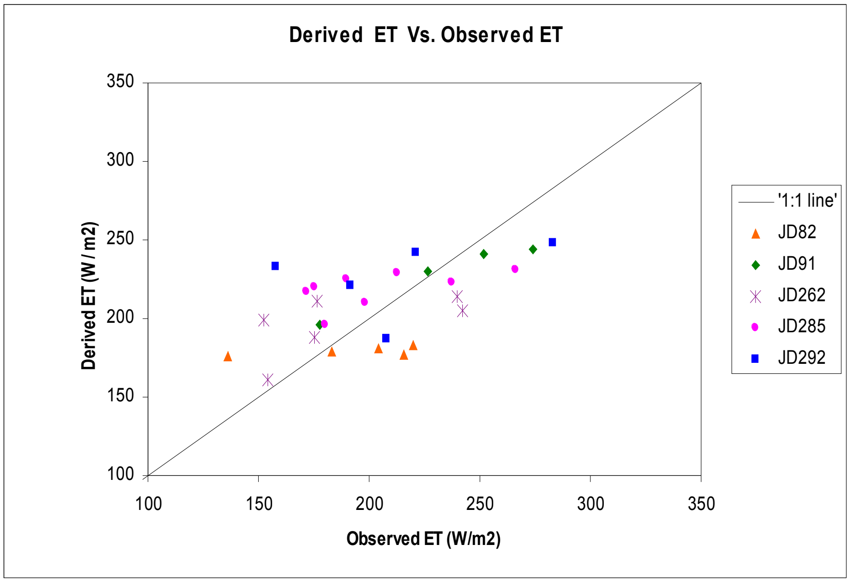

Figure 4: Contrast between calculated and observed ET (Wm^{-2}) for five clear sky days.

application of Grager and Gray's complementary relationship, where resistant factors and wind function were included in the estimates. Figure 5 shows a spatially distributed ET map generated from our proposed model.

	RMSE	BIAS (Obs- Cal)	R^2	Air/Surface condition
JD82	31.65	12.48	0.62	DM/DM
JD91	18.83	4.98	0.97	DM/DM
JD262	30.77	-6.24	0.60	D/DM
JD285	30.47	-14.68	0.56	M/M
JD292	41.38	13.98	0.36	D/DM

Table 3: ET (Wm^{-2}) Comparison between observations and proposed method estimates. (Note: Air/Surface Conditions are D for dry pixels, M for humid pixels and MD for mix of dry and wet pixels.)

6- CONCLUSION AND DISCUSSION

The proposed approach takes Grager and Gray's complementary formulation and establishes a new parameter that relates actual and potential evapotranspiration with simple a readily available data. The friction factor and wind speed relationships are not needed in this formulation. Priestley-Taylor's equation is used to compute Ew, which has been widely used for wet environments, where the main driving force is the available radiant energy. In this application, the relative evaporation is obtained with remotely sensed data acquired from MODIS sensors. The physical realism of the proposed method makes it scalable in space and time.

The key variable introduced in this formulation is Tw, the temperature at which the surface would be saturated without changing the surface actual vapor pressure, e_s. We have estimated Tw from the saturation vapor pressure curve proposed by Buck (1981) assuming that water in unsaturated surfaces behave like in saturated surfaces, however we recognize an adjustment factor needs to be incorporated when the surface is not saturated. A more realistic surrogate for Tw could be obtained from night surface temperature maps, also available from MODIS sensors. The surface thermal inertia depends on the surface moisture, among others factors and it is usually mapped from day-night temperature variation (Rees 2001). Besides, the analogy with dew temperature concept indicates that early morning surface temperature may be a good approximation of Tw.

The results presented here suggest relatively good performance of this methodology. In addition to global metrics, day-to-day comparisons of our estimates with observed ET show a realistic match; with an overall RMSE and bias of 31.68 and -5.11 Wm^{-2} respectively. These results are comparable with those reported with complex formulations (Kustas et al. 2003, Rivas and Caselles 2004, Nishida et al. 2003, Norman et al. 2003, Grago and Crowley 2005).

This work presents a robust new approach for clear sky days. Our ongoing research will address extension of this methodology for partially cloudy

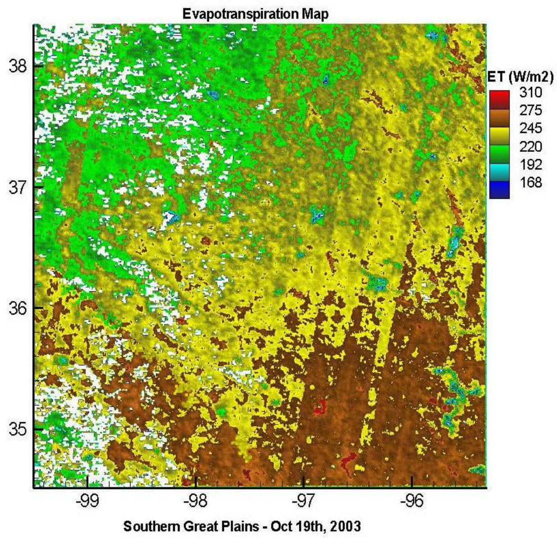

Figure 5: Evapotranspiration (Wm^{-2}) Map for the SGP.

and cloudy days using data from passive microwave sensors, such as the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) instrument on the NASA EOS Aqua satellite.

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