CONTROLLING FACTORS OF POTENTIAL EVAPOTRANSPIRATION ABOVE GRASSLAND IN HUMID AND ARID AREA

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ABSTRACT

Potential evapotranspiration (PET) is an importance process in water balance studies controlled by a number of meteorological factors such as temperature, wind speed, atmospheric pressure, solar radiation, vapor pressure gradient, relative humidity and biological factors such as vegetation type, canopy height and plant density that varied in time-scale and in spatial scale. Of all those variables, determining the most controlling factors of evapotranspiration in humid and arid area is of interest of this paper. Two sites representing humid and arid area i.e. Fermi Prairie site in Illinois and Audubon Research Ranch in Arizona respectively were investigated in this study. The flux data employed in this study was acquired from Ameriflux Netwotk. Penmann-Monteith formula is employed in to estimate evapotranspiration rate in both sites. The result shows that the PET is in dependence on the considered meteorological factor such as shortwave radiation, vapor pressure, air temperature, wind speed, net radiation and vapor pressure deficit. It is also can be inferred from the analysis that PET is also strongly controlled by vegetation factors represented as stomatal resistance.

Keywords: Potential evapotranspiration, Penmann-Monteith, humid, arid.

1 INTRODUCTION

Potential evapotranspiration (PET) that can be expressed in term of mass transfer, energy budget and water budget is an importance process in water balance studies controlled by a number of meteorological factors such as temperature, wind speed, atmospheric pressure, solar radiation, vapor pressure gradient, relative humidity and biological factors such as vegetation type, canopy height and plant density in the spatial scale (Morton, 1968; Jarvis and McNaughton, 1986; Xu and Singh, 1998). Some meteological factors controlling PET above the land surface was found varied in time-scale (Xu and Singh, 1998) and in spatial scale (Hubbard, 1994). Transpiration, which is evaporation from vegetation surface, is controlled by characteristic of leaf that expressed as stomatal resistance and boundary layer resistance that is well described by Penman-Monteith formula (Saugier and Katerji, 1991, Wever, Flanagan and Carlson, 2002).

To relatively simplify the meteorological variability analysis in spatial scale, it is common to divide climate zone as humid and arid zone. In the United States, eastern portion of this continent is defined as humid area, meanwhile western portion starting from midway of Great Plains to Rocky Mountain except western Washington, Oregon and northwest California is classified as arid area (Powell, 1879). Humid area is indicated by the high rate of precipitation instead of that in the arid area in which agricultural water requirements must be charged from irrigation (Powell, 1879). Meteorological factors vary seasonally from winter, spring, summer and autumn that lead to the variability of PET above vegetative surface in which the peak of daily PET occurs in the growing season from May to September and the lowest rate of evapotraspiration occurs in the winter and autumn season (Xu and Singh, 1998, Ripley and Saugier, 1978).

Grassland is one of the interesting vegetation types for the study of environmental response on climate since it shows largest variation of primary production inter-annually in the ecosystem of the continental US (Wever, Flanagan and Carlson, 2002). Many studies have been addressed to C4 and C3 grasses in term of primary production, their response to the environmental changes in spatial scale and time scale. Evatranspiration rate, both hourly and daily rate, is controlled by some factors of the grass such as Leaf Area Index (LAI), canopy height, grass density, stomatal resistance and boundary layer resistance (Wever, Flanagan and Carlson, 2002; Ripley and Sauiger, 1978).

PET can be estimated using mass transfer method, temperate based method, humidity based method and solar radiation based method. Xu and Singh (1998) studied evaporation on meteorological variables and compared various estimation methods such as mass transfer method represented by Penman formula, humidity based method represented by Romanenko equation, radiation based method expressed as Turc equation and temperate based method of Thornthwaite equation found that Penman equation resulted a monthly evaporation that corroborate the pan evaporation while the other methods is found to be underestimate significantly in the cold months. In order to consider the transpiration contribution from vegetative surface to the total losses of water vapor above the surface, Penman-Monteith formula is well known to be the closest approximation of canopy PET (Saugier and Katerji, 1991).
This study was carried out to estimate PET using Penman-Monteith formula from grassland vegetation type in the 2 distinct climate zones of Arizona and Illinois. Comparison was made in term of seasonal variability and spatial variability from 2005 to 2008 available data in the considered area of study. The controlling factors of the PET in the two regions were estimated and discussed based on the variability of seasonal estimated PET that will be computed from the mean value of the available data.

2 METHODOLOGY

2.1 Site Description

Two sites representing humid and arid area which is Fermi Prairie site in Illinois and Audubon Research Ranch in Arizona respectively were investigated in this study. The flux data employed in this study was acquired from Ameriflux Netwotk. Fermi Prairie covered by C4 grass and forbs is situated in Lat. 41.8406 and Long. -88.2410 above silty clay loam topsoil with clay subsoil type at 226 m above mean sea level. The flux is measured at 3.76 m above the ground using rigid aluminum tripod tower. Air temperature is measured using Temperate Probe at 3.76 m, atmospheric pressure, Leaf Area Index (LAI), solar radiation, net radiation, wind speed, relative humidity and precipitation are measured using Barometer at 1.5 m, Ceptometer at 2.4 m, Radiometer at 2.4 m, Net Radiometer at 2.4 m, 3D Sonic Anemometer at 3.76 m, Humidity Probe at 3.76 m , and Tipping Bucket Rain Gauge at 2.0 m respectively. The mean annual precipitation from 1973 – 1985 is 921 mm, Leaf Area Index (LAI) from average of 23 values from 2005– 2007 is 2.43 $m^2 m^{-2}$.

The canopy height of C4 grassland in this sites was estimated to be 10 cm (LS Barden, 1987), leaf diameter was estimated from leaf area of range 2.18 cm^2 – 5.13 cm^2 and can be estimated to be 0.5 cm.

Audubon Research Ranch site situated in Lat. 31.5907 and Long. -110.5092 is covered by 10 – 20 cm of dessert grassland at 1469 m above mean sea level in Arizona. The flux data is measured by 4 m tower installed in this site. Air temperature is measured using Temperate Probe, atmospheric pressure, solar radiation, net radiation, wind speed, relative humidity and precipitation are measured using Barometer, Net Radiometer, Net Radiometer, 3D Sonic Anemometer at 4 m, Humidity Probe, and Tipping Bucket Rain Gauge respectively. The mean annual precipitation is 921 mm, mean annual air temperature is 15.96 °C, maximum air temperature is 38.6 °C, minimum air temperature is -11.6 °C based on 2002 – 2005 data. Leaf Area Index (LAI) taken from Tilden Meyers is 1 m^2 m^{-2}, leaf diameter was simply assumed to be 0.5 cm based on the estimation of C4 grassland.

2.2 Data collection

The data of 2005 – 2008 global solar radiation, net radiation, air temperature, wind speed, relative humidity, precipitation and LAI of these 2 sites were collected from Ameriflux Network. There are 4 level access data available from Ameriflux Network indicating different data process at each level. Compatible data for these sites to be employed in the Penman-Monteith equation was obtained from Level 2 data in form of half hourly data. There are some gaps along this Level 2 data needed to be filled. The gap data was filled using the mean value of data from the same time of preceding day and the following day. The hourly data was estimated by picking up the value of data at hour 1, 2, 3 and so forth except for rainfall data that was estimated by summing the value from hour1 and 1.30, 2 and 2.30 and so forth. Mean daily values of the meteorological data were computed by averaging the value from hour 1 to 24 unless for rainfall data that was calculated by summing the rainfall intensity value from hour 1 to 24.

2.3 Data Analysis

Provided the value of air temperature, global radiation, net radiation, wind speed, relative humidity, PET rate can be estimated using Penman-Monteith equation expressed as:

$$\lambda E = +\frac{\Delta Q_n + \frac{\rho C_p}{rA}(es(T_{atm}) - e_{atm})}{\Delta + \gamma\left(1 + \frac{rst}{rA}\right)} \quad (1)$$

where λE is latent heat flux (W m^{-2}), Q_n is available energy flux density (W m^{-2}) , ρ is air density (kg m-3), C_p is air heat capacity (J kg^{-1} K^{-1}), $es(T_{atm})$ is saturation vapor pressure (hPa), e_{atm} is atmospheric vapor pressure (hPa), Δ is Clausius-Clayperon equation (hPa K^{-1}), γ is psychometric constant (hPa K^{-1}) rst is stomatal resistance (s m^{-1}) and rA is aerodynamic resistance (s m^{-1}). Vapor pressure, saturation vapor pressure, Clausius-Clayperon equation and psychometric are parameters depend on air temperature that can be expressed as follow.

$$e_{atm} = q\ es(T_{atm}) \quad (2)$$

$$es(T_{atm}) = 2.53 \times 10^{11}\ e^{\frac{-5.42\times10^3}{T_{atm}}} \quad (3)$$

$$\Delta = \frac{5.48\times10^8\ \lambda\ e^{\frac{-5.42\times10^3}{T_{atm}}}}{T_{atm}^2} \quad (4)$$

$$\gamma = \frac{C_p\ P_{atm}}{0.622\ \lambda} \quad (5)$$

where T_{atm} is air temperature (K) and P_{atm} is atmospheric pressure (hPa) and q is relative humidity (g g^{-1}).

The idea of Bowen (1926) and Penman (1948, 1953) to collaborate mechanism of separating molecules of liquid water and diffusion mechanism of transferring water from evaporating surface to calculate evaporation from wetland and vegetative surface was completed by Monteith (1965) to compute leaf transpiration from vegetation using stomatal resistance, boundary layer resistance and aerodynamic resistance (Saugier and Katerji, 1991). Aerodynamic resistance consists of bulk density resistance (*ra*) and boundary layer resistance (*rb*) (Ivanov, 2010).

$$ra_0 = \int_{H_{top}}^{Z_{atm}} \frac{1}{Km(z)}\, dz \quad (6)$$

$$ra = \int_{z=0}^{H_{top}} \frac{1}{Km(z)}\, dz \quad (7)$$

$$\frac{1}{rb} = 0.01 \left[\frac{u(z)}{d_{leaf}}\right]^{0.5} dL \quad (8)$$

where ra_0 is bulk density resistance above canopy layer (s m^{-1}), ra is bulk density resistance within canopy layer (s m^{-1}), rb is boundary layer resistance (s m^{-1}), $u(z)$ is mean in-canopy wind speed distribution (m s^{-1}) and d_{leaf} is mean leaf dimension in the direction of wind flow (m).

Stomatal resistance varies from the bottom to the top of canopy and depends on the light received by leaves in which depends on the short waver radiation above the canopy. Stomatal resistance therefore can be approached by

$$rst = \frac{K_0}{S_{atm}(0)e^{(-\alpha_0 L)}}\,[s\ m^{-1}] \quad (9)$$

where $\kappa_0 = 0.9\ x\ 10^5$ is relationship parameter, S_{atm} is short wave radiation (W m^{-2}), α_0 is the decay parameter for shortwave radiation and L is the downward cumulative of LAI (m^2 m^{-2}).

In order to consider evaporation from the soil surface, parameterization of heat transfer from soil surface should be made that can be estimated by using empirically obtained turbulent transfer coefficient between underlying soil and the canopy.

$$ra_4 = \frac{1}{C_s\ U_*} \quad (10)$$

$$C_s = C_s\ bareW_v + C_s dense(1 - W_v) \quad (11)$$

$$W_v = e^{(-(LT+0.2))}$$

$$C_s dense = 1$$

$$C_s bare = \frac{k}{0.13}\left(\frac{z_{om4}}{1.5\times10^{-5}}\right)^{-0.45} \quad (12)$$

where $z_{om4} = 0.01\ (m)$ is the roughness length for bare soil, u_* is friction velocity (m s^{-1}) and LT is Leaf Area Index (m^2 m^{-2}).

3 RESULT AND ANALYSIS

3.1 Evaporation and meteorology variability in humid and arid area

The mean daily PET in humid area of Fermi Prairie and arid area of Audubon Ranch show a consistent annual pattern from 2005 to 2008. The annual pattern of daily PET (Figure 1) shows that PET in Audubon Ranch is greater than that in Fermi Prairie from January – April and from November – December with range of total PET is 134 mm – 180 mm and 190 mm – 250 mm for January – April, 29 mm – 49 mm and 45 mm – 62 mm for November - December in Fermi Prairie and Audubon Ranch respectively. In the growing season (May – October), the daily PET in Audubon Ranch is less than that in Fermi Prairie with range of total PET is 716 mm –

773 mm and 569 mm – 636 mm in Fermi Prairie and Audubon Ranch respectively (Table 1).

The mean PET of 2005 – 2008 in these both sites demonstrates an identical variation (Figure 2) as the individual year value. Fermi Prairie PET has a greater variability in a year than that of Audubon Ranch in which minimum and maximum daily PET are 0.06 mm and 6.7 mm in Fermi Prairie, 0.38 mm and 4.7 mm in Audubon Ranch respectively. The mean daily PET is 2.5 mm/day in humid area and 2.4 mm/day in arid area. The total PET of 917 mm/year in humid area is higher than total precipitation in this area about 870 mm. Niemann and Eltahir (2004) studied water balance in Illinois River Basin using data from 1984 – 1994 reported that PET in this area varies from 850 mm/year – 1150 mm/year with mean PET from the considered data is 956 mm/year. Total PET of 876 mm/year in arid area exceeds the total precipitation about 390 mm/year in this area (Figure 3). Sivakumar (1987) studied evaporation in arid area in Niger found that evaporation of 2600 mm/year is four times of precipitation in the same year. Reich *et al* (1999) calculated PET using open-pan evaporation found that in the desert grassland of Sevilleta, New Mexico, USA, PET of 2428 mm/year is 10 times of the rainfall intensity of 222 mm/year.

These results are confirmed by the great variability of meteorological factors such as air temperature, wind speed, relative humidity, global radiation, net radiation, vapor pressure and vapor pressure deficit (Figure 3, Figure 4 and Table 2). Camargo and Hubbard (1998) studied the spatial and temporal variability of daily weather variables focusing on air temperature, solar radiation, relative humidity, wind speed, PET in sub-humid and semi-arid area in US high plain found that there is a great variability of those meteorological factors from western to eastern US and from winter to autumn season.

Table 1. Total PET in Fermi Prairie and Audubon Ranch 2005-2008

Sites	Total PET (mm)											
	2005			2006			2007			2008		
	Jan-April	May-Oct	Nov-Dec	Jan-April	May-Oct	Nov-Dec	Jan-April	May-Oct	Nov-Dec	Jan-April	May-Oct	Nov-Dec
Fermi	149	723	49	180	716	29	152	773	29	134	725	**
Audubon	226	577	45	190	569	49	222	636	62	250	632	45

** missing data

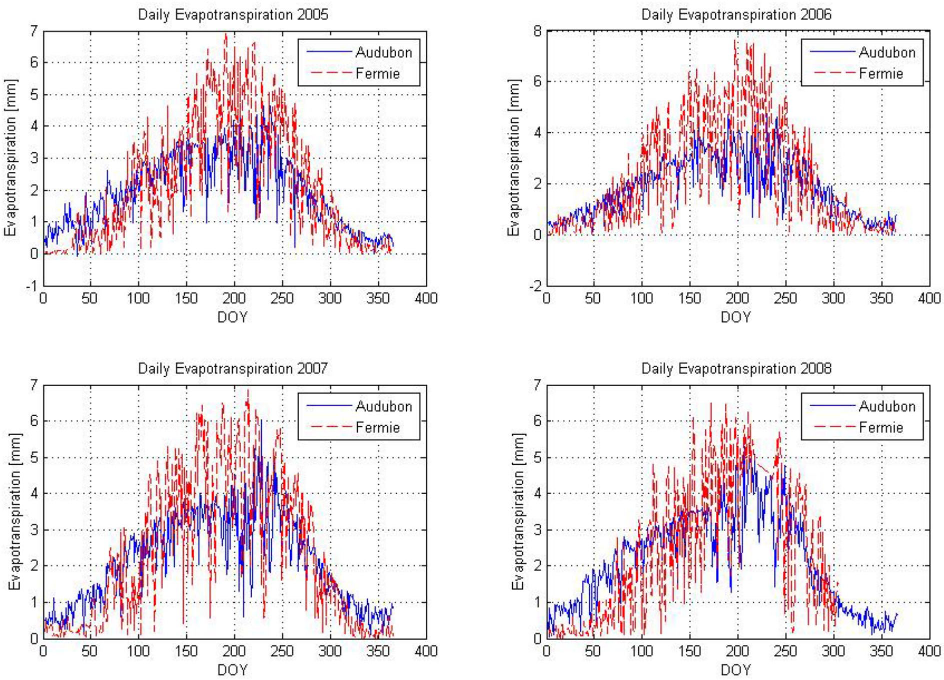

Figure 1. Daily evapotranspiration 2005-2008

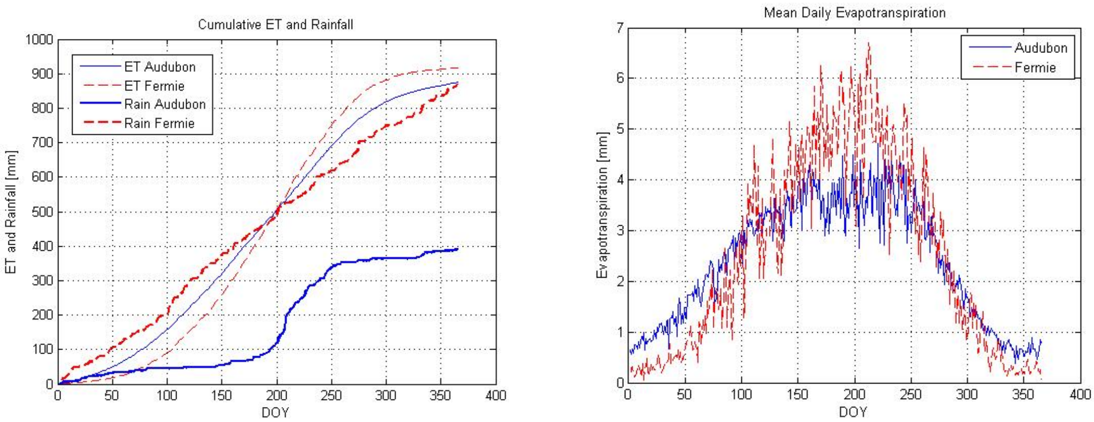

Figure 2. Mean daily PET and cumulative PET

Table 2. Variability of meteorological factors in Fermi Prairie and Audubon Ranch

Variable	Fermi			Audubon		
	Jan-April	May-Oct	Nov-Dec	Jan-April	May-Oct	Nov-Dec
Daily Mean Temperature (C)	1.62	18.56	0.94	10.33	21.40	9.14
Total Shortwave Radiation (W m^{-2})	15204	38530	4055	27598	49373	9715
Total Net Radiation (W m^{-2})	7491	24010	1476	5938	16665	154
Daily Mean Wind Speed (m s^{-1})	3.37	2.44	2.93	2.84	2.38	2.24
Total Precipitation (mm)	296	455	119	48	315	27
Total PET (mm)	125	657	23	181	530	39

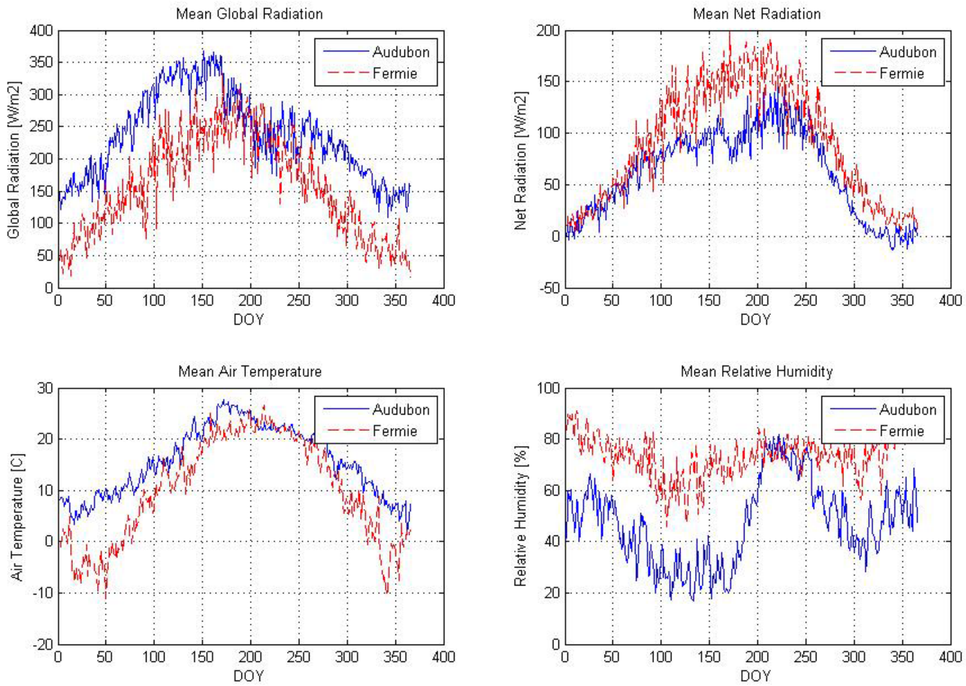

Figure 3. Variability of solar radiation, net radiation, temperature and relative humidity

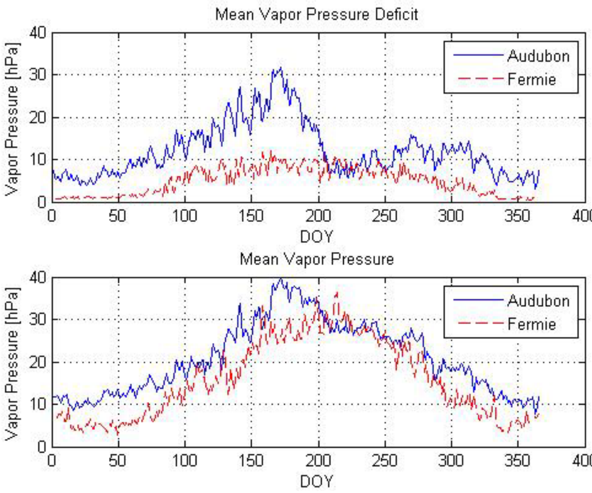

Figure 4. Variability of vapor pressure and vapor pressure deficit

3.2 PET dependence on meteorology

The dimensionless quantity is preferable to comparatively evaluate the dependence of PET on meteorological factors. Standardized value was computed and compared using this transformation equation (Xu and Singh, 1998).

$$Z_i = \frac{X_i - \mu}{\alpha} \tag{13}$$

where Z_i is standardized value, X_i is variate, i is the ith value, μ is the mean of X, and σ is the standard deviation of X. The result is illustrated in Figure 5 .

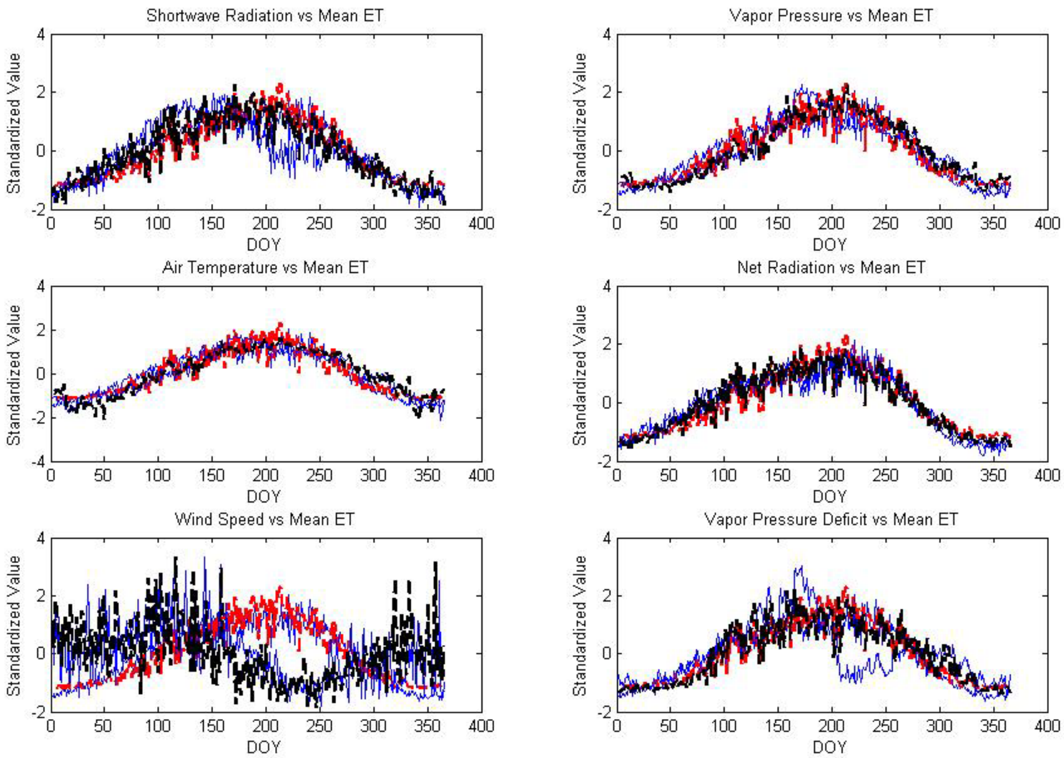

Figure 5. Dependence of evaporation on meteorological factors in different time scale (data from 2005 - 2008)

Figure 5 plotting the standardized value of PET and certain meteorological factor on each graph clearly illustrates the similarity of those value meaning that the PET is in dependence on the considered meteorological factor such as shortwave radiation, vapor pressure, air temperature, wind speed, net radiation and vapor pressure deficit. Xu and Singh (1998) studied the dependence of evaporation on meteorological factors confirmed that relative humidity, short radiation, air temperature, wind speed and vapor pressure deficit is a good indicator of evaporation at a different scale time of hourly 10 daily and monthly. This findings is also in agreement with Linsley statement (1982): *"If radiation exchange and all other meteorological elements were to remain constant over a shallow lake for an appreciable time, the water temperature and evaporation rate would become constant. If the wind speed were then suddenly doubled, the evaporation rate would also double momentarily. The increased rate of evaporation would immediately begin to extract heat from the water at a more rapid rate than what could be replaced by radiation and conduction. The water temperature would approach a new, lower* *equilibrium value, and evaporation would diminish accordingly. On a long-term basis, a change of 10% in wind speed will change evaporation only 1 to 3%, depending on other meteorological factors".*

3.3 PET dependence on vegetation

Figure 3 and Figure 4 in this paper describe clearly that in day between 210 to 230, the values of solar radiation, net radiation, air temperature, relative humidity, vapor pressure and vapor pressure deficit are similar in magnitude showing that at this time the meteorological conditions in the both sites are similar. At this time, wind speed is 1.87 m/s in Audubon and Fermi, air temperature is 22.2 °C and 23.4 °C, vapor pressure is 27 hPa and 30 hPa, short radiation is 231 W/m^2 and 231 W/m^2, relative humidity is 76.27% and 74.64%, vapor pressure deficit is 7.65 hPa and 8.72 hPa in Audubon and Fermi respectively. This similarity of meteorology conditions leads to the consequence that different PET is strongly controlled by vegetation factors represented as stomatal resistance. Figure 6 illustrates that the stomatal resistance in Fermi Prairie at the considered time is lower than that in the Audubon Ranch. At the same time, the PET in Fermi Prairie is higher than that in Audubon Ranch (Figure 7).

Mean hourly PET in Fermi Prairie and Audubon Ranch in day 210 – 240 are 5.2 mm/day and 3.8 mm/day. The difference in value of LAI about 1.43 m^2 m^{-2} resulting from LAI of 2.43 m^2 m^{-2} in Fermi Prairie and 1 m^2 m^{-2} in Audubon Ranch decreases the PET by 1.4 mm/hr. This disparity is resulting from the difference of mean of minimum stomatal resistance about 89 s/m and 126 s/m, aerodynamic resistance of 179 s/m and 158 s/m in Fermi Prairie and Audubon Ranch respectively.

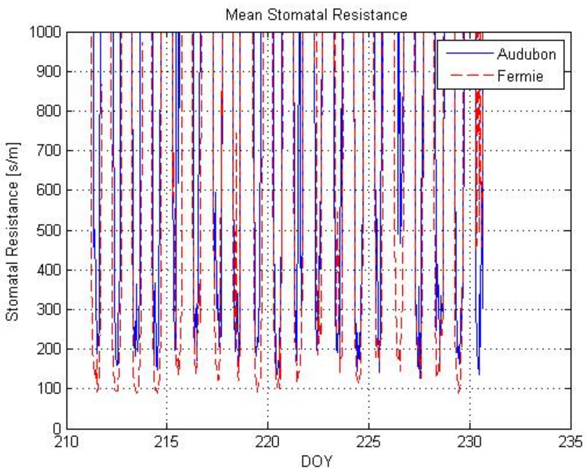

Figure 6. Stomatal resistance in day 210 – 230

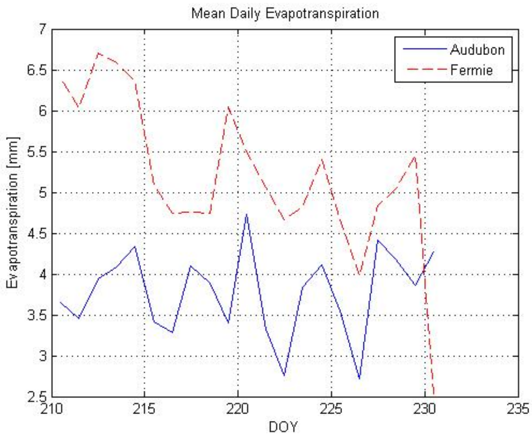

Figure 7. PET in day 210 - 230

4 DISCUSSION

Mean daily PET is 2.5 mm/day in humid area and 2.4 mm/day in arid area. PET from humid area in Fermi Prairie and arid area in Audubon Research Ranch has a typical annual pattern from 2005 to 2008. The PET varies seasonally from winter to autumn in which PET in arid area is greater than that in humid area for January – April and November – December, meanwhile the rate in arid area is less than that in humid area at a growing season from May – October. This variability of PET in humid and arid area is controlled by variability of meteorological factors and grassland characteristic in the considered area. The total PET 917 mm/year in humid area in Fermi Prairie is less than the total precipitation 890 mm/year, meanwhile the total PET in Audubon Ranch of 876 mm/year is double to the total precipitation of 390 mm/year.

The dimensionless quantity analysis demonstrates the dependence of PET on meteorological factors. The data from day 210 – 230 shows the dependence of PET on vegetative factors represented by stomatal resistance. This data also illustrates the significant of Leaf Area Index as a factor controlling PET in which the decrease of LAI about 1.43 m^2 m^{-2} leads the decrease of PET by 1.4 mm/day.

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