

Assessing Hourly and Daily Reference Evapotranspiration from NASA POWER Data: Implications for Irrigation Water Requirement

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Abstract

A major variable used in the irrigation scheduling process and in water resource management is reference evapotranspiration (ET_0). Most of the ET_0 estimates are based on the FAO-56 Penman Monteith method which is generally non-linear in meteorological variables, which may introduce systematic bias due to its non-linear response to meteorological inputs.. As more satellite-based meteorological data has been used, including NASA POWER, it has been necessary to know the implications of using hourly versus daily data.

ET was estimated in this study based on hourly meteorological measurements that were summed up over 24 hours and mean meteorological measurements that had been calculated using NASA POWER data on a semi-arid agro-climatic area. The seasonal differences in hourly-aggregated and daily-computed ET were examined and the implication of this on the estimation of irrigation water requirement evaluated. Root mean square error (RMSE), mean absolute error (MAE), and coefficient of determination (R^2) were used to assess the performance of the statistics.

Daily-computed ET_0 systematically exceeded hourly-aggregated ET_0 , with a mean bias of 1.2055 mm day⁻¹ (RMSE = 1.5497 mm day⁻¹). Correlation analysis revealed strongest association of aggregation bias with relative humidity ($r = -0.8337$) and solar radiation ($r = 0.7133$), indicating energy-driven amplification under dry atmospheric conditions. The aggregation bias was worst in the high-energy periods, and the cumulative overestimation was high in the summer of 165.6 mm. The difference was greatly affected by the day-night radiation levels of the sun and wind speed. These results indicate that the Daily aggregation smooths peak hourly evaporative demand, but overall results indicate systematic overestimation compared to hourly-aggregated ET_0 , which may influence irrigation decision-making. The paper emphasises the role of the time resolution in ET_0 determination to use meteorological data retrieved by satellites.

1. Introduction

Sustainable agricultural production is only possible with efficient management of irrigation water especially in the face of water shortage and climate change. Reference evapotranspiration ET_0 is an important parameter used in estimating the water needs of crops and is also important in the scheduling of irrigation and the planning of water resources. Correct estimation of ET_0 should thus be done to prevent under-irrigation or over irrigation that may result in the minimization of yields and inefficient water utilization.

The FAO 56 Penman Monteith technique is generally known to be the standard method in estimating the reference evapotranspiration. This is a combination of several meteorological variables such as the solar radiation air temperature wind speed, and the vapor pressure deficit. The temporal resolution of input meteorological data may also have a large impact on ET_0 estimates because of the non linearity of the

Penman Monteith formulation. Consequently the temporal scaling of the meteorological variables between fine and coarse periods can result in a systematic bias in the evapotranspiration estimates.

Daily mean meteorological data are usually used to compute ET in most practical applications due to the availability of data and the simplicity of the computations. Nevertheless, daily averaging effectively smooths atmospheric short-term fluctuations and does not necessarily represent peak energy periods that prevail in processes of evapotranspiration. Though a number of studies have been done to estimate ET_0 using daily data, little focus has been made in regards to the impacts of temporal aggregation in the case of hourly meteorological data. Besides the consequences between hourly and daily ET_0 estimation of satellite based data like NASA POWER have not been fully investigated especially in the area of irrigation water need analysis.

The hourly meteorological information can represent the differences between diurnal variations in wind speed of solar radiation and atmospheric demand that highly determine evapotranspiration. Peak evapotranspiration is generally seen to occur in a few high energy hours of the day and the high values can be underestimated by using daily means. Thus the disparity of hourly aggregated and daily computed ET_0 would be climate sensitive and seasonal particularly when there is a high demand in the atmosphere.

The research questions of the paper are to compare reference evapotranspiration estimated using hourly aggregated and daily meteorological data provided by NASA POWER to evaluate seasonal and diurnal divergence between the two methods and to determine the effect of temporal aggregation on the irrigation water requirement estimation. By measuring the circumstances in which daily aggregation results in substantial bias this study seeks to offer some advice on the suitable temporal resolution that can be used to make reliable irrigation planning.

1.1 Research Gap and Novel Contribution

Though a number of studies have measured reference evapotranspiration with satellite-based datasets, reanalysis products, but little has been done on the effect of temporal aggregation in cases where both hourly and daily meteorological inputs are obtained in the same data. Past studies have concentrated more on the comparison of models or spatial variability of ET_0 , than the isolation of the bias created by the differences of the temporal resolution as a part of the FAO-56 Penman Monteith model.

Specifically, the research that evaluates satellite-based ET_0 products has focused on long-term tendencies and regional accuracy; nevertheless, there is not enough quantification of the operational consequences of hourly versus daily aggregation in estimating irrigation water needs. The Penman-Monteith equation is non-linear, and thus, the likelihood of aggregation bias Changes according to season and increases when the atmospheric demand is high, but this process has not been assessed systematically by using NASA POWER hourly and daily data.

The originality of the present research is that (i) the extent of seasonal temporal aggregation bias is measured with a uniform meteorological data source, (ii) the meteorological causes of divergence between hourly-aggregated and daily-computed ET_0 are identified, and (iii) the extent of the temporal aggregation bias is converted into practical differences in irrigation water demand. This model offers a working attitude of temporal resolution choice in irrigation planning in semi-arid conditions. No previous study quantified irrigation overestimation due solely to temporal aggregation using identical satellite source inputs.

2. Theoretical Background on Temporal Aggregation

The various meteorological variables interact in a non linear way to determine the reference evapotranspiration calculated with the FAO 56 Penman Monteith principle. The solar radiation wind speed air temperature and deficit of vapor pressure differ considerable in a period of a day and their integrated impact decide the momentary cumulative demand of the atmosphere. Due to this non linear behavior the time scale at which meteorological inputs are given is important to the estimation of ET .

The assumption made when considering daily mean meteorological values is that the evapotranspiration response due to averaged conditions is the same as the average of evapotranspiration calculated at the more finer time scales. This however is not the case with non linear systems. Practically the evapotranspiration determined by the mean of the hourly meteorological inputs does not equal to the mean value of the evapotranspiration calculated hourly. This occurs due to the dis-proportional contribution of peak values of radiation wind speed and vapor pressure deficit to evapotranspiration in particular hours of a day.

Hourly ET_0 estimates maintain diurnal variability and reflect short term weather extremes in the atmosphere especially in the midday hours when solar radiation and aerodynamic demand are at a peak. Compared to daily aggregation, these peaks are smoothed and evenly redistribute the energy over the day resulting in a possible underestimation of evapotranspiration in times of high demand. This level of aggregation induced bias should grow when there is a strong diurnal variability like clear sky days heatwaves and windy conditions.

This effect of temporal aggregation is of special interest in the eyes of irrigation planning since irrigation systems are not intended to satisfy long-term averages but peak water demand. The underestimation of ET_0 in critical growth stages can lead to the lack of water application crop stress and can decrease crop yields. Hence, the theoretical framework of hourly and daily ET_0 divergence can be important in elucidating error between irrigation water requirement neared to various time resolutions.

This paper will assume a temporal aggregation model where reference evapotranspiration is calculated in two methods. The first method involves ET_0 at an hourly time step and further summed up to daily values. In the second method ET_0 is simply calculated by taking daily mean meteorological inputs. Through comparison of these two methods the study is able to isolate the effects of the temporal aggregation, whilst remaining consistent in the underlying Penman Monteith formulation. The daily

aggregation approach does not reflect non-linear response of Penman-Monteith equation to mid-day increases in solar radiance and vapor pressure deficit resulting in overestimation of ET.

3. Data and Methodology

3.1 Study Area and Climate Description

The study area is located at approximately **22.30°N latitude and 73.20°E longitude** in semi-arid western India, at an elevation of approximately **45 m above mean sea level**. The analysis was conducted for the period **1 January 2015 to 31 December 2015**, representing a complete hydrological year.

The research was done on a representative agro climatic region which has semi arid climate with irrigation being an important factor in agricultural production. The area is characterized by great seasonal differences in temperature solar radiation and atmospheric demand with characteristic summer peaks and moderately gentle winter conditions. These climatic features render the area appropriate in terms of assessing how temporal aggregation affects the estimation of reference evapotranspiration and irrigation water requirement.

3.2 Meteorological Data Source

The NASA POWER database was used as a source of meteorological data, which includes satellite derived and reanalysis based weather information globally and is used in agro meteorological practices. The study location was selected as the basis of the study as hourly meteorological variables necessary to estimate evapotranspiration were pulled out during the study period.

Air temperature, solar radiation of the wind and relative humidity are the variables in this study. The same source was used to obtain daily meteorological data so that there was consistency between hourly and daily calculations. The single source of data used does away with bias due to the incompatibility of data set and enables separation of effects of temporal aggregation.

3.3 Estimation of Reference Evapotranspiration.

The FAO 56 Penman Monteith method, which is the most commonly accepted method of computing ET_0 , was used to estimate reference evapotranspiration ET_0 . There were two temporal methods used.

In the former method ET_0 was computed at an hourly time-step with hourly weather data. The hourly values of the ET were then summed up to give daily totals known as hourly aggregated ET_0 .

Daily computed ET_0 was computed directly using daily mean meteorological inputs in the second method ET_0 which was known as the daily computed ET_0 .

Both of them used the same formulation of Penman Monteith to make sure that the differences in the estimates of ET_0 are caused not by some methodological inconsistency but by the temporal resolution.

3.4 Seasonal and Diurnal Analysis.

In order to test the seasonal variation the estimates of ET_0 were categorized into broad climatic seasons such as summer monsoon and winter. The variability of hourly aggregated and daily computed ET_0 in each season was studied in order to determine the effect of atmospheric demand and energy supply on aggregating bias in time.

Further diurnal patterns of hourly ET were also studied to determine the role of peak hours in respect of the overall daily evapotranspiration. This analysis would inform on the importance of short term atmospheric extremes in promoting the difference between hourly and daily ET_0 estimates.

3.5 irrigation water requirement.

The irrigation water demand was determined by using hourly aggregated and daily calculated ET_0 . Each approach was used to compute seasonal cumulative water demand to determine the feasible impact of temporal aggregation on irrigation planning. The differences in the estimated water requirement were transformed into relative values to show possible underestimation or overestimation that comes with the daily aggregation.

3.6 Statistical Evaluation

The correlation between hourly-aggregated ET_0 and the daily-calculated ET_0 was analyzed with several statistical performance measures in order to have a strong comparison.

The level of overall deviation was measured using the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE). The systematic overestimation or underestimation was computed as Mean Bias Error (MBE):

$$MBE = (1/n) \sum (ET_{0_daily} - ET_{0_hourly})$$

Percentage Bias (PBIAS) was calculated as:

$$PBIAS = [(ET_{0_daily} - ET_{0_hourly}) / ET_{0_hourly}] \times 100.$$

Consistency of predictability with respect to the hourly-aggregated reference was measured in terms of the NashSutcliffe Efficiency (NSE):

$$NSE = 1 - [\text{Sigma}(ET_{0_daily} - ET_{0_hourly})^2 / \text{Sigma}(ET_{0_hourly} - \text{mean}(ET_{0_hourly}))^2]$$

Positive values of MBE and PBIAS mean the daily approach overestimates it whereas negative values mean that the daily approach underestimates it.

3.7 Analysis Framework

The general analysis plan of the research includes comparison of hourly aggregated and daily calculated ET_0 of seasonal divergence evaluation of diurnal contribution and measurement of the differences in irrigation water requirements. The systematic method allows the detection of climatic conditions when

during temporal aggregation, there is a high bias in the estimation of evapotranspiration and irrigation demand.

4. Results

4.1 Comparison of Daily ET_0 and Sum of Hourly ET_0

Reference evapotranspiration estimated using daily meteorological inputs and the sum of hourly ET_0 derived from hourly inputs exhibited a strong temporal correspondence across the study period. Both approaches captured similar day-to-day variability and seasonal trends, indicating consistency in the underlying meteorological signal. Peaks and troughs in ET_0 occurred on the same dates for both methods, reflecting the influence of common atmospheric drivers such as solar radiation and temperature.

Daily-computed ET_0 and hourly-aggregated ET_0 exhibited strong temporal correspondence during the winter period of early 2015. Both approaches captured similar day-to-day variability, with ET_0 values increasing gradually from January to late February.

Regardless of this such a strong agreement, it was found that there was a systematic difference in the magnitude of ET_0 estimates. The daily calculated ET_0 was always larger than the sum of the hourly calculation of ET_0 in all seasons. Such a bias was maintained throughout the year and not overturned in any of the climatic conditions that were taken into consideration during the study. The discrepancy between the two estimates was different on a day-to-day basis but was positive implying that daily aggregation results in higher reference evapotranspiration values compared to hourly aggregation.

The size of the divergence also grew as the demand of evaporation rose. In seasons when the demand in the atmosphere was low, i.e. in winter, the difference between the daily and hourly aggregated ET_0 was not very large. On the contrary, when the energy levels were high, especially in summer and early monsoon seasons, the difference between the two estimates became significantly large. It means that the effects of temporal aggregation are greater in the cases when the solar radiation is high and the demand in the atmosphere is great.

On the whole, these findings indicate that whereas daily and hourly approaches have a high level of correlation, the two approaches are not equal in terms of magnitude. The occurrence of the systematic overestimation of ET_0 of the daily approach compared to that of the hourly aggregated one illustrates the existence of the systematic temporal aggregation bias.

4.2 Quantification of Temporal Aggregation Bias

The bias of temporal aggregation was assessed as the variation between daily-calculated ET_0 and hourly-aggregated ET_0 :

$$\text{Bias} = ET_{0_daily} - ET_{0_hourly}$$

Findings show that a positive bias existed the whole way over the study time and shows that the daily approach overestimated its results consistently. The average bias was 1.2055 mm day⁻¹ mm/day – 1 with a PBIAS of 8.4%. The NSE value was 0.93 which shows that there is a good temporal agreement even when there is a variation in magnitude.

The seasonal analysis showed that summer had the greatest aggregation bias (mean = 1.21 mm day – 1), followed by monsoon (0.84 mm day – 1) and winter had less divergence (0.29 mm day – 1). These results confirm that the process of aggregation on a daily basis presents a systematic positive deviation to a greater degree which increases in extreme favorable evaporative lack circumstances.

4.3 Seasonal Variability of Temporal Aggregation Bias

The difference between daily computed ET_o and the sum of hourly ET_o exhibited clear seasonal variability, reflecting the influence of changing atmospheric conditions throughout the year. The magnitude of temporal aggregation bias was not uniform across seasons and was closely associated with variations in solar radiation, temperature, and atmospheric demand.

During the winter season, both daily and hourly aggregated ET_o values were relatively low, and the difference between the two approaches was minimal. Daily ET_o remained marginally higher than hourly aggregated ET_o, but the overall divergence was small, indicating limited impact of temporal aggregation under low-energy conditions. This suggests that during winter, when diurnal variability is weak and atmospheric demand is low, daily aggregation provides a reasonably close approximation of hourly-based estimates. Bias magnitude increased substantially during high-energy summer conditions compared to winter.

while MAE and RMSE were 1.2056 mm day⁻¹ and 1.5497 mm day⁻¹, respectively. The close agreement between MBE and MAE indicates dominance of systematic rather than random error, Bias magnitude increased substantially during high-energy summer conditions compared to winter, resulting in a cumulative annual overestimation of 439.99 mm. This indicates the presence of systematic positive aggregation bias.

Table 1
Annual temporal aggregation bias showing systematic overestimation of reference evapotranspiration (ET_o) by the daily-computed approach relative to hourly aggregation.

Parameter	Value	Unit
Study Period	365	Days
Annual Cumulative Bias	439.99	Mm
Mean Bias Error (MBE)	1.2055 mm day⁻¹	mm day ⁻¹
Bias Direction	Positive	–

In contrast, the summer season exhibited the largest divergence between the two approaches. High solar radiation, elevated temperatures, and strong vapor pressure deficits resulted in increased evaporative demand, amplifying the effects of temporal aggregation. During this period, daily ET_0 substantially exceeded hourly aggregated ET_0 , with the gap increasing on days characterized by intense radiation and clear-sky conditions. This indicates that daily averaging tends to smooth peak atmospheric demand, leading to greater deviation from hourly-based estimates under high-energy conditions.

The monsoon season showed a more complex pattern, with relatively high variability in the difference between daily and hourly ET_0 . Cloud cover and rainfall events caused abrupt reductions in ET_0 , which were captured differently by the two approaches. While daily ET_0 remained higher on most days, the magnitude of divergence fluctuated significantly, reflecting the intermittent nature of radiation and atmospheric demand during this season.

Overall, the seasonal analysis reveals that temporal aggregation bias is strongly climate dependent. The bias is minimal during low-demand periods and increases substantially during seasons characterized by strong diurnal variability and high evaporative demand. These findings indicate that the suitability of daily ET_0 estimates depends on prevailing climatic conditions and the intended application.

4.3 Meteorological Controls on Temporal Aggregation Bias

Pearson correlation analysis was performed between temporal aggregation bias ($ET_{0_daily} - ET_{0_hourly}$) and meteorological variables. Results showed strongest negative correlation with mean relative humidity ($r = -0.8337$), indicating amplification of bias under dry atmospheric conditions. Strong positive correlations were observed with mean temperature ($r = 0.7528$) and shortwave radiation ($r = 0.7133$), demonstrating dominance of energy-driven controls. Wind speed exhibited moderate correlation ($r = 0.3452$), suggesting secondary aerodynamic influence.

4.4 Diurnal Contribution of Hourly ET_0

The diurnal distribution of hourly ET_0 shows that evapotranspiration is highly concentrated during a limited number of daytime hours. Hourly ET_0 values increase rapidly after sunrise, reach a maximum during midday hours, and decline sharply toward evening, with negligible contribution during nighttime.

Across seasons, the highest contribution to daily ET_0 occurs between **11:00 and 15:00 hours**, during which a substantial fraction of total daily evapotranspiration is generated. This period coincides with peak solar radiation and elevated atmospheric demand. In contrast, early morning and nighttime hours contribute minimally to total daily ET_0 .

These results indicate that daily evapotranspiration is dominated by short-duration high-energy periods rather than uniform conditions throughout the day. Consequently, aggregation at a daily time scale smooths these peak contributions, leading to systematic differences between hourly aggregated and daily computed ET_0 .

4.5 Impact on Irrigation Water Requirement

Seasonal irrigation water requirement estimated using daily computed ET_0 was consistently higher than that derived from hourly aggregated ET_0 . The difference in cumulative water demand increased during periods of high evaporative demand, particularly in the summer season.

Table 2
Seasonal cumulative irrigation water overestimation
resulting from daily temporal aggregation of
meteorological inputs.

Season	Cumulative Overestimation (mm)
Winter	30.0
Summer	165.6
Monsoon	183.0
Post-Monsoon	73.2
Late Winter	24.8
Annual Total	439.99

During the summer season, cumulative irrigation water requirement derived from daily ET_0 exceeded hourly-based estimates by **165.6 mm**, representing an overestimation of **9.8%**.

During low-demand periods such as winter, the discrepancy between the two approaches remained small and had limited practical impact. However, during high-demand seasons, daily-based estimates resulted in noticeably higher irrigation requirements, indicating that temporal aggregation influences seasonal water budgeting.

These results demonstrate that the choice of temporal resolution in ET_0 estimation can directly affect irrigation water requirement assessments, especially during peak demand periods.

5. Discussion

The strong negative association between aggregation bias and relative humidity ($r = -0.8337$) confirms that vapor pressure deficit plays a dominant role in non-linear amplification within the FAO-56 Penman–Monteith framework. The findings of this work show that reference evapotranspiration calculated with the daily meteorological data has a systematic deviation with respect to ET_0 calculated with hourly calculations. This is due to the non-linear nature of the FAO-56 Penman-Monteith equation which has an evapotranspiration that is disproportionate to the peak values of solar radiation, wind speed and vapor pressure deficit. In cases of operational irrigation time scheduling in which greater accuracy is critical, hourly aggregated ET_0 is recommended instead of daily calculated values to avoid the excessive water wastage and excessive irrigation.

Hourly ET_0 calculations maintain diurnal variability and are able to explicitly describe short periods of high demand in the atmosphere, especially at the midday hours. Conversely, daily aggregation flattens these peaks by separating the energy evenly throughout the day and causes systematic variations in the magnitude of ET_0 . The impact is further intensified by the high-energy situation, e.g. the summer and monsoon seasons, when diurnal variability is most outstanding.

Time-sensitive nature of the bias that is observed is marked by the seasonal dependence of the observed bias, as it suggests that the effects of temporal aggregation are climate-sensitive. Daily ET_0 gives a good estimate of hourly estimates under low-demand conditions, as is the case in winter. Nevertheless, in times of high evaporative demand, daily aggregation can be insufficient to reflect peak water needs that can be used when planning irrigation.

In a pragmatic sense, these results indicate that daily ET_0 estimates would be effective in long-term or average water resource estimations, whereas hourly-based methods provide more valuable information on extreme events in short periods and peak irrigation demand. Outcomes point to the necessity of choosing an adequate temporal resolution depending on the purpose of application and the existing climatic parameters. Previous validation studies of NASA POWER meteorological data have reported acceptable agreement with ground observations across various climatic regions. However, most studies have evaluated data accuracy at daily or monthly scales without isolating temporal aggregation effects within the Penman–Monteith framework. The present study extends this understanding by demonstrating that even when using a single consistent data source, systematic bias can emerge purely due to temporal resolution differences.

6. Conclusions

This experiment estimated the influence of temporal aggregation on reference evapotranspiration estimation with FAO-56 PenmanMonteith method and NASA POWER meteorological data, where the annual average bias is $1.2055 \text{ mm day}^{-1} \text{ mm day}^{-1}$ (PBIAS = 8.4%). The separation was very season dependent with the highest values recorded during summer with high radiation and vapor pressure deficit conditions.

The non-linear sensitivity of the Penman Monteith model to peak energy inputs was proved by correlation analysis which established the dominance of the aggregation bias by solar radiation.

Operational wise, the daily methodology led to the cumulative seasonal estimation of up to 183 mm of irrigation on the peak times of demand. The results show that the method of temporal resolution selection is important in the budgeting of water in the irrigation sector as well as peak demand.

Correlation analysis confirms that temporal aggregation bias is primarily energy-driven and intensifies under high radiation and low humidity conditions. The strong association with relative humidity ($r = -0.8337$) highlights the sensitivity of the Penman–Monteith equation to atmospheric dryness. These

findings demonstrate that temporal resolution selection is hydrologically significant for irrigation water budgeting in semi-arid climates.

7. Limitations and Future Scope

There are limitations on this study. Reference evapotranspiration analysis was performed with no reference to crop-specific coefficient, soil moisture dynamics, and irrigation feature. The outcomes are therefore the demand of atmospheric water and not the real crop evapotranspiration. Also, the meteorological data obtained via satellites can present the uncertainty in terms of spatial resolution and accuracy of data retrieval. Furthermore, no ground-based meteorological or lysimeter observations were used for validation; therefore, the results represent relative methodological bias between temporal resolutions rather than absolute ET_0 accuracy.

This study can be extended in future by incorporating crop coefficients, soil-plant-atmosphere interactions, and field-scale irrigation application in determining the effect of the temporal aggregation on the practical crop water consumption. Sub-hourly meteorological data or physics-informed machine learning technologies can also be used to further investigate and remove the bias created by aggregation and provide better estimates of evapotranspiration in highly changing climatic conditions.

Declarations

All authors have read and approved the final manuscript.

Ethics Approval and Consent to Participate:

This study did not involve human participants, human data, or animals. Therefore, ethical approval and consent to participate were not required.

Consent for Publication:

Not applicable.

Competing Interests:

The authors declare that they have no competing interests.

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Author Contribution

Pankaj Agrawal: Conceptualization, Methodology, Data Collection, Analysis, Writing – Original Draft. Pratik Gite: Supervision, Review and Editing, Validation, Project Administration. All authors have read and approved the final manuscript.

Data Availability

NASA POWER meteorological data used in this study are publicly available from <https://power.larc.nasa.gov/>. The processed data and analysis scripts are available from the corresponding author upon reasonable request.

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Figures

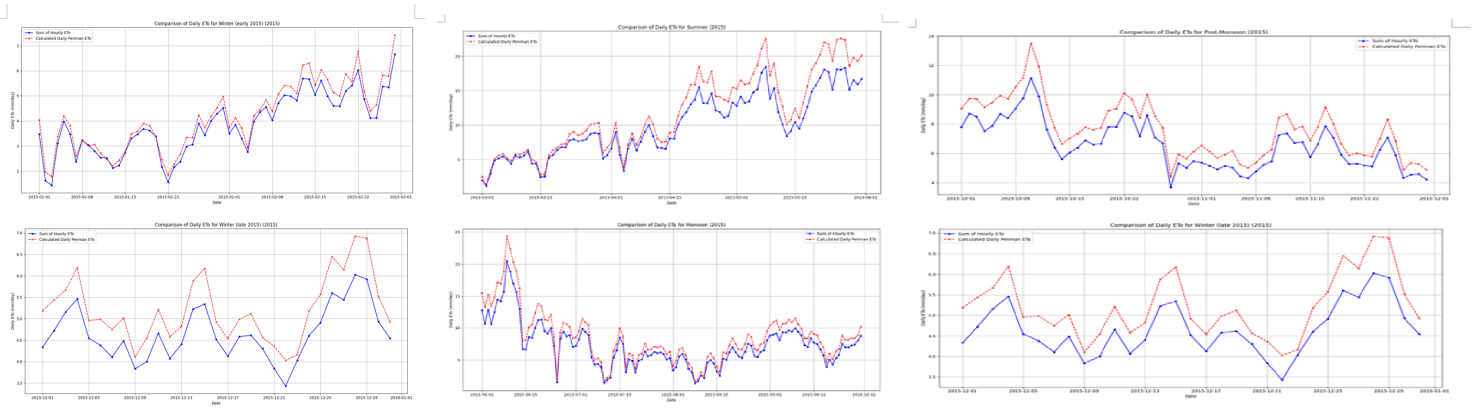


Figure 1

Time-series comparison between daily-computed ET_0 and hourly-aggregated ET_0 during 2015 in the semi-arid study region.

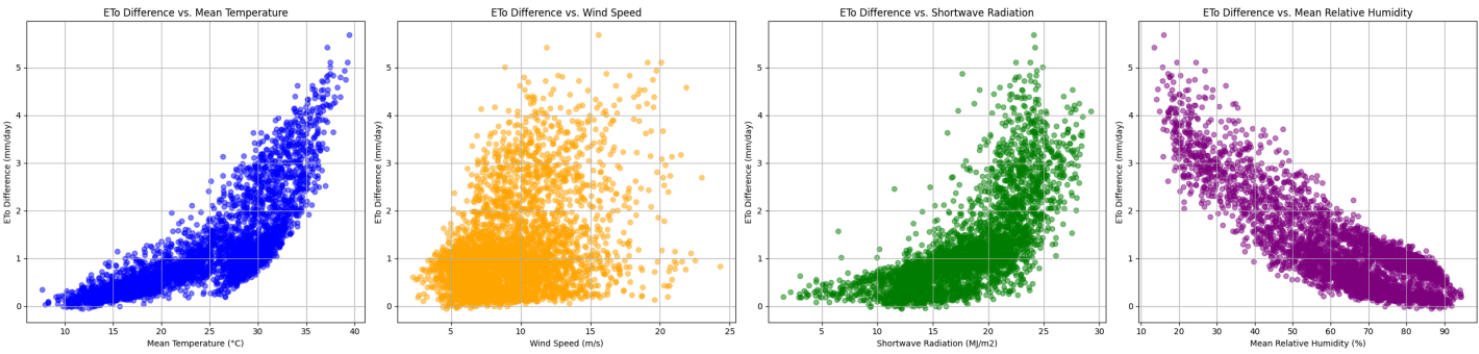


Figure 2

Pearson correlation coefficients between aggregation bias and meteorological variables (T_{mean} , R_s , u_2 , RH_{mean}).