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William Farmer*, Kenneth Strzepek*, C. Adam Schlosser*, Peter Droogers†, and Xiang Gao*

Abstract

Measures of reference evapotranspiration are essential for applications of agricultural management and water resources engineering. Using numerous esoteric variables, one can calculate daily reference evapotranspiration using the Modified Penman-Monteith methods. In 1985, Hargreaves developed a simplified method for estimating reference evapotranspiration. Similarly, Droogers and Allen improved upon Hargreaves' method in 2002. Both methods provide excellent estimates of average daily rates for a given month, based on monthly climatology. The Hargraeves method also estimates daily rates based on daily data, though the Modified Hargreaves approach developed by Droogers and Allen is largely accepted as a stronger metric. Here efforts are made to improve the functionality of Droogers and Allen's approach and to adapt it to provide daily estimates of reference evapotranspiration based on daily weather. The Hargreaves and Modified Hargeaves are used to calculate daily reference evapotranspiration based on daily data. The coefficients in these equations are then optimized to reduce the root mean squared difference between each estimate and the baseline value calculated by the Modified Penman-Monteith approach. The adapted method for daily reference evapotranspiration proves promising; estimating rates near a root mean squared difference of 1.07 mm/day. These results are validated with data from 1976-1980; here the root mean squared difference is 1.06 mm/day. Results are evaluated spatially and temporally. Weaknesses are seen in the estimates around clearly-defined summers. Further weaknesses are seen in pole-ward regions. Still, at the 1% significance level, the daily optimization of the Modified Hargreaves equation is found to be the best replica of the Modified Penman-Monteith method, globally. Finally, specific caveats and further avenues of research are noted. Overall, the daily Modified-Hargreaves method is advocated for general use in global studies where daily data and variation is of the utmost concern.

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1. INTRODUCTION

Measures of reference evapotranspiration, as defined by Allen *et al.* (1998), are essential to modeling and managing agricultural and water resources, from crop selection to irrigation allocation, streamflow and watershed analysis. Depending on the desired application and time-

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step, there are numerous ways to calculate reference evapotranspiration. Due to the high data-demand associated with daily methods, a large number of models have focused on the use of monthly methods of calculation (McKenney and Rosenberg, 1992). While monthly estimates are valuable as a baseline for understanding, further applications require the details acquired at the daily scale. For example, the unique nature of crops and their responses to weather and soil moisture are more appropriately represented at a daily time step.

Currently, the Modified Penman-Monteith, as developed in FAO Irrigation & Drainage Paper No. 56 (1998), is a widely-used method for calculating reference evapotranspiration on a daily time step. Unfortunately, the data demands make this method somewhat problematic, especially for applications in data-poor, developing regions of the globe. These intensive data demands also make this method unpalatable for use with global databases, which often contain only a restricted set of variables. Furthermore, when working with climate change within a set of general circulation models (GCMs), the data demands of the Modified Penman-Monteith method are rarely met in all cases.

Among the key inputs of the Modified Penman-Monteith method are measurements of temperature, wind speed, net radiation, and vapor pressure deficit. While these variables are often available within extensive atmospheric models for coupled climate and weather prediction, comprehensive sets of field measurements containing all these terms are uncommon, even at monthly time steps. As such, Droogers and Allen (2002) confronted the issue of inaccurate or incomplete data on a monthly time step by augmenting the method of Hargreaves *et al.* (1985) to calculate average monthly reference evapotranspiration (mm/day) based on a limited number of variables. Specifically, it was shown that reasonable estimates of reference evapotranspiration could be calculated from monthly average temperature, temperature range and precipitation. This approach is advantageous, as these atmospheric variables are generally available with some confidence across the globe. However, the method remains somewhat unpalatable to most agricultural modeling applications because this reference evapotranspiration represents an estimate for an average day of the month, based on monthly climate conditions. Again, this is problematic because so many applications thrive on daily fluctuations of weather and the variation of those fluctuations.

The purpose of this exercise is to extend the work of Droogers and Allen (2002) by introducing a new algorithm that is able to calculate daily reference evapotranspiration from daily environmental data. The ability of this algorithm to resolve the daily variations - and the extremes - of reference evapotranspiration will substantially benefit natural resource planning, development planning and water resource engineering. This ability allows for a better evaluation of risk-based assessment and the distribution of current and future climate variables at the daily scale. In the next section, we briefly describe the algorithms and data sets employed, as well as the metrics used to evaluate the daily reference evapotranspiration algorithm. Results from the suite of simulations are then presented, and concluding remarks are provided.

2. METHODS

In general, this exercise will use daily climate data from grid cells across the globe to calculate daily reference evapotranspiration using a number of different methods. This approach is largely a replication of the methods used by Droogers and Allen (2002). The Modified Penman-Monteith method (Allen *et al.*, 1998) will be used as the best approximation, and thus referred to as the baseline estimate. The Hargreaves and Modified-Hargreaves methods (Droogers and Allen 2002) will be compared to the baseline and a measure of their error will be calculated. By varying the coefficients of these equations, the error will be minimized. The results of this variation will be a robust daily method for calculating reference evapotranspiration. The experiment is outlined in detail below.

To generate the required daily inputs for the various evapotranspiration calculations, we employed the Community Land Model Version 3.5 (CLM3.5, Oleson *et al.*, 2004) in "stand-alone" mode in which the atmospheric conditions are prescribed. For this study, atmospheric weather conditions were provided by the National Centers for Environmental Prediction (NCEP). This data, called the NCC dataset, consists of reanalysis data that has been bias corrected to match monthly estimates by the Climate Research Unit (CRU) at the University of East Anglia CRU (Ngo-Duc *et al.*, 2005). CLM was run globally at a spatial resolution of 1˚x1˚ to provide all the near-surface variables needed to calculate reference evapotranspiration via the Modified Penman-Monteith (Allen *et al.*, 1998), Hargreaves (Har) and Modified-Hargreaves (MH) methods (Droogers and Allen, 2002). For this exercise, daily variables were taken for the period of 1971 through 1976. Looking only at one-degree-square, over-land grids, 25, 252, 525 individual estimates were evaluated.

For this evaluation of the various methods of evapotranspiration calculation, the Modified Penman-Monteith estimate served as the baseline reference evapotranspiration rate. Reference evapotranspiration was then calculated using the Hargreaves equation (Droogers and Allen, 2002):

$$ET_0 = 0.0023 \cdot 0.408 RA \cdot \left(T_{avg} - 17.8\right) \cdot TD^{0.5} \tag{1}$$

where RA is incoming solar radiation, T_{avg} is mean daily temperature and TD is the daily temperature range. Similarly, reference evaporation was then calculated by forcing the Modified-Hargreaves equation with daily data, where all variables are the same as in (1), except for an additional term for daily precipitation:

$$ET_0 = 0.0013 \cdot 0.408 RA \cdot \left(T_{avg} + 17\right) \left(TD - 0.0123 P\right)^{0.76} \tag{2}$$

It is important to note that Droogers and Allen (2002) optimized the Modified-Hargreaves equation for a monthly input of precipitation, yielding ET_0 in mm/day; here we keep the coefficients the same and use daily data. After this calculation, this method will be expanded upon by applying (2) with daily data and re-estimating the parameters represented by certain coefficients.

As mentioned, the outputs of the Hargreaves equation and the Modified-Hargreaves equation were compared with the Modified Penman-Monteith calculations. Their level of consistency was assessed via the Pearson R^2 correlation coefficient and the root mean squared difference from Droogers and Allen (2002):

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n} \left(Pen_i - Calc_i\right)^2}{n}} \tag{3}$$

where *Pen* is the reference evapotranspiration calculation from Modified Penman-Monteith and *Calc* is the same as calculated by the Hargreaves and Modified-Hargreaves. The equation coefficients were estimated by optimizing the correlation coefficient and RMSD using a least-squared regression algorithm. This was done by varying the lettered coefficients of the generalized Hargreaves and Modified-Hargreaves equations given as:

$$ET = a \cdot 0.408 RA \cdot \left(T_{avg} + b\right) TD^{0.5} \tag{4}$$

$$ET = a \cdot 0.408 RA \cdot \left(T_{avg} + b\right) \left(TD - c \cdot P\right)^{d} \tag{5}$$

In this manner, the values of a, b, c and d were changed until the RMSD was minimized.

For analyses, the RMSDs and correlation coefficients were evaluated for seven latitudinal regions described in **Table 1**, as well as for each season and on an annual basis. The seasons were defined as December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON). It is important to note that the parameters of equations (4) and (5) were calibrated globally, then the results were assessed regionally and seasonally. No attempt was made to recalibrate the parameters for each season or region. Finally, the results were tested for significance to determine which equation was the best tool for each spatio-temporal region.

Table 1. Seven regions for analysis.

Region	Lower Latitude	Upper Latitude
1	45	60
2	30	45
3	15	30
4	-15	15
5	-30	-15
6	-45	-30
7	-60	-45

3. RESULTS

3.1 Global Analyses of Optimization (1971-1975)

3.1.1 Annual Results

Table 2 summarizes the coefficients of each equation, with their root mean square difference (RMSD) and regression coefficients. Calculations were based on the 25, 252, 525 estimates obtained from all the 1˚x1˚ grids from 1971-1975. The equations noted as 'daily' are the equations optimized for daily inputs. The R^2 and RMSD metrics were obtained by pairing each estimate at every grid point against the corresponding Modified Penman-Monteith result.

Table 2. Statistical measures of the strength of different methods for calculating reference evapotranspiration, 1971-1975.

Equation	R^2	RMSD	a	b	c	d
Hargreaves (Har)	0.8320	1.4720	0.0023	17.8		
Daily Hargreaves (dailyHar)	0.8321	1.1390	0.0028	19.1869		
Modified Hargreaves (MH)	0.8591	1.2630	0.0013	17	0.0123	0.76
Daily Modified Hargreaves (dailyMH)	0.8564	1.0650	0.0019	21.0584	0.0874	0.6278

Modifying the original coefficients of the MH and Har methods (4) and (5) allowed for a reduction in the RMSD of the Hargreaves equation from 1.4720 mm/day to 1.1390 mm/day without corrupting the regression coefficient. This represents a reduction in the RMSD metric of 22.62%.

The original Modified-Hargreaves equation yielded a larger RMSD than the fitted Hargreaves equation, although the regression coefficient is slightly stronger.

The daily Modified-Hargreaves equation yields the most accurate result, coupling a similar regression coefficient with the lowest RMSD, 1.0650 mm/day. This is a 15.68% RMSD improvement on the Modified Hargreaves equation and a 6.50% RMSD improvement on the daily Hargreaves equation.

The optimization of the Modified-Hargreaves equation for daily data was able to reduce the RMSD of all the observations by almost 0.25 mm/day without dramatic changes to the regression coefficient. Nevertheless, it is equally important to understand the effects of this optimization on smaller spatial and temporal scales. To this end, the results of the optimization will be evaluated across different seasons and across different latitudes. Again, note that the results are merely evaluated regionally and seasonally; no recalibration is conducted. Finally, the optimized equations will be validated using a second period of data, from 1976 through 1980.

3.1.2 Seasonal Evaluation

Seasons were defined as December-January-February (DJF, cyclical days 335 through 59), March-April-May (MAM, days 60 through 151), June-July-August (JJA, days 152 through 243) and September-October-November (SON, days 244 through 334). The RMSD for the original Hargreaves (Har), optimized Hargreaves (dailyHar), Modified-Hargreaves (MH) and optimized Modified-Hargreaves (dailyMH) are presented in **Table 3**. (R^2 values can be found in Appendix, Table A1.)

Table 3. Global, seasonal RMSD values, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	1.3082	1.4309	1.6191	1.5832	1.4730
dailyHar	1.0214	1.1265	1.2782	1.1642	1.1405
MH	1.1768	1.2515	1.3358	1.3614	1.2684
dailyMH	0.9369	1.0820	1.1947	1.0820	1.0664

As seen for the annual results in Table 2, for all seasons the RMSD was reduced by each optimization while the R^2 was maintained. In each season, the dailyMH equation provided the lowest RMSD, making it the strongest equation for the calculation of reference evapotranspiration.

It is interesting that almost all seasons provided a slightly higher RMSD than the all-inclusive RMSD. The largest inaccuracies are found in the JJA season, or the summer of the northern hemisphere. Noting that some 61% of the observations were in the northern hemisphere, this high RMSD seems to suggest that the estival seasonality complicates the accuracy of reference evapotranspiration calculations, as will be discussed below.

At first glance, a slight decrease in the effectiveness of the dailyMH equation during the northern-hemisphere summer can be seen (Table 3). In the northern-hemisphere winter and autumn, the dailyMH equation improves upon the MH equation some 20.39% and 20.52%, respectively. In the spring and summer the improvement is only 13.55% and 10.56%, respectively.

3.2 Regional Analyses of Optimization (1971-1975)

Schlosser and Gao (2010) found that the consistency among modeled evapotranspiration is less robust for high latitudes as well as in the tropics. It is therefore important to look at the optimized data under these considerations. Given this, the results were further pooled by 15° latitude bands (Table 1). The number of individual estimates for each geographic region and season is given in **Table 4**.

Table 4. Number of estimates evaluated in each region and season.

N	DJF	MAM	JAJ	SON	All
Region 1	1,552,050	1,586,540	1,586,540	1,569,295	6,294,425
Region 2	1,227,150	1,254,420	1,254,420	1,240,785	4,976,775
Region 3	1,007,100	1,029,480	1,029,480	1,018,290	4,084,350
Region 4	1,440,450	1,472,460	1,472,460	1,456,455	5,841,825
Region 5	660,150	674,820	674,820	667,485	2,677,275
Region 6	271,800	277,840	277,840	274,820	1,102,300
Region 7	67,950	69,460	69,460	68,705	275,575
Global	6,226,650	6,365,020	6,365,020	6,295,835	25,252,525

Tables 5-11 display the seasonal and annual RMSD for all seven regions. (R^2 values can be perused in Appendix, Tables A2-8.) Instances where RMSD was increased after the optimization are highlighted in red. It is important to note here that these tabulated results are

based on the *global, annual-based* optimization (Section 3.1.1) of the RMSD results, made on the annual estimates. In this way, we are testing the robustness and the degree of ubiquity in the global, annual optimization, by the extent to which it holds on a regional and seasonal basis. The coefficients were not recalibrated for each region.

Table 5. Seasonal RMSD values for Region 1, 1971-1975. Instances where RMSD was increased after the optimization are highlighted in red.

Equation	DJF	MAM	JJA	SON	All
Har	0.4350	0.6783	0.9871	0.8929	0.7784
dailyHar	0.4083	0.8711	1.2595	0.7183	0.8712
MH	0.5546	0.7387	0.9381	0.8786	0.7917
dailyMH	0.3967	0.8427	1.1734	0.6990	0.8277

Table 6. Seasonal RMSD values for Region 2, 1971-1975. Instances where RMSD was increased after the optimization are highlighted in red.

Equation	DJF	MAM	JJA	SON	All
Har	0.8951	1.1215	1.8394	1.6697	1.4350
dailyHar	0.7501	1.0370	1.3957	1.1885	1.1183
MH	0.9101	0.9785	1.3918	1.4198	1.1976
dailyMH	0.7085	1.0063	1.3336	1.0866	1.0581

Table 7. Seasonal RMSD values for Region 3, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	1.7926	2.2669	2.4282	2.3633	2.2270
dailyHar	1.2133	1.4935	1.6835	1.6187	1.5132
MH	1.4971	1.6927	1.7867	1.8763	1.7185
dailyMH	1.1209	1.4279	1.5322	1.4667	1.3962

Table 8. Seasonal RMSD values for Region 4, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	1.2673	1.2146	1.2023	1.1443	1.2062
dailyHar	1.0843	0.9962	0.8886	0.9898	0.9904
MH	1.2882	1.2893	1.2500	1.2573	1.2702
dailyMH	1.0120	0.9950	0.8702	0.9705	0.9619

Table 9. Seasonal RMSD values for Region 5, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	2.0884	1.9811	1.8715	2.1295	2.0185
dailyHar	1.6202	1.4585	1.3100	1.5081	1.4770
MH	1.6157	1.7058	1.5422	1.5865	1.6132
dailyMH	1.3939	1.3287	1.1788	1.3601	1.3168

Table 10. Seasonal RMSD values for Region 6, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	1.8595	1.4976	1.1447	1.3004	1.4729
dailyHar	1.4380	1.0777	0.8789	1.0860	1.1363
MH	1.6146	1.3753	1.1236	1.1815	1.3363
dailyMH	1.3832	1.0359	0.8667	1.0720	1.1036

Table 11. Seasonal RMSD values for Region 7, 1971-1975. Instances where RMSD was increased after the optimization are highlighted in red.

Equation	DJF	MAM	JJA	SON	All
Har	0.9401	0.7474	0.5226	0.6738	0.7353
dailyHar	1.1954	0.6556	0.4787	0.8936	0.8470
MH	0.9857	0.8124	0.5683	0.7186	0.7849
dailyMH	1.0951	0.6599	0.4903	0.8234	0.7969

Regions one and seven (**Tables 5 and 11**) show an increase in annual RMSD as a result of the daily, global optimization. Nevertheless, it is important to note that RMSD hovers around 0.80 mm/day, which is lower than the RMSD viewed annually, across the globe (Table 1). More importantly, the increased RMSD were seen exclusively in the summer months, especially JJA. This suggests that the optimization performed on a global, annual basis is likely to be weakened at high-latitude estimates, and is qualitatively consistent with the results of Schlosser and Gao (2010).

Regions two and six represent a majority of the midlatitude regions. The results in region two (**Table 6**), spanning 30˚N through 45˚N, are similar to those seen in region one. Here, we find that the daily-optimized MH estimate produces a slightly higher RMSD – but only in MAM, where the increase is much smaller than the increases seen for MAM and JJA in region one. Further, for the remaining seasons, the RMSDs for the optimized dailyMH show decreases, most notably in DJF and SON, and thus support the use of the global, annual optimization approach. For JJA, the RMSDs remain slightly higher than all other seasons, though the optimization still reduces it by ~4%. For region 6 (30˚S to 45˚S), in all seasons the global, annual-based optimizations are improvements on previous methods for calculating reference evapotranspiration. Additionally, there is indication of seasonality in these results as the improvements are 24.68% and 22.86% in MAM and JJA, respectively, while only 14.33% and 9.27% in DJF and SON, respectively.

Regions three and five (**Tables 7 and 9**) represent a large portion of the northern and southern subtropics, respectively. These regions show some of the largest RMSDs encountered –

particularly for the original Har and MH methods. In both regions there is only a weak seasonality present in the RMSD metric. In the northern hemisphere, the season of JJA contains the most inaccurate estimates, as seen in other regions, and the RMSDs are larger than the global averages for almost all seasons (Table 3). The same can be said of DJF and SON in region five, strengthening the characterization of larger estival inaccuracies. Nevertheless, the daily optimization results in a notable improvement on the previous methods. Similar to the southern midlatitude region 6, the percent improvement of the RMSDs indicates a marked seasonality. For region three there is a 22.16% and 21.83% improvement in DJF and SON, respectively, compared with only a 15.64% and 14.25% improvement in MAM and JJA, respectively. For region five the improvement is 22.11% and 23.56% in MAM and JJA, respectively, and only 13.73% and 14.27% in DJF and SON, respectively. Overall, we can characterize the percentage improvement in RMSD in the midlatitudes and sub-tropics for the warm seasons as roughly half of that seen in the cold seasons.

Region four, while covering the largest surface area, encompassing the tropics from 15˚S to 15˚N, is second in the total number of estimates binned in this zonal discretization (Table 4). Here, the global, annual optimization brings sizeable decreases – at least 20% in all seasons – in the RMSDs. All but DJF result in RMSDs below one millimeter per day. There is no indication of seasonality in the optimization results for this region. Seasonality in optimized estimates would not be expected in this region due to minimal seasonal fluctuations in precipitation and temperature around the equator.

In conclusion, evaluating results by season and by region highlights two important considerations regarding the global, annual-based optimization of the Har and MH methods for calculation of reference evapotranspiration. Firstly, these estimates of reference evapotranspiration continue to be more inaccurate in the subtropics and tropics. Secondly, performing a global, annual based optimization procedure will likely result in little improvement, and even slight degradations, to the previous methods for high-latitude, estival estimates. These notes should be taken into consideration when assessing the application of this method.

This observed seasonality could also be the result of bias introduced by using a RMSD calculated in real-space. The real-space error tends to focus on errors in large values. For example, the optimization of RMSD in real-space would tend to focus on reducing a five-percent difference in large values of PET, like those seen in low latitudes, and ignore a 25% difference in small values of PET, like those seen in high latitudes. This result could be resolved by examining the RMSD in a space similar to the log-space, but this is suggested for further research. Of course, due to the frequency of zero values, log-space itself is not functional here.

4. VALIDATION OF OPTIMIZATION (1976-1980)

The above discussion analyzes spatial and temporal patterns of 25, 252, 525 estimates used to optimize methods of calculating reference evapotranspiration. It is important to show that these results hold for periods outside of those used for the optimization: that is, a split-sample validation is needed. To this end, the same number of samples was taken from the period 1976-1980 and will be evaluated below. These samples break down similar to those of the period of 1971-1975 (Table 4). Showing that the results seen in the 1971-1975 data hold for the period of 1976 through 1980 provides a validation for the optimization developed here. As shown below, the results are indeed quite similar.

For comparison, **Table 12** shows the global results when the optimized equation is applied to the validation period. The results are qualitatively identical to those shown in Table 2.

Table 12. Statistical measures of the strength of different methods for calculating reference evapotranspiration, 1976-1980.

Equation	R^2	RMSD
Har	0.8344	1.4580
dailyHar	0.8345	1.1315
MH	0.8610	1.2538
dailyMH	0.8584	1.0597

4.1 Seasonal Evaluation

Table 13 presents the RMSD values for all seasons at the global scale. Here, as in the 1971-1975 period, the optimized daily methods out-performed the previous methods for calculating reference evapotranspiration. In all cases, the dailyMH equation provided the lowest RMSD. In addition, we see a peak in RMSD around the northern-hemisphere summer (JJA). Weakened estival improvements are seen as well. The corresponding correlation coefficients can be seen in Appendix, Table A9. As similarly noted in the optimization period, the dailyMH improvement on the MH equation in DJF and SON (19.94% and 20.43%, respectively) is almost double the improvement in MAM and JJA (12.89% and 9.94%, respectively).

Table 13. Global, seasonal RMSD values, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	1.3092	1.4278	1.5961	1.5525	1.4580
dailyHar	1.0203	1.1281	1.2687	1.1388	1.1315
MH	1.1676	1.2494	1.3197	1.3287	1.2538
dailyMH	0.9349	1.0883	1.1885	1.0573	1.0597

4.2 Regional Evaluation

Using the same regions defined in Table 4, the results for 1976-1980 have been evaluated by region and season. **Tables 14-20** present the RMSD values of these results (R^2 values can be perused in Appendix, Tables A10-16).

Table 14. Seasonal RMSD values for Region 1, 1976-1980. Instances where RMSD was increased after the optimization are highlighted in red.

Equation	DJF	MAM	JJA	SON	All
Har	0.4355	0.6808	0.9671	0.8960	0.7735
dailyHar	0.4100	0.8724	1.2473	0.7266	0.8690
MH	0.5437	0.7455	0.9375	0.8837	0.7926
dailyMH	0.3970	0.8476	1.1635	0.7065	0.8270

Table 15. Seasonal RMSD values for Region 2, 1976-1980. Instances where RMSD was increased after the optimization are highlighted in red.

Equation	DJF	MAM	JJA	SON	All
Har	0.9171	1.0872	1.7901	1.6498	1.4102
dailyHar	0.7601	1.0196	1.3632	1.1540	1.0967
MH	0.9241	0.9565	1.3463	1.3937	1.1748
dailyMH	0.7194	1.0027	1.3127	1.0568	1.0448

Table 16. Seasonal RMSD values for Region 3, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	1.7756	2.2232	2.3948	2.2380	2.1706
dailyHar	1.1981	1.4826	1.6630	1.5039	1.4718
MH	1.4669	1.6628	1.7312	1.7501	1.6562
dailyMH	1.1039	1.4351	1.5135	1.3618	1.3626

Table 17. Seasonal RMSD values for Region 4, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	1.2486	1.1897	1.1488	1.1111	1.1740
dailyHar	1.0741	0.9801	0.8724	0.9856	0.9789
MH	1.2718	1.2814	1.2376	1.2439	1.2578
dailyMH	0.9996	0.9806	0.8585	0.9631	0.9504

Table 18. Seasonal RMSD values for Region 5, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	2.1208	2.0802	1.9273	2.1731	2.0759
dailyHar	1.6433	1.5191	1.3691	1.5449	1.5210
MH	1.6309	1.7526	1.5971	1.5987	1.6457
dailyMH	1.4176	1.3761	1.2342	1.3873	1.3546

Table 19. Seasonal RMSD values for Region 6, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	1.8590	1.5589	1.1792	1.3493	1.5062
dailyHar	1.4016	1.1128	0.9042	1.1100	1.1444
MH	1.5751	1.4118	1.1470	1.1967	1.3426
dailyMH	1.3495	1.0662	0.8872	1.0779	1.1061

Table 20. Seasonal RMSD values for Region 7, 1976-1980. Instances where RMSD was increased after the optimization are highlighted in red.

Equation	DJF	MAM	JJA	SON	All
Har	0.9752	0.7352	0.5324	0.6702	0.7444
dailyHar	1.2668	0.6630	0.4947	0.8830	0.8732
MH	1.0210	0.7986	0.5720	0.7194	0.7933
dailyMH	1.1670	0.6619	0.5008	0.8115	0.8207

The results from the 1976-1980 period are almost identical to the results of the 1971-1975 period, lending strength to the validity of the optimized dailyMH method. Again we see a slight weakening of the estimates around the summer months for all regions experiencing some seasonality. In addition, we see an increase of RMSD in the pole-ward latitudes overall and especially in the summer months, though the magnitude of the RMSDs remains small (owing, in part, to the fact that the magnitude of reference evapotranspiration will be lower in these regions).

While degradations in the pole-ward estimates are clear (red text in tables) a glance at the percent improvement highlights the estival reduction in improvement between dailyMH and MH. For region two the JJA is only 2.50%, while the DJF improvement in some 22.15%. For region six the improvements are 24.48% and 22.65% in MAM and JJA, respectively, compared with 14.32% and 9.93% in DJF and SON, respectively. Region five shows improvements of 21.48% and 22.65% in MAM and JJA, respectively, with only 13.08% and 13.22% in DJF and SON, respectively. Finally, region three shows a 24.75% improvement in DJF and a 22.18% improvement in SON, matched against 13.70% and 12.57% improvements in MAM and JJA, respectively. In all cases, the estival improvements are much less than the other two seasons.

The similarity of these results to the optimized period lends support to the effectiveness of the methods employed in this study. Overall, the daily Modified-Hargreaves equation has been demonstrated to be the most consistently performing algorithm at reproducing the Modified Penman-Monteith reference evapotranspiration estimate, but with fewer and more readily available input variables required.

5. CLOSING REMARKS

Overall, these results indicate that, of all the methods examined, the daily Modified Hargreaves method is the most accurate reproduction of the Modified Penman-Monteith approach. Two major concerns have been noted: estival and pole-ward inaccuracies, but the significance of these results is a further consideration.

In order to confidently advocate a single method, efforts were made to test the significance of inaccuracies. **Table 21** represents the results of stringent significance testing. Using a one-tailed, paired t-test, the estimates were tested against the Modified Penman-Monteith value at the 1% significance level. Each equation was tested against the other three in that region. In Table 21, only the equation that performed significantly better than all other equations is noted; a single equation was most significant in all cases.

Again, we see that at the 1% significance level the dailyMH equation is not the strongest in pole-ward summers. The dailyMH equation even fails throughout the southernmost region. These results may be of some concern for individuals focusing solely in these regions. On the whole, it is more important that the dailyMH equation succeeds across all temporal regions when looking at the globe. This result, at the 1% significance level, suggests that it is indeed justified to use the dailyMH equation, over the other methods considered here, for the estimation of daily reference evapotranspiration rates. In particular, this method performs as the most effective surrogate to the Modified Penman-Monteith method, while requiring much fewer input requirements.

Table 21. The results of significance testing, noting the most significantly accurate equation.

Best Equation	DJF	MAM	JJA	SON	Annual
Region 1	dailyMH	Har	MH	dailyMH	Har
Region 2	dailyMH	MH	MH	dailyMH	dailyMH
Region 3	dailyMH	dailyMH	dailyMH	dailyMH	dailyMH
Region 4	dailyMH	dailyMH	dailyMH	dailyMH	dailyMH
Region 5	dailyMH	dailyMH	dailyMH	dailyMH	dailyMH
Region 6	dailyMH	dailyMH	dailyMH	dailyMH	dailyMH
Region 7	Har	dailyHar	dailyHar	Har	Har
Global	dailyMH	dailyMH	dailyMH	dailyMH	dailyMH

This new, fitted, daily Modified-Hargreaves (6) is able to predict daily reference evapotranspiration with some measure of increased confidence, as a supplement to the Modified Penman-Monteith approach, across the globe, allowing for previously-noted caveats. RMSDs of one millimeter/day are considered an acceptable level of error, due to the uncertainties of daily data and estimates.

$$ET_0 = 0.0019 \cdot 0.408 RA \cdot \left(T_{avg} + 21.0584\right)\left(TD - 0.0874P\right)^{0.6278} \quad (6)$$

Figure 1 displays the sample of the original Modified-Hargreaves calculations against the Modified Penman-Monteith equations in red. The blue points are the results of the fitted daily Modified-Hargreaves. The upward movement symbolizes the reduction of the RMSD. In addition, it is evident that the equation is stronger, as a surrogate to Modified Penman-Monteith, in the region of lower reference evapotranspiration.

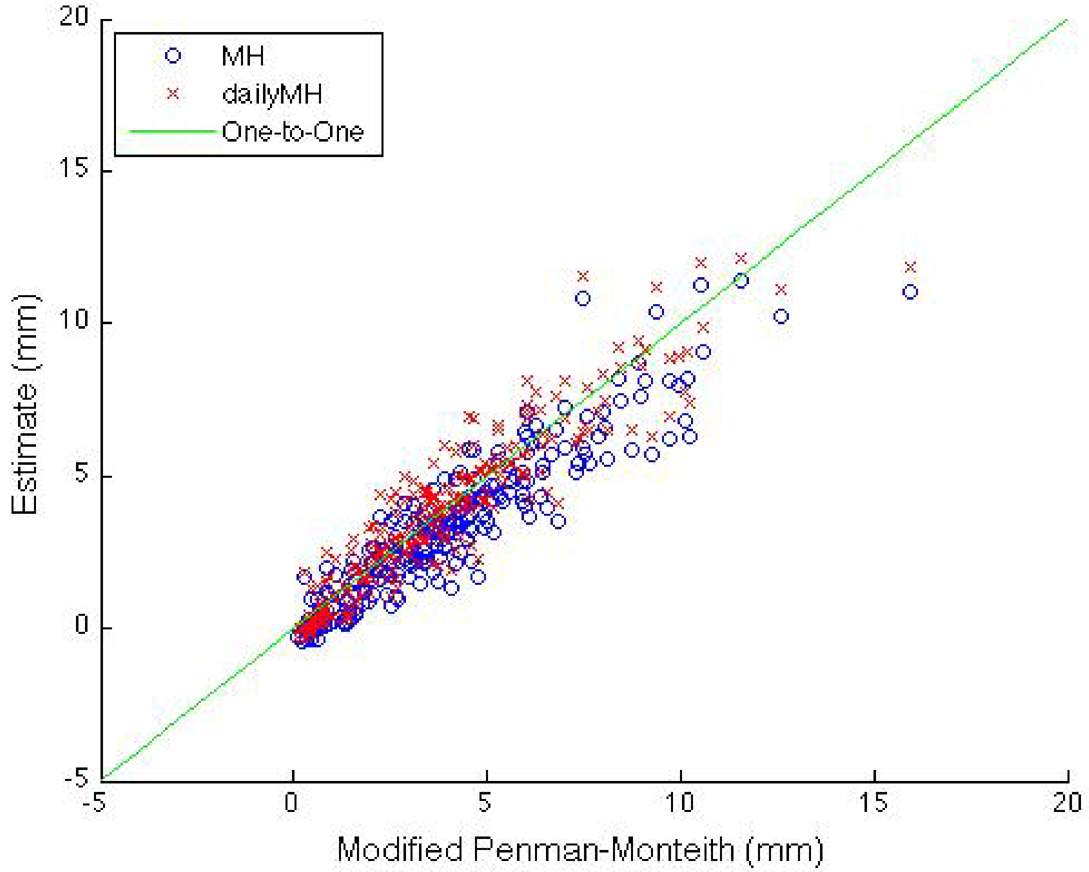

Figure 1. A sampling (0.001% of 25,252,525 estimates) of Modified-Hargreaves (blue) and fitted Modified-Hargreaves (red) against the Modified Penman-Monteith calculations of reference evapotranspiration.

This method allows researchers to confidently assess the daily rates of reference evapotranspiration, without the use of formulae requiring inputs not commonly observed. These calculations can be used to more accurately calibrate and run daily crop and impact models, and be applied to investigations of potential climate changes in all areas of water resources engineering, planning and development.

Following the methods of Droogers and Allen (2002), there may be a way to introduce a new parameter in an effort to strengthen the accuracy of daily calculations. For this exercise, this was considered to complicate the problem. Efforts were made to use a similar form because, as Droogers and Allen (2002) note, other climate variables are not available with much certainty.

The results of this exercise are far from a perfect representation of methods for calculating daily reference evapotranspiration. Further analysis is always advocated. Firstly, the oddities seen in high latitudes and summer months could be the result of unfair weighting in the RMSD. The low magnitude of evapotranspiration rates in the high latitudes cause this particular error statistic to focus on observations with larger discrepancies in real-space. Future analyses should explore the possibility for optimizing coefficients based on the RMSD calculated in a space similar to log-space. Allowing the presence of zero values prohibits the use of log-space, but a similar transformation may reduce the effects of this unfair weighting.

Also in the realm of further research: it may be of some interest to measure how much the coefficients would change in the daily equations if those parameters were re-evaluated for each region and season. For this experiment, the interest was in developing a global approach to estimating daily evapotranspiration. It was thus decided that a recalibration for each arbitrary region and season would result in too much complexity and too many equations, with marginal rates of return. It may be that recalibration is warranted for highly localized studies.

Finally, it would be of some interest to understand when monthly methods should be used instead of the daily methods. Calculating the average monthly reference evapotranspiration from the Modified-Hargreaves approach by using monthly data and comparing it to strictly daily results from the daily Modified-Hargreaves method with daily data might shed some light on appropriate use of these equations. This understanding of when monthly data is more applicable than daily data may be of extreme importance to future modeling efforts.

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APPENDIX

This appendix contains tables of all the R^2 values, matching the tables of RMSD in the text.

Table A 1. Global, seasonal R^2 values, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	0.8624	0.8330	0.8046	0.8130	0.8319
dailyHar	0.8634	0.8330	0.8038	0.8140	0.8319
MH	0.8913	0.8445	0.8302	0.8517	0.8590
dailyMH	0.8904	0.8447	0.8259	0.8473	0.8562

Table A 2. Seasonal R^2 values for Region 1, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	0.1353	0.7245	0.6963	0.7425	0.8260
dailyHar	0.1507	0.7276	0.6965	0.7447	0.8256
MH	0.1534	0.7364	0.7280	0.7690	0.8458
dailyMH	0.1870	0.7515	0.7303	0.7739	0.8460

Table A 3. Seasonal R^2 values for Region 2, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	0.4955	0.7838	0.8030	0.7802	0.8359
dailyHar	0.5044	0.7865	0.8028	0.7829	0.8357
MH	0.5413	0.8125	0.8003	0.8217	0.8637
dailyMH	0.5664	0.8149	0.8052	0.8204	0.8592

Table A 4. Seasonal R^2 values for Region 3, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	0.7367	0.7862	0.8432	0.7786	0.8046
dailyHar	0.7389	0.7868	0.8431	0.7803	0.8057
MH	0.7448	0.7789	0.8362	0.8085	0.8238
dailyMH	0.7503	0.7898	0.8440	0.8096	0.8275

Table A 5. Seasonal R^2 values for Region 4, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	0.6350	0.7752	0.7308	0.6688	0.7077
dailyHar	0.6360	0.7749	0.7320	0.6686	0.7081
MH	0.6951	0.7866	0.7637	0.6956	0.7400
dailyMH	0.6853	0.7845	0.7617	0.6916	0.7354

Table A 6. Seasonal R^2 values for Region 5, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	0.8197	0.6068	0.5588	0.6966	0.6961
dailyHar	0.8206	0.6115	0.5658	0.7005	0.6989
MH	0.8301	0.7180	0.6293	0.7381	0.7725
dailyMH	0.8244	0.6976	0.6251	0.7390	0.7610

Table A 7. Seasonal R^2 values for Region 6, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	0.7181	0.7329	0.5983	0.7334	0.7906
dailyHar	0.7184	0.7345	0.6003	0.7339	0.7906
MH	0.7298	0.7751	0.6340	0.7505	0.8142
dailyMH	0.7367	0.7741	0.6403	0.7552	0.8147

Table A 8. Seasonal R^2 values for Region 7, 1971-1975.

Equation	DJF	MAM	JJA	SON	All
Har	0.5746	0.6151	0.0789	0.6216	0.7086
dailyHar	0.5714	0.6141	0.0807	0.6198	0.7066
MH	0.5883	0.6374	0.1039	0.6311	0.7208
dailyMH	0.5869	0.6370	0.1113	0.6347	0.7197

Table A 9. Global, seasonal R^2 values, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	0.8653	0.8323	0.8065	0.8179	0.8344
dailyHar	0.8662	0.8323	0.8058	0.8189	0.8345
MH	0.8940	0.8435	0.8332	0.8557	0.8610
dailyMH	0.8927	0.8438	0.8289	0.8516	0.8584

Table A 10. Seasonal R^2 values for Region 1, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	0.1088	0.7332	0.6827	0.7311	0.8248
dailyHar	0.1244	0.7364	0.6828	0.7334	0.8246
MH	0.1372	0.7433	0.7146	0.7598	0.8425
dailyMH	0.1627	0.7583	0.7175	0.7646	0.8436

Table A 11. Seasonal R^2 values for Region 2, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	0.5364	0.7856	0.8063	0.7921	0.8404
dailyHar	0.5440	0.7884	0.8062	0.7945	0.8402
MH	0.5793	0.8136	0.8065	0.8275	0.8670
dailyMH	0.5986	0.8168	0.8115	0.8271	0.8629

Table A 12. Seasonal R^2 values for Region 3, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	0.7401	0.7864	0.8499	0.7848	0.8109
dailyHar	0.7420	0.7870	0.8497	0.7863	0.8118
MH	0.7502	0.7799	0.8435	0.8133	0.8295
dailyMH	0.7540	0.7903	0.8513	0.8138	0.8329

Table A 13. Seasonal R^2 values for Region 4, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	0.6467	0.7755	0.7085	0.6503	0.7023
dailyHar	0.6475	0.7752	0.7096	0.6499	0.7026
MH	0.7035	0.7848	0.7415	0.6755	0.7327
dailyMH	0.6945	0.7845	0.7380	0.6710	0.7285

Table A 14. Seasonal R^2 values for Region 5, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	0.8240	0.6417	0.5303	0.6979	0.6959
dailyHar	0.8247	0.6457	0.5378	0.7020	0.6986
MH	0.8316	0.7387	0.6051	0.7433	0.7726
dailyMH	0.8266	0.7210	0.5995	0.7422	0.7602

Table A 15. Seasonal R^2 values for Region 6, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	0.7510	0.7440	0.6120	0.7458	0.8004
dailyHar	0.7510	0.7456	0.6142	0.7462	0.8003
MH	0.7590	0.7821	0.6483	0.7665	0.8254
dailyMH	0.7640	0.7821	0.6528	0.7707	0.8247

Table A 16. Seasonal R^2 values for Region 7, 1976-1980.

Equation	DJF	MAM	JJA	SON	All
Har	0.5482	0.5604	0.0545	0.5875	0.7021
dailyHar	0.5456	0.5605	0.0573	0.5874	0.7009
MH	0.5590	0.5804	0.0761	0.5920	0.7097
dailyMH	0.5606	0.5853	0.0869	0.6023	0.7129

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