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Evaluation of Global Daily Reference ET Using Oklahoma's Environmental Monitoring Network—MESONET

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Abstract The objective of this study is to evaluate the potential utility of the USGS Global Data Assimilation System (GDAS) 1-degree, daily reference Evapotranspiration (ET_0) products by comparing them with observed Oklahoma mesonet daily ET_0 over a 2 year period (2005–2006). The comparison showed a close match between the two independent ET_0 products, with bias within a range of 10% for most of the sites and the overall bias of −2.80%. The temporal patterns are strongly correlated, with a correlation coefficient above 0.9 for all groups. In summary, we conclude that (1) the consistent low bias shows the original GDAS ET_0 products have high potentials to be used in land surface modeling; (2) the high temporal correlations demonstrate the capability of GDAS ET_0 to represent the major atmospheric processes that control the daily variation of surface hydrology; (3) The temporal

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and spatial correspondences in trend between independent datasets (GDAS and MESONET) were good. The finding in Oklahoma, a different hydro-climate region from a similar regional study conducted in California by Senay et al. (J Am Water Res Assoc 44(4):969–979, 2008), reconfirms the reliability and potential of using GDAS reference ET for regional energy balance and water resources management in many parts of the world.

Keywords Evapotranspiration (ET) · Reference ET · GDAS · Oklahoma MESONET

1 Introduction

As one of the major components of the hydrologic cycle, land surface evapotranspiration (ET) represents the transport of water into the atmosphere from surfaces including soil (evaporation, E) and vegetation (transpiration, T) (Chauhan and Shrivastava 2009). The process of evaporation and transpiration occurs simultaneously for vegetated areas. For example, for small crops water is lost mainly by soil evaporation, but for well developed crops transpiration becomes the dominating process (Allen et al. 1998). In arid and semi-arid regions, ET is the major source of water depletion. Therefore, quantification of ET is critical for various disciplines especially to those involved in hydrologic budgeting, water resources planning, agricultural irrigation, and ecological system risk management (Allen 2007; Sabziparvar et al. 2010)

Penman (1956) originally defined potential ET as the amount of water transpired per unit time by a short green crop, completely shading the ground, of uniform height and never short of water. This method takes into account a comprehensive range of meteorological factors such as radiation intensity, temperature, humidity, and wind with a number of simplifying assumptions (Krishnan and Kushwaha 1971). Potential ET is gradually being replaced with Reference ET (ET_0) to conform to standard terminology (Allen et al. 1994a, b), particularly in the field of water resources management and irrigation applications according to Senay et al. (2008). The concept of reference ET (ET_0) makes it relatively easy to transfer the calibrated crop-specific coefficients to new study areas (Senay et al. 2008). For further explanation on evapotranspiration and applications, the readers are referred to Penman (1956), Jensen et al. (1990), Shuttleworth (1992), Nokes (1995) and Senay et al. (2008).

Recently, due to the increasing availability of hydrometeorological remote sensing products covering the entire globe, the task of estimation of ET_0 at large scales has become feasible due to affordable computational costs. A multi-year, global ET_0 estimate database at daily 1-degree spatiotemporal resolution has been calculated from the National Oceanic and Atmospheric Administration (NOAA) Global Data Assimilation System (GDAS) (GDAS 2008) (http://earlywarning.usgs.gov/Global/index.php) using global-scale meteorological datasets.

The central objective of this study is to evaluate the potential utility of the GDAS ET_0 products in regional water resource research by comparing with ET_0 data from the Oklahoma Regional Mesoscale Meteorological Observational Network (MESONET). This study evaluated the performance of GDAS in estimating ET_0 in the South Great Plains climatologic zone by comparing in-situ ET_0 calculated from MESONET.

2 Study Area and Methodology

2.1 Study Area

The study area is located in central Oklahoma, USA (Fig. 1). Oklahoma typically has irrigated agriculture, rain-fed agriculture, wetlands, and riparian vegetation, all of which transmit water into the atmosphere through the ET process. It has a semi-arid climate with annual precipitation of about 870 mm. The agriculture predominantly relies on irrigation. Figure 1 also shows the topography of the state of Oklahoma and a daily GDAS ET_0 distribution at 1-degree spatial resolution on a randomly selected day of October 20th 2007.

2.2 ET Models

2.2.1 MESONET ET Model

The Oklahoma MESONET, established in January 1994, measures a wealth of atmospheric and hydrologic variables including solar radiation, humidity, temperature, wind speed and direction, and soil moisture to aid in operational weather forecasting and environmental research across the state (Brock et al. 1995; Oklahoma Mesonet 2008; http://www.mesonet.org). The MESONET network consists of 120

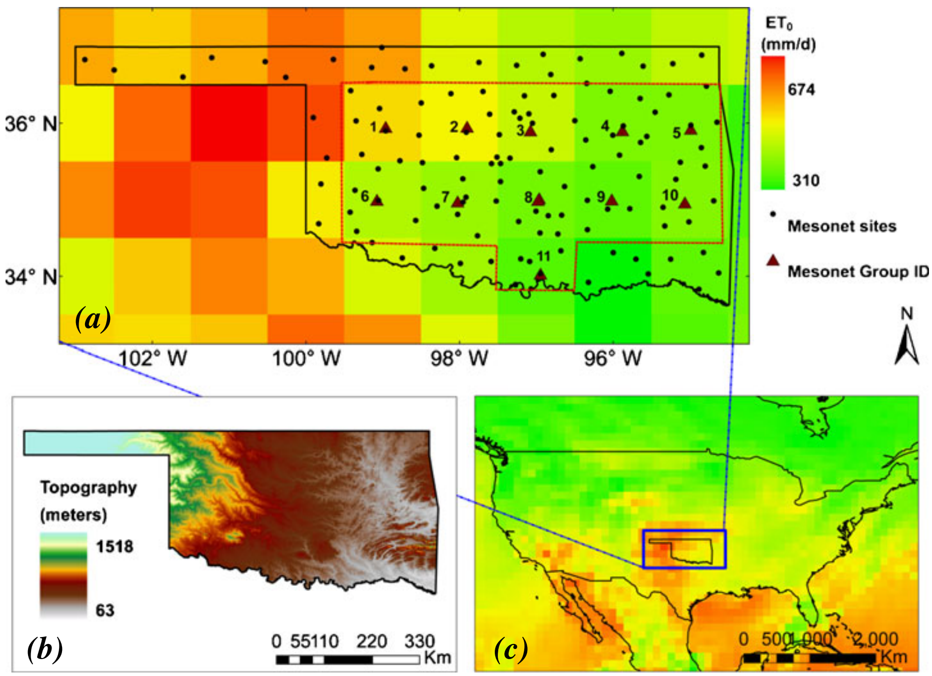

Fig. 1 Study area and GDAS ET_0 data: **a** the Oklahoma 120 MESONET stations (*dots*) grouped under 11 GDAS ID groups (*triangles*) with at least four MESONET stations within each group for this study; **b** the relative flat of Oklahoma topography, particularly over the study area; and **c** the daily 1-degree GDAS ET_0 data on October 20th 2007 over continental USA

automated stations across the state of the Oklahoma, at least one station in each of Oklahoma's 77 counties. At each site, measurements are taken with a set of instruments (the set consists of a lightning rod, a solar panel, a battery, a radio transmitter, a special micro-computer called a data logger and rain gauge) located on or near a 10-m-tall tower. Certain instruments are located at every Mesonet site to measure the standard-primary variables. These variables and sensors are as follows: RM Young Wind Monitor for wind speed; Thermometrics Air Temperature for Air Temperature; Vaisala Barometer for Pressure; and Campbell Scientific 229-L for Delta. The measurements are packaged into observations every 5 min. Then the observations are transmitted to the Oklahoma Climatological Survey (OCS) at the University of Oklahoma (OU), where the observed data are processed and verified for their quality and made public. It only takes 5 to 10 min from the time the measurements are made until they become available to the public. The facility is available 24 h per day, year-round for processing and quality control.

Among many retrieval algorithms and derived products, the MESONET ET model is essentially a weather-based tool that estimates potential water loss through the combined processes of evaporation (from soil) and plant transpiration (Sutherland et al. 2005). The reference ET model is based on the standardized Penman-Monteith reference evapotranspiration equation recommended by the American Society of Civil Engineers (ASCE) and the computational procedures found in Allen et al. (1994a, b). The ASCE Standardized Reference ET equation is given in Eq. 1 as (Jensen et al. 1990):

$$\text{Reference ET} = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{C_n}{T+273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + C_d u_2\right)} \tag{1}$$

Where:

Reference ET	Standardized reference evapotranspiration (mm day^{-1})
R_n	Calculated net radiation at the crop surface (MJ m^{-2} $day^{-1}$for daily time steps)
G	Soil heat flux density at the soil surface (MJ m^{-2} $day^{-1}$for daily time steps)
T	Mean daily or hourly air temperature at 1.5 to 2.5-m height (°C),
u_2	Mean daily or hourly wind speed at 2-m height (m s^{-1}),
e_s	Saturation vapor pressure at 1.5 to 2.5-m height (kPa), for daily computation, the value is the average of e_s at maximum and minimum air temperature,
e_a	Mean actual vapor pressure at 1.5 to 2.5-m height (kPa),
Δ	Delta, the slope of the saturation vapor pressure-temperature curve (kPa $°C^{-1}$),
γ	Psychrometric constant (kPa $°C^{-1}$),
C_n	Numerator constant that changes with reference type and calculation time step
C_d	Denominator constant that changes with reference type and calculation time step.

In this study, all 5-min weather variables observed from the MESONET are accumulated to hourly time scales, in order to compute the reference ET. Then site-based ET_0 is calculated hourly from MESONET stations and accumulated to daily ET_0 for a 2 year period (2005–2006). The 2 years of MESONET ET_0 datasets were chosen to correspond with the availability of a complete daily dataset from GDAS ET_0. A total of 72 MESONET sites, located in Oklahoma, are grouped into 11 GDAS ID groups with at least 4 MESONET stations within each group for the analysis (Fig. 1).

2.2.2 Global Data Assimilation System (GDAS) ET Model

The three steps used to compute the daily GDAS ET_0 are summarized in Fig. 2 and briefly described below (Senay et al. 2008).

Step one: Acquire raw data

The NOAA produces GDAS analysis field files every 6 h in Gridded Binary (GRIB) format. The GDAS fields that are used as input to

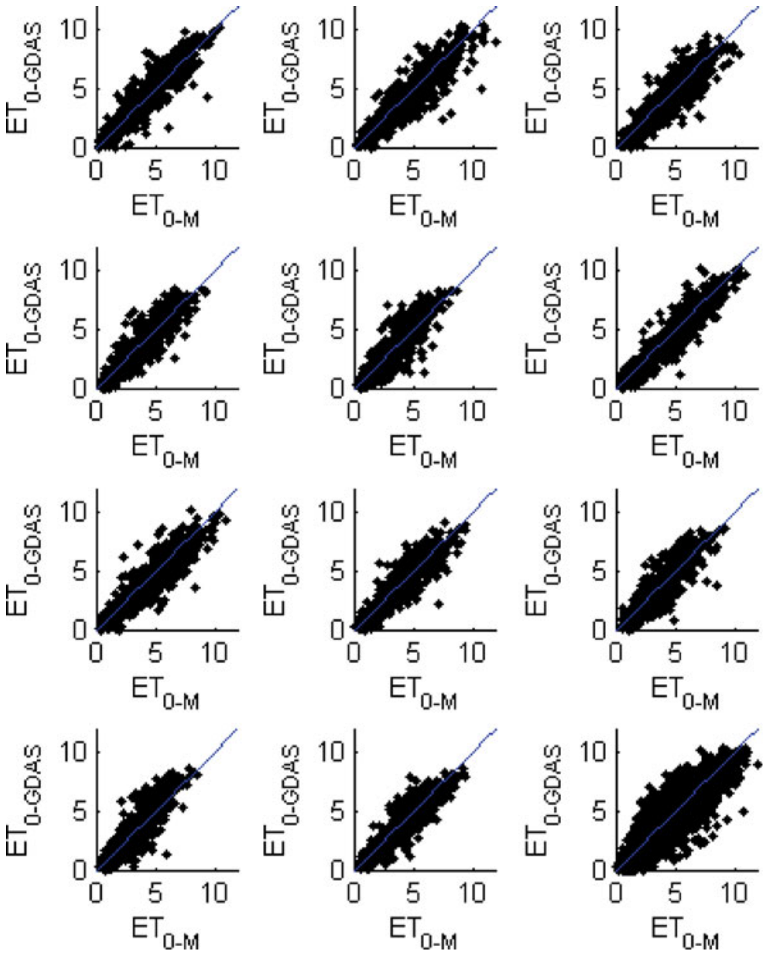

Fig. 2 Scatter plot of daily ET_0 values between MESONET and GDAS for the 11 GDAS grids and total for 2 year period 2005 and 2006

the reference ET calculation include: air temperature, atmospheric pressure, wind speed, relative humidity, and solar radiation (long wave, short wave, outgoing, and incoming). Some of these data are downloadable from http://earlywarning.usgs.gov/Global/dwnglobalpet.php (GDAS 2008).

Step two: Extract input parameters to calculate 6-h ET_0

After the eight files for each day (two files for each 6-h period) have been retrieved, the weather parameters (radiation, air temperature, wind speed, relative humidity, and pressure) for 6-h ET_0 calculation are extracted from the GRIB formatted files. Six-hour reference ET was calculated using the relation given by Shuttleworth (1992) for reference crop evaporation. The FAO publication 56 is used to normalize the 6-hourly reference ET calculations (Allen et al. 1998), similar to Eq. 1 but accumulated from an hourly time step. Afterwards they are converted to ARC/INFO GRID (ESRI 2004) format for the intended accumulation time period.

Step three: Accumulate 6-h ET_0 to daily ET_0

Afterward, the four six-hourly ET_0 grids are then accumulated to obtain the daily total. A day is defined as beginning at 00 hours GMT. The daily ET_0 values are scaled up (i.e. multiplied) by a factor of 100 to preserve the precision to 0.01 mm *[FEWS NET*: http://earlywarning.usgs.gov/Global/ET_0readme.php]. The grids produced are in geographic coordinate systems having a ground resolution of 1° and an extent of −180° to +180° longitude by −90° to +90° latitude.

In order to subset the GDAS ET_0 to Oklahoma region, the geographic coordinates of MESONET sites (Fig. 1) were used to extract the daily ET_0 pixel values from the GDAS grids. The data was extracted using ModelBuilder and Python in ArcGIS. Because one GDAS grid box contains more than one MESONET site, we averaged the values of all MESONET sites within a single GDAS grid. Afterward, 11 GDAS grids that contained at least four MESONET sites each were identified and assigned unique GDAS IDs. The maximum number of MESONET sites in a single GDAS grid was 8 (see GDAS_IDs-3,-4,-7) (Fig. 1).

2.3 Evaluation Indices

For the evaluation, we employed commonly used performance indicators: relative bias, absolute bias, root mean square error, and correlation coefficient for each of the 2 years and the 2 years combined.

Relative Bias (Bias) It is a measure of total volume difference between two time series. The relative bias between MESONET and GDAS was then calculated in Eq. 2 as:

$$\text{Relative .bias}\,(\%\,) = \frac{\sum_{i=1}^{N} \mathrm{ET0}_{\mathrm{GDAS}i} - \sum_{i=1}^{N} \mathrm{ET0}_{\mathrm{M}i}}{\sum_{i=1}^{N} \mathrm{ET0}_{\mathrm{M}i}} \times 100 \tag{2}$$

Where $ET0_{GDASi}$ is the GDAS Reference ET, $ET0_{Mi}$ is MESONET reference ET

Absolute Bias It is a measure of the timing difference between the two time series besides the volume difference. For example, if the percent bias measure between two time series is small and at the same time, the absolute percent bias measure is large, then one can say the two time series have close total volume but their timing are not as close. A good agreement between the two requires that both percent bias and absolute percent bias are small. The absolute percent bias, shown in Eq. 3, is always greater than or equal to percent bias.

$$\text{Abs. bias}\ (\%) = \frac{\sum_{i=1}^{N} |ET0_{GDASi} - ET0_{Mi}|^2}{\sum_{i=1}^{N} ET0_{Mi}} \times 100 \tag{3}$$

Root Mean Square Error (*RMSE*) Here we adopted relative RMSE, Eq. 4, that measures the relative error of magnitude as a percentage (%) of observations (i.e. MESONET in this study).

$$\text{RMSE}\ (\%) = \frac{\sqrt{\frac{\sum_{i=1}^{N}\left(ET0_{GDASi} - ET0_{Mi}\right)^2}{N}}}{\overline{ET0_{Mi}}} \times 100 \tag{4}$$

Correlation Coefficient (*R*) The correlation coefficient (R), Eq. 5, is used to assess the relation between MESONET and GDAS ET_0 values.

$$R = \frac{\sum_{i=1}^{N}\left(ET0_{GDASi} - \overline{ET0_{GDAS}}\right) \cdot \sum_{i=1}^{N}\left(ET0_{Mi} - \overline{ET0_{M}}\right)}{\sqrt{\sum_{i=1}^{N}\left(ET0_{GDASi} - \overline{ET0_{GDAS}}\right)^2 \cdot \sum_{i=1}^{N}\left(ET0_{Mi} - \overline{ET0_{M}}\right)^2}}. \tag{5}$$

Where $ET0_{GDASi}$ is the GDAS Reference ET, $ET0_{Mi}$ is MESONET reference ET.

And $ET0_M$ $ET0_{GDAS}$ are the mean of MESONET and GDAS ET_0, respectively. Correlation statistics were also calculated to test the correlations between MESONET ET_0 and GDAS ET_0 at differently aggregated time intervals (1-, 2-, 3-, 4-, 5-, 10-, and 15-day moving averages) for all sites.

3 Results and Discussions

3.1 GDAS ET_0 Evaluation

In this study, comparison between MESONET ET_0 and GDAS ET_0 was conducted primarily at a daily time scale. Table 1 presents a summary of the statistics for the 2 years (2005 and 2006) of daily ET_0 comparison. The relative bias values in all groups are within the range of −7.12% to 7.19%. The lowest relative bias is 1.53%, observed in GDAS_ID group Five. The lowest absolute bias is 14.69%, observed in GDAS_ID group six. R for all groups are above 0.9. The maximum R obtained is about 0.94 in

Table 1 Statistical evaluation results of GDAS daily ET_0 using MESONET ET_0 are in the eleven 1-degree GDAS_ID grids for 2 years (2005–2006) period

GDAS_ID	GDAS mean (mm/day)	MESONET mean (mm/day)	Relative.bias (%)	Abs. bias (%)	RMSE (%)	R	Variance of station ET	Number of sites
1	3.9113	3.8469	1.6753	16.5058	22.8465	0.9279	0.1941	7
2	3.9707	4.2380	−6.3072	16.8972	23.6860	0.9221	0.1742	5
3	3.7186	3.9598	−6.0909	17.7699	23.8247	0.9162	0.1212	8
4	3.5408	3.6563	−3.1594	18.7007	24.3461	0.9139	0.1122	8
5	3.4521	3.4000	1.5313	20.2799	27.3041	0.9061	0.1067	6
6	4.1750	4.4337	−5.8353	14.6946	19.6978	0.9381	0.4195	6
7	3.9659	4.2711	−7.1450	16.8043	22.6835	0.9197	0.1655	8
8	3.6959	3.9132	−5.5516	17.0588	22.5274	0.9169	0.1407	7
9	3.6425	3.7148	−1.9459	18.4345	24.6246	0.9045	0.1148	6
10	3.6665	3.4204	7.1940	21.9059	28.6686	0.9158	0.1255	7
11	3.6922	3.9753	−7.1218	16.4438	21.4055	0.9227	0.0865	4
Total	3.7633	3.8853	−2.8536	17.8501	23.8742	0.9183	0.1601	72

Note that the small variance relative to the mean is due to the flat topography of Oklahoma in each grid

GDAS_ID group six. The RMSEs from all GDAS_ID locations are within 28.67% and GDAS_ID-6 gave the best result among all sites (RMSE = 19.70%). As shown in Fig. 2, GDAS ET_0 and MESONET ET_0 have shown strong linear correlations among the 11 groups and the total for the year 2005 and 2006. However, the variations among the 11 groups shown in Table 1 and Fig. 2 can probably be attributed to the micro-climate difference within the Southern Great Plain (Brotzge and Richardson 2003).

Figure 3 shows a 5-day moving average ET_0 (daily) for group 6 and group 9. N is the number of MESONET sites in a GDAS group. Figure 3a shows a good

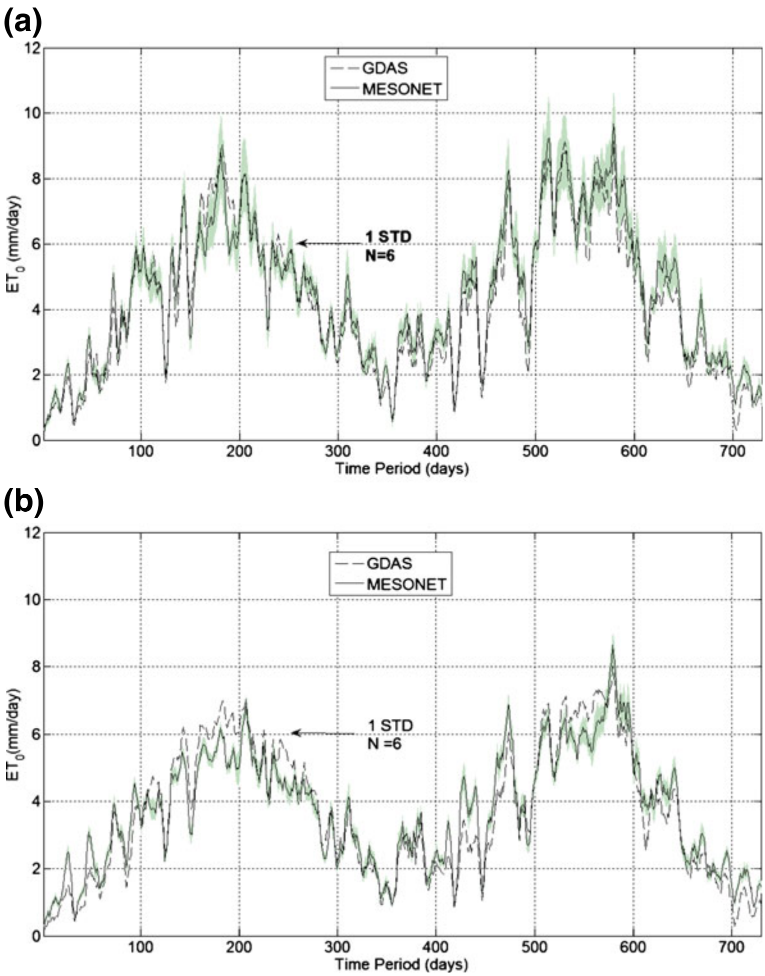

Fig. 3 **a** 5-day moving average ET_0 (daily) plots for the GDAS_ID group 6 over year 2005 and 2006. Note that *N* indicates numbers of MESONET sites in the group and one standard deviation of the MESONET site-based ET_0 estimates in each GDAS grid is shown as *error bars*. **b** 5-day moving average ET_0 (daily) for the GDAS_ID group 9 over the year 2005 and 2006. Note that *N* indicates numbers of MESONET sites in the group and one standard deviation of the MESONET site-based ET_0 estimates in each GDAS grid is shown as *error bars*

Table 2 Correlation coefficient between MESONET daily ET_0 and GDAS daily ET_0 at different aggregation times for 2005 and 2006

Aggregation period (days)	0	1	2	3	4	5	10	15
GDAS_ID								
1	0.9279	0.9481	0.9565	0.9613	0.9645	0.9667	0.9723	0.9749
2	0.9221	0.9466	0.9565	0.9627	0.9665	0.9685	0.9734	0.9755
3	0.9162	0.9410	0.9513	0.9571	0.9609	0.9632	0.9691	0.9710
4	0.9139	0.9411	0.9518	0.9577	0.9616	0.9643	0.9718	0.9747
5	0.9061	0.9381	0.9505	0.9610	0.9609	0.9640	0.9720	0.9753
6	0.9381	0.9609	0.9693	0.9732	0.9755	0.9770	0.9819	0.9844
7	0.9197	0.9470	0.9576	0.9628	0.9658	0.9673	0.9718	0.9744
8	0.9169	0.9418	0.9511	0.9561	0.9593	0.9612	0.9657	0.9680
9	0.9045	0.9329	0.9444	0.9510	0.9552	0.9580	0.9649	0.9681
10	0.9158	0.9431	0.9540	0.9603	0.9645	0.9673	0.9749	0.9783
11	0.9227	0.9481	0.9578	0.9627	0.9654	0.9675	0.9729	0.9758
Total	0.9183	0.9442	0.9544	0.9603	0.9635	0.9657	0.9717	0.9744

association between MESONET and GDAS ET_0 for GDAS group ID:6; the one standard deviation of daily ET_0 from the six MESONET sites is shown as error bars at each day. From this group however, we can see that the magnitude of the standard deviation of MESONET sites varies seasonally. The maximum standard deviations occurred in the summer months, the 11 groups, good temporal correlations are generally observed even if there are some differences in the statistical parameters among the groups. Figure 3b shows a association between MESONET and GDAS ET_0 for GDAS group ID 9. According to Table 2 group ID 9 gave the worst correlation coefficient among all groups. In general, Fig. 3 indicates that the absolute differences and magnitude of the standard deviation of MESONET sites show seasonal patterns, higher in summer and lower in other seasons; however, the normalized one standard deviation shows no, or insignificant, seasonal pattern.

Table 2 shows the correlation coefficient between MESONET ET_0 and GDAS ET_0 at different moving average time steps, from zero-day moving averaging to 15 days (0, 1, 2, 3, 4, 5, 10, and 15 days) for all sites in 2005 and 2006. For example, the correlation coefficients in GDAS_ID-6 are very high, ranging from 0.94 on zero-day to 0.98 for a 15-day average aggregation. It is also observed that the correlation has shown an increasing trend as the aggregation period increases. The increment has been very high from 0-day to 1-day aggregation (from 0.9381 to 0.9609 or by 0.0228). The smallest change (<0.0015) is observed from 4-day to 5-day aggregation from among the 4-day through 15-day aggregation periods. We observed similar results among the other groups. This justifies the use of the 5-day aggregation for the display of temporal charts in Fig. 3 without losing any information on the correlation composition.

As shown in Table 2, the correlation coefficients between GDAS ET_0 and MESONET ET_0 at 5-day aggregation for both 11 groups and all 72 sites are more than 0.95, although their annual ET_0 difference varies (Table 1). This indicates that despite a quantitative difference in some of the sites, the temporal patterns between GDAS ET_0 and MESONET ET_0 are strongly correlated. This demonstrates the capability of GDAS ET_0 to represent the major atmospheric processes that contribute to daily variations of important hydrological aspects.

4 Summary and Conclusions

The central objective of this study is to evaluate the utility of the operational USGS/EROS GDAS 1-degree daily ET_0 product in regional water resource research. For the evaluation we used the Oklahoma MESONET's daily ET_0 data for 2005–2006. It showed that most of the 11 groups (i.e., 72 MESONET sites) demonstrated a close match between the two independent datasets (GDAS and MESONET) during the 2 years, with relative bias within a range of 10% and total relative bias averaged −2.8%. The consistent low relative bias shows that GDAS ET_0 products have a very high potential to be used in climate modeling particularly for macro-scale land surface and regional climate modeling. Furthermore, despite site difference, the temporal patterns between GDAS ET_0 and MESONET ET_0 are strongly correlated, with a correlation coefficient more than 0.9 for all groups. This demonstrates the capability of GDAS ET_0 to represent the major atmospheric processes that contribute to daily variations of important hydrological parameters.

In summary, we conclude that (1) the consistent low relative bias shows the original 1-degree GDAS ET_0 products have a high potential to be used in climate modeling, particularly for macro-scale land surface and regional climate modeling; (2) the high temporal correlations demonstrate the capability of GDAS ET_0 to represent the major atmospheric processes that control the daily variation of surface hydrology. The finding in Oklahoma, a different hydro-climate region from a similar study conducted in California by Senay et al. (2008), reconfirms the reliability and potential of using GDAS reference ET for regional energy balance (thermal data-based) and water balance (soil moisture-based) management in many parts of the world. On a side note, for practical purposes, various ET modeling techniques estimate actual ET as a fraction of ET_0 based on the soil–water content and vegetation conditions (Senay et al. 2007, 2008). Therefore, the availability of global daily GDAS ET_0 product as an operational model undoubtedly provides an opportunity of estimating actual ET on a global basis; however more thorough evaluation of GDAS ET_0 at other hydro-climate regions are recommended for extensive usage of such products worldwide.

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