SPATIAL AND TEMPORAL VARIABILITY IN REFERENCE EVAPOTRANSPIRATION IN OKLAHOMA

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ABSTRACT

Reference evapotranspiration (ET_{ref}) is an important indicator of a region's climate, specifically its evaporative demand. Evapotranspiration (ET) is a key component of the energy and water balance of a given environment. Information on ET_{ref} is essential in the quantification of water use in agricultural, natural and urban landscape systems. Various formulations of ET_{ref} have been used over the past several decades. Recently, the Task Committee of American Society of Civil Engineers (ASCE) Evapotranspiration in Irrigation and Hydrology Committee developed a standardized procedure for computing reference evapotranspiration for grass (ET_{os}) and alfalfa reference crops. Accurate ET_{ref} computations using data from a network of weather stations require a careful check of the data quality and the similarity of site surface conditions to reference standards when data is acquired. Despite a lack of coastal effects or significant orographic influences, Oklahoma appears to exhibit considerable spatial and temporal variability in evaporative demand. The availability of the Oklahoma Mesonet, a comprehensive automated weather station network, provides an opportunity to study ET_{ref} patterns across the state and through time. The Mesonet is a network of 115 well-distributed and well-maintained stations. Using seven years of quality assured data from this network, daily ET_{os} has been calculated for 40 sites representing the diverse Oklahoma climate. Spatial and temporal variability in ET_{os} is discussed. This analysis is a precursor to on-line mapping of reference evapotranspiration and identification of geo-spatial ET_{os} zones.

INTRODUCTION

Quantification ET_{ref} in space and time is required in the analysis of irrigation water management in agricultural and urban landscapes. Evapotranspiration is also a major component in water quantity and quality models.

The rate of ET from soil and vegetated surfaces is dependent upon the atmospheric demand for water and the surface characteristics. In the commonly applied two-step approach to estimating ET, the atmospheric demand is quantified through the calculation of ET_{ref} and the surface characteristics are incorporated into a crop coefficient (K_c). The product of these two parameters provides an

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estimate of the actual ET. ET_{ref} has been defined as "the rate at which water, if readily available, would be removed from the soil and plant surface of a specific crop, arbitrarily called a reference crop" (Jensen et al., 1990). Thus, ET_{ref} computation forms an integral part of water balance studies.

Several ET equations are used to compute ET_{ref}, creating confusion about which to use. To minimize the confusion and facilitate ET comparisons across regions, the ASCE Evapotranspiration in Irrigation and Hydrology Committee has recently adopted a standard reference ET computation method and procedure to compute reference ET for grass and alfalfa crops (Walter et al., 2000). The standard also simplifies the transfer of K_c's from one region to another. The standard equation for daily ET_{os} (mm d^{-1}) is as follows:

$$ET_{os} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1+0.34u_2)} \tag{1}$$

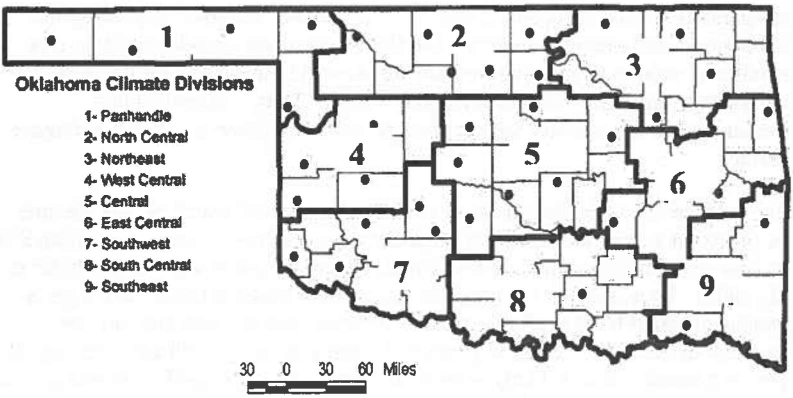
where R_n is net radiation (MJ m^{-2} d^{-1}); G is soil heat flux density at the soil surface (MJ m^{-2} d^{-1}) ; T is mean daily temperature at a 1.5 to 2.5 m height (°C); u_2 is mean daily wind speed at 2-m height (m s^{-1}); e_s is mean saturation vapor pressure at a 1.5 to 2.5-m height above the surface (kPa); e_s is the average of e_s at maximum and minimum air temperature; e_a is mean actual vapor pressure at a 1.5 to 2.5-m height above the surface (kPa); Δ is the slope of the vapor pressure-temperature curve (kPa) and γ is the psychrometric constant (kPa $°C^{-1}$).

As the need for timely ET information continues to grow, the advancement in electronic instrumentation and communication have expanded real time operated automatic weather stations. These stations measure weather variables that enable one to compute ET_{ref} directly. The Oklahoma Mesonet is a unique network with a high density of well-maintained and operated stations. It has 115 stations covering the entire state with an average spacing of 32 kilometers (Elliott et al., 1994). At each site, standard weather and soil variables are sensed every few seconds (Brock et al., 1995), logged at 5-minute intervals, transmitted to a central facility every 15 minutes, and then verified and made available to customers in near real-time. The availability of the Mesonet's quality data allows the study of the spatial and temporal patterns in ET_{os} across the state, as well as the ability to provide on-line ET_{os} tables and maps for customers. ET_{ref} computations require good quality weather data collected under standard reference surface conditions, i.e., an extensive open surface covered by green grass or other short vegetation that is not short of water. Thus, it is necessary to understand site conditions before computing ET_{ref} directly from data measured at any weather stations.

CLIMATE OF OKLAHOMA

Oklahoma climate is somewhat correlation with its topography. The land surface elevation generally decreases from the west to the east. The vegetation becomes gradually more dense from the semiarid western plains in the Panhandle to the eastern woodlands. Mean annual precipitation ranges from 380 mm in the western plains to 1270 mm in the southeast, and there can be large seasonal and inter-annual variations. Most of the moisture for precipitation is carried from the Gulf of Mexico by the southerly winds. The average annual temperature gradually increases from north to south. The state is divided into nine climate divisions (OCD) as shown in Figure 1.

Figure 1. The Oklahoma climate divisions (OCD) and the locations of the 40 Mesonet sites used in the study.



METHODOLOGY AND PROCEDURE

A total of 40 Mesonet sites with adequate fetch and representing the different climatic regions of the state were selected using site information and photographic documentation (http://okmesonet.ocs.ou.edu/siteinfo/). Three to seven best reference sites with continuously measured data for 1994 to 2000 were chosen from each climate division. For the selected sites, data quality and reference condition checks were made and ET_{os} values were computed for each site daily for seven years. Then, the monthly mean daily ET_{os} ($ET_{os\text{-}m}$) for each month of each year was calculated for each site. Finally the seven years mean ($ET_{os\text{-}7Yav}$), maximum, and minimum of the $ET_{os\text{-}m}$ were determined and their spatial and temporal variability analyzed.

Data quality assurance procedure

The Oklahoma Mesonet has a comprehensive data quality assurance system that incorporates an instrument laboratory, routine and emergency field visits, automated computer routines, and manual inspection of data (Shafer et al., 2000). Each Mesonet datum is archived together with a quality control flag that indicates its degree of accuracy. In our computations of ET_{os}, we used only data that were flagged to be of good quality. In this study, additional data integrity checks such as comparing measured clear day solar radiation to theoretical solar radiation envelopes, and average dew point temperature to daily minimum temperature, were made using guidelines given by Allen (1996).

Check of reference conditions

The standard weather variables that need to be measured under reference conditions and required for ET_{ref} computation include solar radiation, air temperature, wind speed, and humidity. The weather variables, especially the temperature and humidity to be used in the Penman type one-dimensional flux equations, need to be measured within the internal boundary layer that is in complete equilibrium with the reference surface. Thus, it is critical that measurements of reference weather data be collected above a standard reference surface.

Some of the site selection standards used by the Mesonet specified that the sites be placed in a rural and relatively large flat open area free of obstacles within 300 m, and covered with a uniform low-cover, preferably grass vegetation (Shafer et al., 1993). Thus, most of the Mesonet sites are covered with short native grass and have a good fetch in all directions. However, the Mesonet sites are not irrigated to keep the vegetation green and transpiring fully at all times during the growing season. This is likely to be more of a problem for shallow rooted grasses as compared to deep rooted and drought-resistant native vegetation. During the growing season, the extent that a Mesonet site will be at or near reference conditions depends on the availability of adequate soil moisture for reference vegetation to meet its ET demand. Hence, the net rainfall (that infiltrating into the soil) is critical. Depending on the net rainfall at a site, the surface condition can vary from a reference type to one covered with dried vegetation and with negligible ET. Thus for the Mesonet sites, the rainfall amount, frequency and distribution become key in determining whether the site surface condition is that of reference. It is necessary to identify any extended dry periods and examine the data and ET_{os} computed during such periods carefully.

On clear days, the partitioning of the energy balance on a non-reference surface generates high sensible heat due to the relatively less or non-transpiring vegetation, thus increasing the temperature measured above the surface. The high temperature and the low humidity due to the dry air above the surface result in a higher calculated vapor pressure deficit than what it would have been under a normal reference condition. Vapor pressure deficit can also be transported from a surrounding dry area. This non-reference effect will result in the over prediction of ET_{os}. For example, Brown (2001) reported the impact of extreme site aridity at Parker, AZ, that showed significant increase in monthly total ET_{os} (18-26%) during June through September. The non-reference effect of over predicting ET_{os} is particularly important during peak ET periods because they directly affect the size of irrigation systems. For irrigation scheduling, unrealistically high ET_{ref} values can translate into inefficiencies due to over watering, but that may in fact be more desirable than under irrigation that results in crop stress.

Since reference surface conditions directly modify the temperature and humidity measurements at a given weather stations, comparing these two measurements with their corresponding ranges under standard reference conditions helps us to identify potential non-reference conditions. Under reference conditions, the maximum relative humidity (RH_{max}) generally exceeds 90% during early morning hours, especially when skies are clear and winds are light, and minimum relative humidity RH_{min} is expected to be above 25%. The minimum temperature (T_{min}) will also approach the dewpoint temperature (T_{dew}) and T_{min} minus T_{dew} (T_{min}-T_{dew}) is often less than 2°C and in a semiarid environment it is likely to be less than 4 or 5°C (Allen, 1996; Allen et al., 1998). Although most of Oklahoma, especially the western part, is characterized by high winds that strengthen the mixing of the boundary layer and increase the transport of air properties from the surroundings making the processes more dynamic and complex the assessment variables mentioned above could help us identify non-reference days. Thus, in our checks for reference conditions, plots of RH_{max} and RH_{min}, as well as the trend in both T_{min} and T_{dew} combined with the precipitation data were used to identify days where the site conditions are more likely to be of a non-reference condition.

Checking the daily data for the 40 sites, the growing season's T_{min}-T_{dew} for days with significant rainfall (greater than 8 mm) is on average lower than 7°C for the semi-arid sites in the western part of the state and 4°C for the more humid sites in the east. The RH_{max} for these reference days is above 90% most of the time and in particular approaches 100% for the sites in the east. On non-reference days T_{min}-T_{dew} reached as high as 20°C in the west and 10°C in the east. Querying the growing season daily data for a site, using T_{min}-T_{dew} of greater than 5°C and RH_{max} of less than 90% appears to best capture the non-reference days across the sites. In this study, if both of the above criteria were met, the day was assumed to be a non-reference day. In general, the sites in the western part of the state which are characterized by relatively less rainfall and high winds were found to have a greater occurrence of non reference conditions compared to the sites in the east. Moreover, sites within the same OCD showed different patterns of non-reference periods through the months and the years due to the variation in the amount of rainfall received at each site. For most of the sites the month with most non-reference days during the seven years period was September, followed by August. The non-reference days at a site per month varied from zero days up to three weeks. A long dry period in August and September 2000 affected all 40 sites. During this dry period, the non-reference days at a site in August and September varied from 39 days in the Panhandle to 2 days in the southeast. On the other hand, June and July 1999 were without non-reference days for most of the sites.

ET_{os} for each site was computed using all the data for the seven years as well as after removing all non-reference days identified at each site. The results showed that the $ET_{os\text{-}m}$ without removing the non-reference days was higher by 2-18% compared to the $ET_{os\text{-}m}$ after removing the non-reference days. The effect of not filtering non-reference days is high in our ET_{os} especially during the peak ET_{os} days. The yearly peak daily ET_{os} overestimation at a site varied from 0 to 49%. Most of the peak daily ET_{os}s computed at a site were found to be associated with non-reference days. Allen et al. (1998) and Temesgen et al. (1999) suggested simple empirical adjustment procedures for air temperature and humidity data measured under non-reference conditions. In this study, no attempt was made to correct data for non-reference conditions. But, all ET_{os} for the non-reference days, as identified above, were excluded in the analysis to be discussed in the next section.

<u>Spatial and temporal trend analysis procedures for computed ET_{os}</u>

Spatial and temporal trends of $ET_{os\text{-}m}$ and $ET_{os\text{-}7Yav}$ were studied. Analysis were limited to growing-season months as these periods are of most interest to agriculture and are characterized by active vegetation growth consistent with the reference ET computation. The spatial and temporal analysis of variance of the $ET_{os\text{-}m}$ and $ET_{os\text{-}7Yav}$ were analyzed using Statistical Analysis Software (SAS), (SAS Institute Inc., 2000) and other standard statistics that measure variability and the extremes. Separation of means was determined by the least significant difference (LSD) method. For the SAS analysis of the $ET_{os\text{-}7Yav}$, a probability level $\propto = 0.05$ is implied whenever significant difference is mentioned in the text. The coefficient of variation (CV), the ratio of the standard deviation to the mean, is used to measure spatial variability and consistency of ET_{os} across the sites. In addition, the maxima and the minima of $ET_{os\text{-}m}$ and $ET_{os\text{-}7Yav}$ provide insight about extreme values. Using the above statistics the temporal variability of $ET_{os\text{-}7Yav}$ across the growing season months and years and the spatial variability across the OCDs were identified and discussed.

RESULTS AND DISCUSSION

The seven years (1994-2000) growing season $ET_{os\text{-}7Yav}$ computed for the 40 sites representing the nine climatic divisions of Oklahoma are in Figure 2. The elevations of the sites are included in the figure. On the abscissa of Figure 2, the sites within each OCD (the character following site ID on the abscissa designates its OCD) are arranged from left to right in a decreasing longitude (west to east) and in a decreasing site elevation. The top and bottom smooth lines enclosing the growing season's $ET_{os\text{-}7Yav}$ in Figure 2 indicate the seven-year maximum and minimum $ET_{os\text{-}m}$ at each site. In the same figure, the maximum $ET_{os\text{-}7Yav}$ for most of the sites occurred in July followed by June or August, and the minimum occurred in October. $ET_{os\text{-}7Yav}$ of 7.34 mm d^{-1} in July and 2.36 mm d^{-1} in October are the extremes. In general, $ET_{os\text{-}7Yav}$ for all the months uniformly decreases with decreasing elevation from the western part of the state to the east. Linear regression of each month's $ET_{os\text{-}7Yav}$ on elevations for all sites resulted in r^2 that ranged from 0.66 in October to 0.36 in April with an overall value of 0.54 for all the months. Analysis of the 40 sites, seven years monthly averages showed vapor pressure deficit and wind speed to be the major factors determining the spatial and temporal distributions of ET_{os}. The linear regression of each month's seven years average vapor pressure deficit in kPa and U_2 in m s^{-1} on site longitude in decimal degrees resulted in an average r^2 of 0.64 and 0.62 respectively.

Temporal variability

The temporal variation of $ET_{os\text{-}m}$ and $ET_{os\text{-}7Yav}$ through the growing season months and the seven years is summarized in Tables 1a and 1b. Table 1a is arranged such that each year's $ET_{os\text{-}m}$ mean, maximum, minimum and the CV are given in rows followed by their seasonal mean at the end of the row. The rows at the bottom of the table show similar statistics for the $ET_{os\text{-}7Yav}$. The bottom of Table 1a shows that the mean $ET_{os\text{-}7Yav}$ for all the 40 sites is the highest in July with 6.27 mm d^{-1} and the lowest in October with 3.06 mm d^{-1}. The extremes in the $ET_{os\text{-}m}$ for each year show that the highest was in June 1998 with 8.81 mm d^{-1} at site ALTU (Altus) in OCD 7, and the minimum in October 1994 with 1.58 mm d^{-1} at IDAB (Idabel) in OCD 9. The growing season average $ET_{os\text{-}7Yav}$ is given as 4.81 mm d^{-1}. Analysis of variance on $ET_{os\text{-}m}$ for the growing season months and $ET_{os\text{-}7Yav}$ for the seven years showed significant temporal variability. Pair-wise comparisons on the means based on LSD showed that only June and August are not significantly different from each other (with p value < 0.0001). See the first column in Table 1b. Similar statistical analysis on the yearly mean of $ET_{os\text{-}m}$ showed that some of the years are not significantly different from one another as shown in the second column of Table 1b.

Spatial variability and ET_{os} grouping

As shown in Figure 2 and as discussed above, the $ET_{os\text{-}7Yav}$ variation across the state as we go from west to the east is evident. This variation is also related to the gradually decreasing site elevations from west to east. It appears that a cursory comparison of the growing season $ET_{os\text{-}7Yav}$ for all sites and the respective OCD, as depicted in Figure 2 results in three groupings of the OCDs depending on the magnitude, and the pattern with which the $ET_{os\text{-}7Yav}$ changes within OCD, and the elevations of the sites. The first group could include the sites in the eastern third of the state, those within OCD 3, 6 and 9. These sites show a relatively low and uniform magnitude of $ET_{os\text{-}7Yav}$ compared to the sites in the rest of the central and west OCDs. The second group could consist of the sites in the central part of the state in OCD 2, 5 and 8, which is in a transition from the other zones in the west to those in group one in the east. The third group could be the sites situated in the western third of the state (OCD 1,4 and 7), which are those with a relatively higher ET $_{os\text{-}7Yav}$. However, analysis of variance based on the 40 sites ET $_{os\text{-}7Yav}$ showed significant difference among the nine OCDs ET $_{os\text{-}7Yav}$s. Pair-wise comparisons on the means of the OCD's average ET $_{os\text{-}7Yav}$ based on LCD resulted in four groups as shown in the last column of Table 1b, agreeing with group one and group three discussed earlier. But OCD 2 was identified to be unique, and OCD 8 and OCD 5 could join group one.

In Table 1a, the CVs for each month and in each year indicate the spatial variability of $ET_{os\text{-}m}$ across the 40 sites. Similarly the CVs at the bottom of the table show the spatial variation of ET $_{os\text{-}7Yav}$.across all the sites for each month. The seven years average CVs show that May and June, have relatively higher variability across the sites than the months of April and August.

SUMMARY

The Oklahoma Mesonet provides a high quality, spatially dense, and temporally continuous quality weather data set that allows the study of spatial and temporal patterns in ET_{os} across the state. Rainfall amount and frequency influence the number of reference quality data available to compute ET_{os} at a site. Non-reference days were identified as those with daily T_{min} minus T_{dew} of greater than 5 °C and RH_{max} of less than 90%. Sites in the western part of the state had more non-reference days than those in the east. Analysis of the growing season $ET_{os\text{-}m}$ and $ET_{os\text{-}7Yav}$ over a seven-year period showed a significant temporal and spatial variation across the state. Overall the highest $ET_{os\text{-}7Yav}$ is in July and the lowest in October. In general $ET_{os\text{-}m}$ increased from east to west with increase in site elevation. Vapor pressure deficit and wind speed are the major factors that determine the spatial and temporal distributions of ET_{os} across Oklahoma. The comparison of the climate division means of the $ET_{os\text{-}7Yav}$ resulted in three groups, thus identifying the potential ET_{os} zones for the state.

Figure 2. Growing season ET $_{os\text{-}7Yav}$, maximum and minimum ET$_{os\text{-}m}$ for the 40 sites

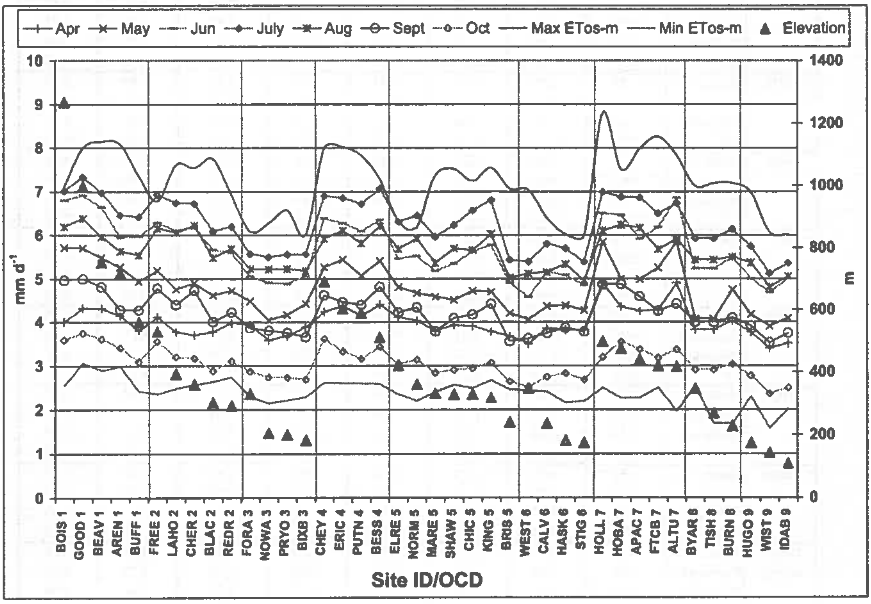


Table 1a. Statistics for monthly and yearly $ET_{os\text{-}m}$ and $ET_{os\text{-}7Yav}$ for the 40 sites

Period	Statistics	April	May	June	July	August	Septembe	October	Mean
		mm d^{1}	mm d^{1}	mm d^{1}	mm d^{1}	mm d^{1}	mm d^{1}	mm d^{1}	mm d^{1}
1994	Mean	4.30	4.26	6.52	6.28	5.86	4.36	2.71	4.90
	Maximum	5.84	5.83	8.21	7.98	7.19	5.98	3.82	6.41
	Minimum	3.31	1.68	5.24	4.83	4.39	3.35	1.58	3.48
	CV	0.13	0.21	0.15	0.15	0.16	0.17	0.15	0.16
1995	Mean	3.69	3.77	5.28	6.32	5.77	3.45	3.67	4.57
	Maximum	4.31	4.83	6.67	7.34	7.39	4.67	4.68	5.70
	Minimum	3.04	3.20	4.40	5.16	5.06	2.99	1.96	3.69
	CV	0.08	0.11	0.09	0.10	0.09	0.10	0.15	0.10
1996	Mean	4.77	5.73	6.13	5.47	4.70	3.52	3.24	4.80
	Maximum	6.68	7.94	7.35	6.34	5.51	4.37	3.96	6.02
	Minimum	3.69	4.17	4.82	4.50	3.89	2.88	2.14	3.73
	CV	0.13	0.16	0.12	0.08	0.08	0.11	0.14	0.12
1997	Mean	3.39	4.76	5.31	6.21	4.94	4.26	2.73	4.52
	Maximum	3.65	5.70	6.20	7.66	5.81	5.23	3.83	5.44
	Minimum	3.02	4.06	4.43	5.09	4.03	3.22	2.01	3.70
	CV	0.05	0.08	0.09	0.12	0.11	0.12	0.16	0.10
1998	Mean	3.97	5.26	6.83	6.79	5.65	4.65	2.88	5.15
	Maximum	4.96	6.62	8.81	8.00	6.52	5.94	3.75	6.37
	Minimum	3.21	4.17	5.31	5.57	4.91	3.39	2.24	4.12
	CV	0.09	0.12	0.12	0.09	0.08	0.14	0.17	0.11
1999	Mean	3.86	4.68	4.92	6.65	6.03	4.14	3.53	4.83
	Maximum	5.08	5.92	6.79	7.84	6.96	5.63	4.90	6.16
	Minimum	3.18	3.69	3.92	5.14	5.18	3.28	2.82	3.89
	CV	0.12	0.12	0.15	0.10	0.07	0.12	0.15	0.12
2000	Mean	3.94	4.97	4.76	6.24	6.62	5.16	2.65	4.90
	Maximum	5.09	6.26	6.68	7.81	7.83	6.09	3.06	6.12
	Minimum	3.07	3.92	3.80	5.04	5.78	4.34	2.26	4.03
	CV	0.10	0.14	0.15	0.13	0.08	0.09	0.07	0.11
7 years average	Mean	3.99	4.77	5.68	6.27	5.65	4.22	3.06	4.81
	Maximum	4.91	5.86	6.91	7.34	6.39	5.00	3.75	5.74
	Minimum	3.40	3.91	4.58	5.13	4.81	3.52	2.36	3.96
	CV	0.08	0.12	0.12	0.10	0.08	0.10	0.11	0.10

Table 1 b. Summary of statistics for temporal (yearly, monthly) and spatial (OCD) variability for the 40 sites.

Month	*Mean $ET_{os\text{-}m}$ mm d^{-1}	Year	*Mean $ET_{os\text{-}m}$ mm d^{-1}	OCD	*Mean $ET_{os\text{-}7Yav}$ mm d^{-1}
April	3.99^{a}	1994	4.90^{a}	1	5.27^{a}
May	4.78^{b}	1995	4.57^{b}	2	4.97^{b}
June	5.68^{c}	1996	4.80^{a}	3	4.33^{c}
July	6.28^{d}	1997	4.52^{b}	4	5.25^{a}
August	5.65^{c}	1998	5.14^{c}	5	$4.68^{d,c}$
September	4.22^{e}	1999	4.83^{a}	6	4.29^{c}
October	3.06^{f}	2000	4.91^{a}	7	5.29^{a}
				8	4.57^{c}
				9	4.18^{c}

*Means with the same letter, within a column, are not significantly different at the probability level $\propto = 0.05$.

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