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Correcting Hargreaves-Samani formula using geographical coordinates and rainfall over different timescales

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Abstract

The United Nations Food and Agricultural Organization (FAO) approved the Hargreaves-Samani formula (HAR-85) as an alternative to the standard Penman-Monteith method (FAO-PM) for estimating grass reference evapotranspiration (ETo). With much less data demand, HAR-85 is unequivocally useful where meteorological variables are often scarce, incomplete or unavailable. Herein, we evaluate HAR-85 against FAO-PM across 2.505 million km^2, representing Sudan and South Sudan and encompassing wide hydroclimate domains including the Nile River. We further propose simple year-round and seasonal adjustment models to correcting HAR-85 across the entire study area. The models express HAR-85's error in multiple linear regressions in terms of latitude, longitude, altitude and/or monthly rainfall. Varying data periods, including odd, even and all years, are used in the evaluation and the adjustment models development and validation processes to investigate the influence of changing data period. A suit of eight performance indicators shows dependency of the original bias of HAR-85 on the geographical location, monthly rainfall amount, season of the year and data period. All error indicators amplify southward from the hyper-arid region to the dry sub-humid zone. For example, the mean bias error (MBE) ranges from −0.51 to 1.29 mm/day, respectively. Study area-wide, HAR-85 least represents FAO-PM during the hottest month and the transitional month (between the wet and dry-cool seasons) with MBE of 0.65 and 0.70 mm/day, respectively. Conversely, it represents FAO-PM the most in the wettest month, with smallest MBE of 0.32 mm/day. Beholding this spatiotemporal trait, the final yearly and seasonal adjustment models developed herein enormously moderate the predominant overestimation of the original HAR-85. The former model explains 46.7% of the error variance whereas 36.9% to 62.3% of the variation in the error is explainable by the latter models. These adjustment models narrow the monthly MBE among the stations from −0.71-2.17 to −0.80-1.20 and −0.65-0.99 mm/day, respectively. Without undermining the accuracy, the year-round adjustment model can still be feasibly recommended for general use across the study area.

KEYWORDS
arid climates, evaluation, FAO Penman-Monteith method, grass reference evapotranspiration, Hargreaves-Samani method, sub-humid climates, Sudan, validation

1 | INTRODUCTION

The Penman-Monteith (PM) method is strongly recommended by the United Nations Food and Agricultural Organization (FAO) as the standard equation for estimating grass reference evapotranspiration (ETo) (Allen et al., 1998). However, this method – hereinafter FAO-PM – is data-intensive, requiring input data such as solar radiation, sunshine duration, wind speed, air temperature, and humidity. Observing and gathering the full range of weather parameters may be difficult, and the quality of data may be questionable in a given location. The application of this method can thereby be seriously limited and inappropriate, particularly in developing countries, where weather variables are incomplete or of poor quality due to limited financial resources (Droogers & Allen, 2002; Jabloun & Sahli, 2008; Woldesenbet & Elagib, 2021). In such circumstances (Samani & Pessarakli, 1986), the Hargreaves and Samani (1985) equation (HAR-85) is known to be a simplified ETo equation for use with limited weather data (Allen et al., 1998). It requires only measured air temperature.

Hargreaves (1968), Hargreaves and Hill (1977) and Hargreaves and Samani (1982, 1985) characterized a standard method as the one which: (1) is accurate and applicable to short and long period, (2) uses data readily available to users, (3) is relatively simple to apply and (4) is consistent, reliable and applicable over all climatic conditions. Nevertheless, transferring a highly empirical estimation method to another site would not achieve acceptable accuracy unless the geographical and climatic conditions are comparable (Hargreaves & Samani, 1985). Due to the empirical nature and negligence of some environmental processes affecting ETo contained in almost all estimation methods (Allen & Pruitt, 1986), these methods require verification or some type of local calibration when used within a new geographic and climatic area. The lack of dependable ETo measurements makes it impossible sometimes to verify or calibrate the intended estimation method. One has to resort to a well-established and physically sound method instead for comparison and adjustment.

During the past two decades, a plethora of studies have evaluated the universal applicability of this simple method (HAR-85) in many countries and climatic conditions. The ensuing results of these investigations offered possible contradiction with its direct applicability. In spite of its simplicity, it appeared to be less impacted by non-ideal conditions, that is, when data were collected from arid or semi-arid, non-irrigated sites, and compared favourably with FAO-PM in irrigated sites (Hargreaves & Allen, 2003). By using lysimeter station at an experimental farm located in a semi-arid climate of Spain, the HAR-85 method was found to be the second most accurate among seven tested methods next to FAO-PM method (López-Urrea et al., 2006). Er-Raki et al. (2010) compared the HAR-85 formula with FAO-PM method under semi-arid conditions in central Morocco and Northwest Mexico and found it to be accurate for estimating the spatio-temporal variability of ETo. They argued that this good performance was expected because the method was originally developed for semi-arid environments. However, several studies have contradicted this argument. For instance, this method produced underestimates in the semi-arid Karaj region in Iran (DehghaniSanij et al., 2004).

Using three selected weather stations located in the humid coastal plains in eastern North Carolina, HAR-85 over-predicted annual FAO-PM ETo (Amatya et al., 1995). To determine the model that can be used to estimate ETo with small data requirements and high accuracy, Tabari (2010) used data from 12 synoptic stations in four climates, namely arid, semi-arid, cold humid and warm humid, of Iran. Likewise, the study found that the Hargreaves model overestimated annual FAO-PM ETo at all locations except one, and was the worst in cold humid climate among four ETo models evaluated against FAO-PM. In a mild humid climate in northern Iran, a cross-comparison of 31 ETo methods based on a single station ranked the HAR-85 formula the fourth best-suited one for estimating FAO-PM ETo (Tabari et al., 2013). In the southern coast of the Caspian Sea situated in northern Iran, evaluation of this temperature-based formula revealed more suitability of the equation in an intermediate humidity region with slight improvement after calibration (Rahimikhoob et al., 2012). Across a range of Mediterranean climates, covering hyper-arid to humid, Todorovic et al. (2013) pointed out the similarity in the performance of both HAR-85 and FAO-PM methods in hyper-arid and arid zones. Under different geographical and meteorological conditions in Andalusia, Southern Spain, the effectiveness of Hargreaves equation showed high spatial variability, thus generally under-predicted FAO-PM values at coastal areas but provided good estimation for inland (Gavilán et al., 2008). However, despite providing the closest average values to FAO-PM for the same region, Espadafor et al. (2011) reported inability of this equation to detect any trend in ETo. Other studies revealed tendency of the HAR-85 to underestimate the values obtained using FAO-PM in humid locations, such as Western Balkans in South East Europe (Trajkovic & Kolakovic, 2009). Compared to FAO-PM method, the HAR-85 underestimated ETo at all the meteorological stations on the Tibetan Plateau (Ye et al., 2009).

Gavilán et al. (2006, 2008) found that the underestimates or overestimates of the HAR-85 formula were somewhat influenced by wind speed and temperature. Several other studies based on results for semi-arid conditions in Spain proposed local calibration of the original HAR-85 coefficient 0.0023 in terms of wind speed for non-windy locations (Martí et al., 2015; Martínez-Cob & Tejero-Juste, 2004). This result also agreed with results for Fars Province in Iran, where the calibrated coefficients had to be used under conditions of low wind speed (Fooladmand & Haghighat, 2007). Owing to the exclusion of the role of wind speed in the former method, Raziei and Pereira (2013) observed discrepancies between ETo estimates of HAR-85 and FAO-PM methods in arid and hyper-arid climates of eastern and southern Iran. Ogunrinde et al. (2022) attributed the better performance after calibration under sub-humid and humid regions compared with arid and semi-arid regions of northern Nigeria to the peculiarity of the stations, resolution of the data and climatological features, including high variations in the wind speed and relative humidity. The review and investigation carried out by Shahidian et al. (2013) of the most promising parameters used for calibrating the HAR-85 for California and Bolivia showed some interesting results. First, because the correlation between HAR-85 and FAO-PM shows poor performance during the humid months and progressive improvement along the dry season, annual calibration of the HAR-85 against FAO-PM can be misleading. Second, the average monthly wind speed is a suitable spatial and seasonal calibration parameter. Third, the calibration can also be achieved using elevation and precipitation. In fact, Samani (2000) pointed out the latitude and elevation among the factors influencing the empirical coefficient 0.0023 in the HAR-85 equation. The effect of precipitation in improving the performance of this simple formula goes in line with results obtained by Droogers and Allen (2002), who found that adding a precipitation term to the HAR-85 equation enabled it to better reproduce ETo as calculated using the PM method. However, these results were rebutted by Mohawesh and Talozi (2012), who concluded that inclusion of the additional rainfall term did not improve the accuracy of the formula using data from weather stations in Jordan. Considering Köppen climate class in Iran, Akhavan et al. (2018) also found that a version of the HAR-85 formula with local elevation-based calibration performs better than the original formula in climate classes in Iran. Similar finding was obtained using data from the Alpine River Basins that the error in the standard HAR-85 equation correlates with the station elevation above mean sea level (Ravazzani et al., 2012). This finding was associated with overestimation observed at low elevation and underestimation at higher elevations.

The above literature review shows how the performance of the simple HAR-85 can vary temporally, spatially and geographically. It also realizes the dispersal and dearth of studies devoted to developing countries in Africa. As stated by a number of researchers (e.g., Martínez-Cob and Tejero-Juste (2004); Almorox & Grieser, 2016), the use of climatic elements other than the widely available input and commonly recorded data such as temperature to adjust the HAR-85 equation would violate its simplicity and applicability. This state of violation is especially relevant to the case of developing countries in Africa, where lack of climatic data is an inherent problem. In this study, Sudan and South Sudan are used as a case study to represent vast climate zones from within the African continent and the Nile River basin aiming at:

1. evaluating the HAR-85 to explore if a substantial deviation exists from FAO-PM in estimating ETo across the two countries.
2. examining the presence of evidence of role played by the geographical coordinates and rainfall in adjusting HAR-85 formula to provide a simple option and an effective solution to the spatio-temporal correction to the formula.
3. investigating the effect of varying the study data period on the performance of HAR-85 formula. Here, we propose a new approach to handling the datasets in the evaluation, adjustment and validation of the formula to enable these processes beholding the full range of climate variability within the study period.

2 | STUDY AREA

Twelve stations were used in the evaluation in this study (Figure 1). Nine of these stations are located in Sudan whereas the rest three stations are situated in South Sudan. The two countries comprise an area as big as 2 505 813 square kilometres. These stations possess a wide range of geographical and climate features. They are located in four climatic zones, namely hyper-arid, arid, semi-arid and dry sub-humid (Elagib, 2002), between latitudes of 4° and 20° N, between longitudes of 25° and 38° E and at elevations above mean sea level of 5–730 m. During the data period, annual rainfall in the study area had a mean of 12.7 mm at Dongola in the north to 1085.9 mm at Wau in the southwest (Alvi & Elagib, 1996; Elagib & Mansell, 2000a). Total monthly rainfall ranged from nil in the hyper-arid zone to around 300.0 mm in the dry sub-humid zone. Mean monthly temperature took the range 17.6 to 33.7°C, recorded at Dongola and Kassala/Shambat, respectively (Elagib & Mansell, 2000a).

3 | DATA AND METHODS

The data used and methodology carried out in this study are shown in the flowchart of Figure 2.

3.1 | *ET*$_o$ data and estimation

The monthly data of the climate elements originally used to calculate *ET*$_o$ in mm/day for the 12 stations under study were obtained from Sudan Meteorological Authority (SMA: http://www.ersad.gov.sd/) including rainfall, maximum and minimum temperatures, sunshine duration and wind speed. Detailed description of the quality of the temperature data are discussed by Elagib and Mansell (2000a) and Elagib (2010). The original data used to calculate FAO-PM ETo were administered by SMA luckily during a period (1960–1990) when the highest quality control was assured. The *ET*$_o$ datasets derived from the FAO-PM method (Equation (1)) were obtained from Elagib and Mansell (2000b) and Al Zayed et al. (2015).

$$ET_o = \frac{1}{\lambda}\left[\frac{\Delta(R_n - G) + 86400\rho\, c_p (e_a - e_d)/r_a}{\Delta + \gamma(1 + r_s/r_a)}\right], \qquad (1)$$

where λ is the latent heat of vaporization (MJkg^{-1}); Δ is the slope of the saturation vapour pressure–temperature curve (kPa°C^{-1}); R_n = net radiation available at the surface (MJm^{-2} day^{-1}); G is the soil heat flux density (MJm^{-2} day^{-1}) and is equal to 0 for periods over 10–30 days; 86 400 is a term which converts resistance time units from seconds to days; ρ is the density of the air (kgm^{-3}); c_p is the specific heat of moist air at constant pressure and is equal to

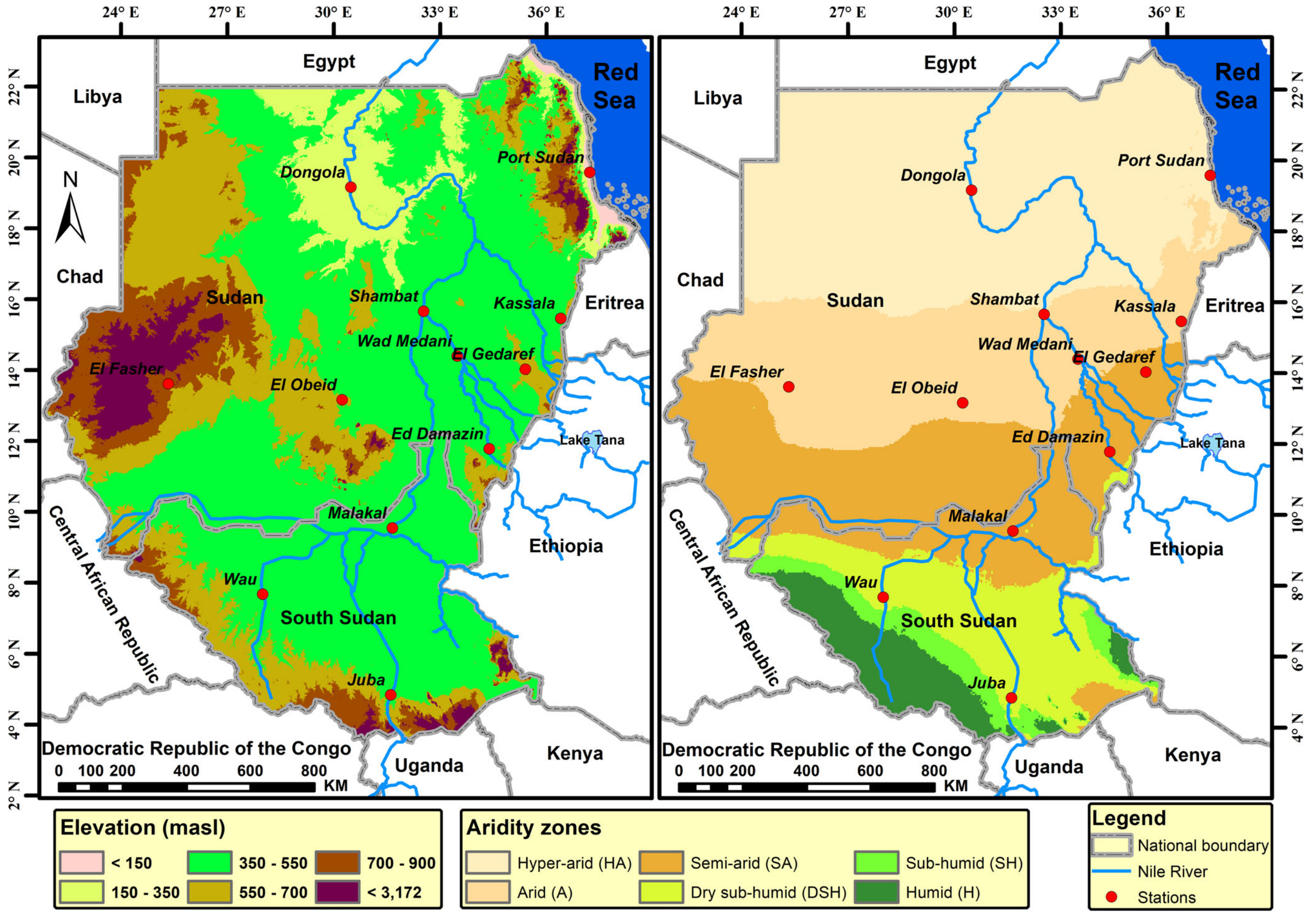

FIGURE 1 Study area (Sudan and South Sudan) showing its topography (left panel), stations under consideration and aridity zones (right panel). The aridity zones were based on the aridity index of the United Nations Environment Programme (UNEP, 1992) defined as the ratio of annual rainfall to annual reference evapotranspiration using 1961-1990 data from Abatzoglou et al. (2018). Data portal: http://www.climatologylab.org/terraclimate.html.

1.013×10^{-3} MJkg^{-1}°C^{-1}; e_a is the saturation vapour pressure at the current air temperature (kPa), that is, the average of saturation vapour pressures at T_{max} and T_{min}; e_d is the saturation vapour pressure at the dew point temperature, i.e. actual vapour pressure of the air (kPa), where the dew point temperature is set approximately equal to T_{min} for ideal well-watered condition; r_a is the aerodynamic resistance to vapour and heat diffusion (sm^{-1}), γ is the modified psychrometric constant (kPa°C^{-1}) and r_s is the bulk surface resistance of the crop canopy and soil (sm^{-1}). Since FAO-PM method requires global radiation data that can be obtained based on sunshine duration, useful formulae of this parameter were developed as a function of sunshine hours by Elagib et al. (1999a), Elagib and Mansell (2000c) and Elagib (2009b).

For seven of the stations, i.e. those located between latitudes 10° and 16° N (Figure 1), ET_o using HAR-85 formula (Equation (2)) were taken from Elagib (2009a, 2014). The estimates of HAR-85 ET_o for the remaining five stations were obtained independently – also based on Equation (2) – for the purpose of the present work. Extraterrestrial radiation data required for calculating HAR-85 ET_o for those five stations were extracted from Elagib et al. (1999b).

$$ET_o = 0.0023\,R_a\,(T_{mean} + 17.8) \times (T_{max} - T_{min})^{0.50}, \qquad (2)$$

where R_a is the extraterrestrial radiation in the same units of water evaporation (mm/day), and T_{mean}, T_{max} and T_{min} are the mean, maximum and minimum air temperatures, respectively, in °C. The difference between the two temperature elements defines the diurnal temperature range (DTR).

3.2 | Strategies of data splitting for evaluation, adjustment and validation

As shown in Table 1, the datasets employed in this study extend from 22 years at Ed Damazin to 50 years at Wad Medani. This span of data period should meet the desired consideration of variability in climate and the desired improvement of the reliability of the proposed adjustments (Er-Raki et al., 2010). By the same token, these reasonably long time series permitted three splits of data for each

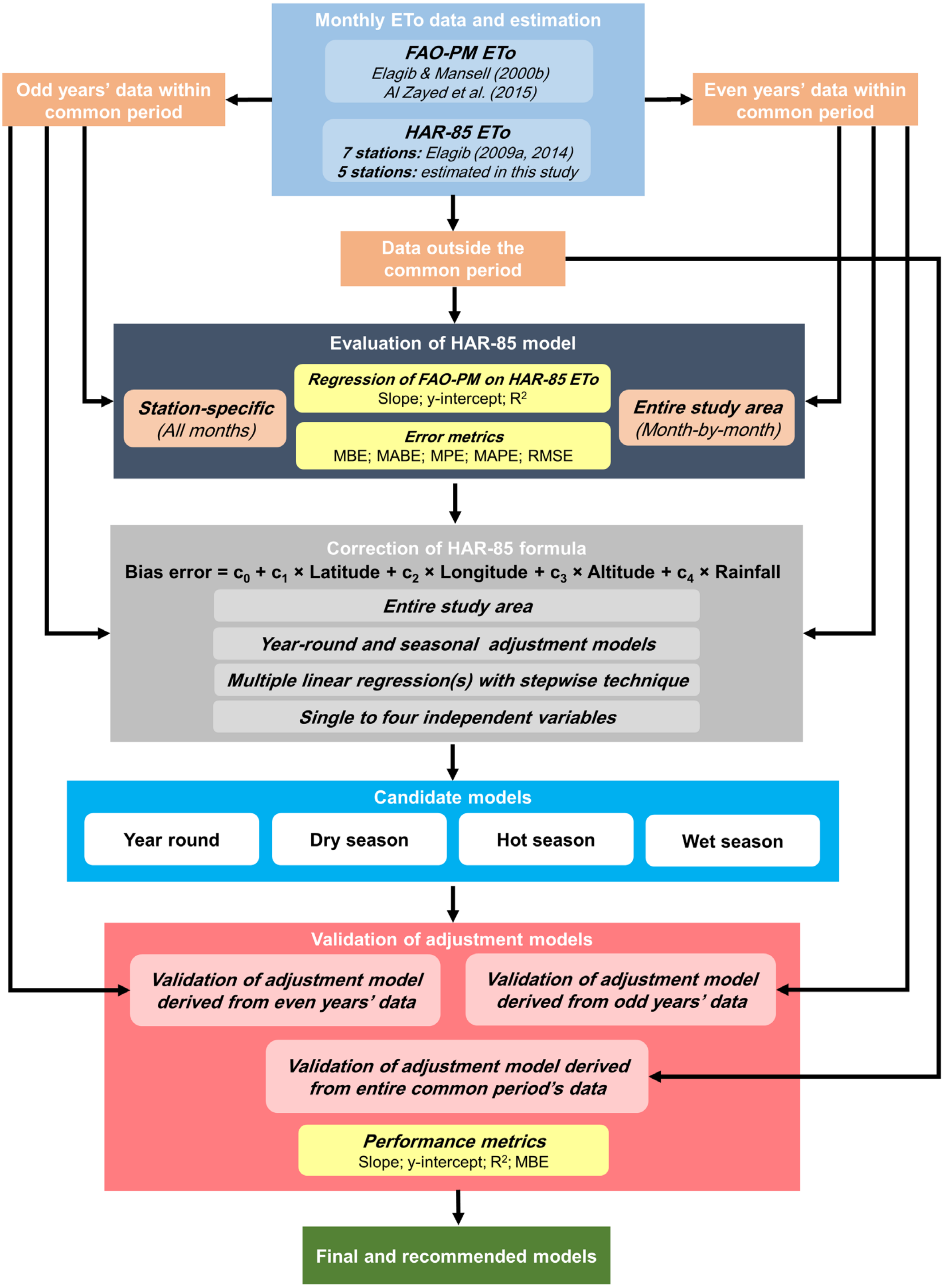

FIGURE 2 Flowchart of the methodology.

station, that is, odd and even years' data of the common data period (1968–1984) among all the stations and data that fall outside the common period. The length of data was thus 8, 9 and 5–33 years, respectively.

Testing an ET_o method for its efficiency on seasonal (Amatya et al., 1996; Mohan et al., 1996) and long-term (Smith, 1965) bases is important since the reliability of the method is a function of season-to-season and of year-to-year variability. Against this backdrop, we undertook the following three approaches in the evaluation of the HAR-85 method with reference to the data periods displayed in Table 1.

i. A station-by-station evaluation was performed using the full available odd or even years' data separately. Here, the datasets

TABLE 1 Data periods and splits selected for the evaluation of HAR-85 method and development and validation of adjustment models

Country	Station	Full data period	Common data period among all the stations	Period(s) outside the common data period
Sudan	Port Sudan	1961–1996	Exchanged odd and even years within 1968–1984	1961–1967; 1985–1996
	Dongola	1968–1990		1985–1990
	Shambat	1961–1996		1961–1967; 1985–1996
	Kassala	1961–1990		1961–1967; 1985–1990
	Wad Medani	1961–2010		1961–1967; 1985–2010
	El Gedaref	1966–1996		1966–1967; 1985–1996
	El Fasher	1961–1996		1961–1967; 1985–1996
	El Obeid	1961–1996		1961–1967; 1985–1996
	Ed Damazin	1963–1984		1963–1967
South Sudan	Malakal	1961–1987		1961–1967; 1985–1987
	Wau	1961–1986		1961–1967; 1985–1986
	Juba	1961–1984		1961–1967

were composed of a minimum of 11-year (at Ed Damazin and Dongola) to a maximum of 25-year (at Wad Medani) time series when the odd years' data were used. When the even years were considered, the data size ranged from 11 years at Ed Damazin to 25 years at Wad Medani. This way, the data size ranged from 132 records (11 years × 12 months) to 300 records (25 years × 12 months).

ii. An evaluation was carried out for each station to check the performance month-by-month: (a) following the odd and even years approach using the common period data and (b) using each station's data outside the common period. This way, the data size for each month was 8 for the odd years, 9 for the even years and 5–33 for the years outside the common period.

iii. A monthly-specific evaluation was also performed in which the data of the entire study area (i.e., the 12 stations encompassed by the two countries) were considered as one set to look into the role of spatial agent in the performance of the HAR-85 formula. In this case, the common data period among all the stations that governed the analysis was used. The data size was thus 96 (8 years × 12 stations) in the case of the evaluation that used odd years and 108 (9 years × 12 stations) otherwise.

Based on the described datasets, three strategies were adopted in the development and validation of the adjustment models. In the first one, the data related to the odd years (Data size: 8 years × 12 stations × 12 months = 1152) were used for the development of the adjustment models while that related to the even years (Data size: 9 years × 12 stations × 12 months = 1296) were employed in the verification stage. The opposite approach was adopted in the second strategy, that is, exchanging the even and odd years' data for the formulation and validation, respectively. In the third one, the combined odd and even years' data of the common period were used for the formulation of the final adjustment models while the data that fall outside the common period were employed in the station-by-station validation. This third approach contained 17 years × 12 stations × 12 months = 2448 records for adjustment and 5–33 years × 12 stations × 12 months = 720–4752 records for validation. These strategies thus permitted considering the extent of climate variability within the data period for operational development and verification processes of adjustment models.

The odd-and-even years split sampling has become a popular technique in use for calibrating and validating hydrological models. Unlike the traditional block-type (two-period) sampling method, the former technique has a couple of advantages (Arsenault et al., 2015, 2018; Chen et al., 2013; Essou et al., 2016; Yang et al., 2020). One advantage is that it responds to non-stationary climate conditions, such as trends arising in long climate time series (decadal or multi-decadal natural variability), occurrence of wetter- and drier- than-average periods or inconsistency in data due to addition or removal of weather stations. Moreover, by taking the entire spectrum of available values and interannual variability of the climate system into account, this technique thus avoids the risk of over-fitting of model to a certain effect of condition over the other.

3.3 | Evaluation criteria

To evaluate the HAR-85 method, this study considered several performance indicators simultaneously as adopted by Parmele and McGuinness (1974). Here, the method is said to yield accurate results if it gives low absolute difference from the values given by the reference method (FAO-PM), y-intercept closest to zero, a slope closest to 1.0 and the highest correlation coefficient (or alternatively determination coefficient, R^2) in a regression analysis of the FAO-PM versus HAR-85 datasets. Al-Sha'lan and Salih (1987) also adopted the smallness of the intercept as an evaluation criterion among other performance indicators. Other performance metrics used herein were Mean Bias Error (MBE), Mean Absolute Bias Error (MABE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), and Mean Absolute Percentage Error (MAPE). In this study, the bias error was of particular interest in the evaluation of the HAR-85 model. It was used not only in the appraisal of the HAR-85 performance, but was also useful in proposing adjustment formulae as will be described in the following section. Furthermore, we explored the effect of geographical coordinates (latitude, longitude and altitude) on these performance indicators across the two countries using linear and polynomial regression forms. The effect of rainfall on the bias error before and after adjusting the HAR-85 estimates was also explored.

3.4 | Formulation of adjustment models

It is the main purpose of this study to investigate the possibility of expressing the deviation of HAR-85 estimates from the FAO-PM values of ET_o as a simple function of readily available parameters. Latitude and elevation were identified as factors influencing the HAR-85 formula (Samani, 2000). Droogers and Allen (2002) added monthly precipitation to the HAR-85 formula to improve its agreement with FAO-PM method. Their assumption was that 'monthly precipitation can in some regards represent relative levels of humidity' in situations of limited weather data availability. Moreover, a large part of the study area lies in the African Sahel region, which exhibits very strong north–south (latitudinal) temperature and rainfall gradients during June to September (Funk et al., 2012; Hulme & Tosdevin, 1989). Therefore, the distribution of aridity zones is highly governed by this latitudinal gradient of rainfall (Figure 1). Both HAR-85 and FAO-PM involve latitude in their formulations through the calculation of the extraterrestrial radiation. Finally, the effect of altitude is embedded in the FAO-PM method through the adjustment formula of the wind speed when it is measured at a height other than 2 m. In fact, there is already a physical relationship between wind speed and altitude in a power-low profile (Johnson, 1959; Linsley Jr et al., 1988).

All the reasons laid above are physical basis justifying the use of these independent variables to correct HAR-85 estimates. In this study, we explored the possibility of expressing the bias error (dependent variable) in the HAR-85 estimates on a single or a combination of independent variable(s), namely geographical location (latitude, longitude and altitude) and monthly rainfall. Apart from the geographical coordinates, the use of rainfall as independent variable is favourable in the sense that it is readily available unlike other climate elements. We used all the stations' data within the common data periods, i.e. odd or even years separately or the entire common period's data, to develop year-round and season-specific adjustment models based on the bias error using multiple linear regression of the following form:

$$\text{Bias error} = c_0 + c_1 \times \text{Latitude} + c_2 \times \text{Longitude} + c_3 \times \text{Altitude} + c_4 \times \text{Monthly rainfall}, \tag{3}$$

where c_0 to c_4 are regression constants (or coefficients). To develop the seasonal adjustment models, three seasons identified by Elagib and Mansell (2000a) as dry, hot and wet were considered (Figure S1). The inclusion or exclusion of a given independent variable in Equation (3) for the odd, even or entire common years' dataset was determined by a stepwise technique in the multiple linear regression analysis. Hence, this regression analysis resulted in linear models of a single to four independent variable(s), that is, latitude, longitude, altitude and/or rainfall, depending on whether the dataset used referred to odd years, even years or entire common period. The criteria for selecting a candidate adjustment for validation were: (1) inclusion of rainfall as an independent variable so that it is dynamic unlike a 'static' model with only geographical coordinates that are constant, (2) a model with statistically significant regression coefficient(s) and (3) having highest and significant R^2. There exists an exception as regards the first criterion since rainfall does not occur throughout the year at all the stations. This exception is expected to relate to the hot and/or the dry seasons' models. These bias error models can thus be used to correct the HAR-85 model as follows:

$$\text{Corrected HAR-85}\, ET_o = \text{Original HAR-85}\, ET_o \pm \text{Bias error model (Equation 3)}. \tag{4}$$

The sign (±) in Equation (4) can be explained as follows. If the bias error of the original HAR-85 is negative, that is, referring to an underestimation; then, the absolute value of this bias error must be added to the corresponding original HAR-85 ET_o. When the bias error is found to be positive, indicating an overestimation, the magnitude of bias must then be subtracted from the original HAR-85 ET_o.

To decide on which adjustment model(s) out of the candidate yearly and seasonal models to choose as final specific season models, we considered the common period's candidate models and compared the absolute MBE between the year-round and seasonal models. The final model was, thus, the one that gave lower MBE. Adjustment was regarded unnecessary, i.e. the original HAR-85 formula was deemed of sufficient accuracy. This means that the adjustment model rendered higher absolute MBE than or did not change the absolute value of its original counterpart. Finally, we recommended a single model out of a set of final adjustment models for general use across the study area.

4 | RESULTS

4.1 | Evaluation of the HAR-85 formula

4.1.1 | Station-specific evaluation

Figure 3 shows the performance of HAR-85 against FAO-PM as measured by the eight indicators, namely MBE, MABE, RMSE, MPE, MAPE, and intercept, slope and R^2 of the scatter plot of the non-adjusted HAR-85 ET_o calculated using the odd and even years' data. Both evaluations show comparable results. The chief and most salient feature is that the powerfulness of the HAR-85 in capturing the FAO-PM ET_o deteriorates from north to south. There is a distinguishable nature of the error as presented by MBE and MPE that this formula underestimates ET_o in the hyper-arid zone and overestimates it elsewhere. However, the coastal station (Port Sudan) in this zone shows lesser bias than that exhibited by the inland station (Dongola). The MBE increases

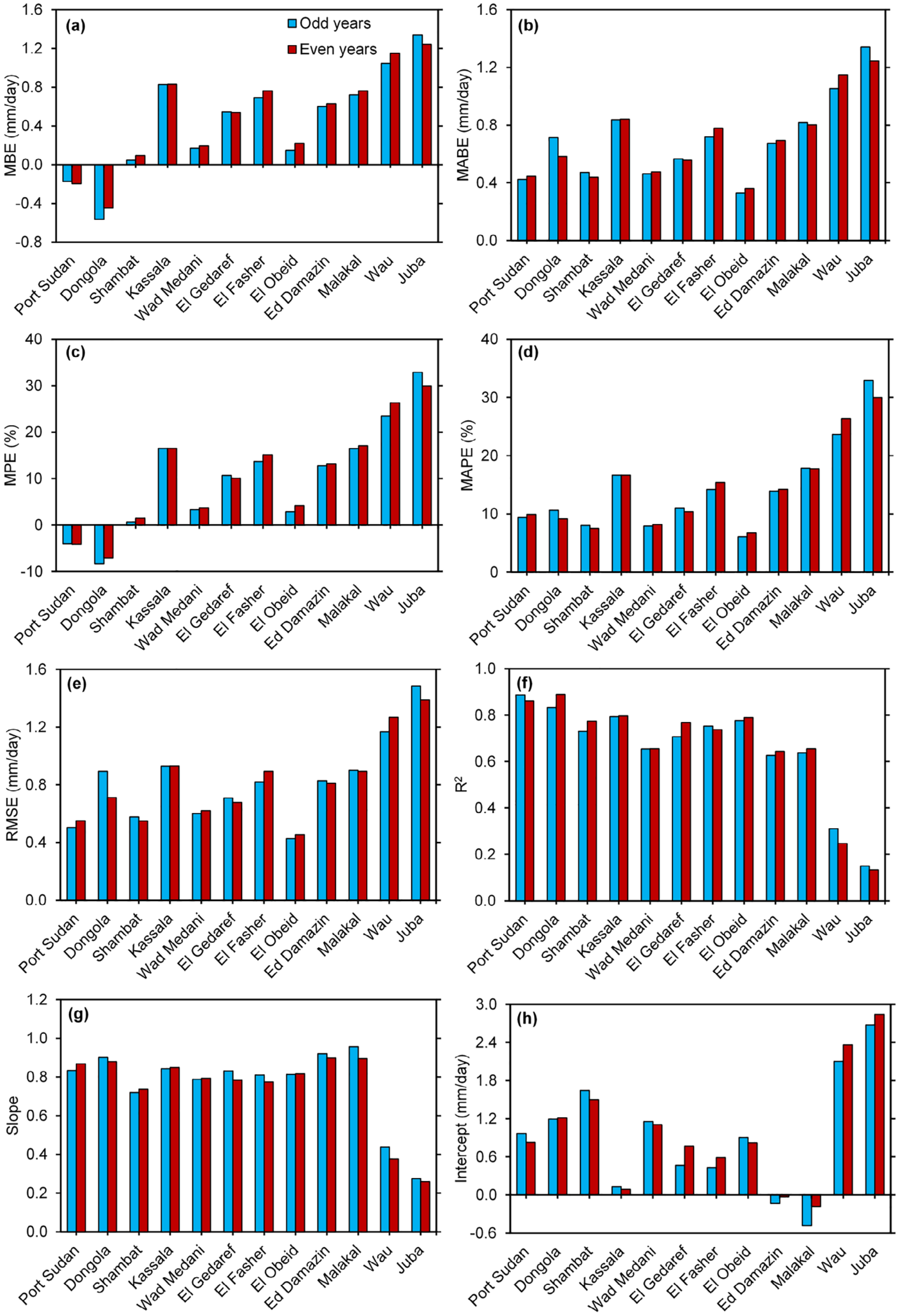

FIGURE 3 Station-specific comparison of performance indicators of HAR-85 formula between odd and even years evaluations with the stations arranged in order of decreasing latitude.

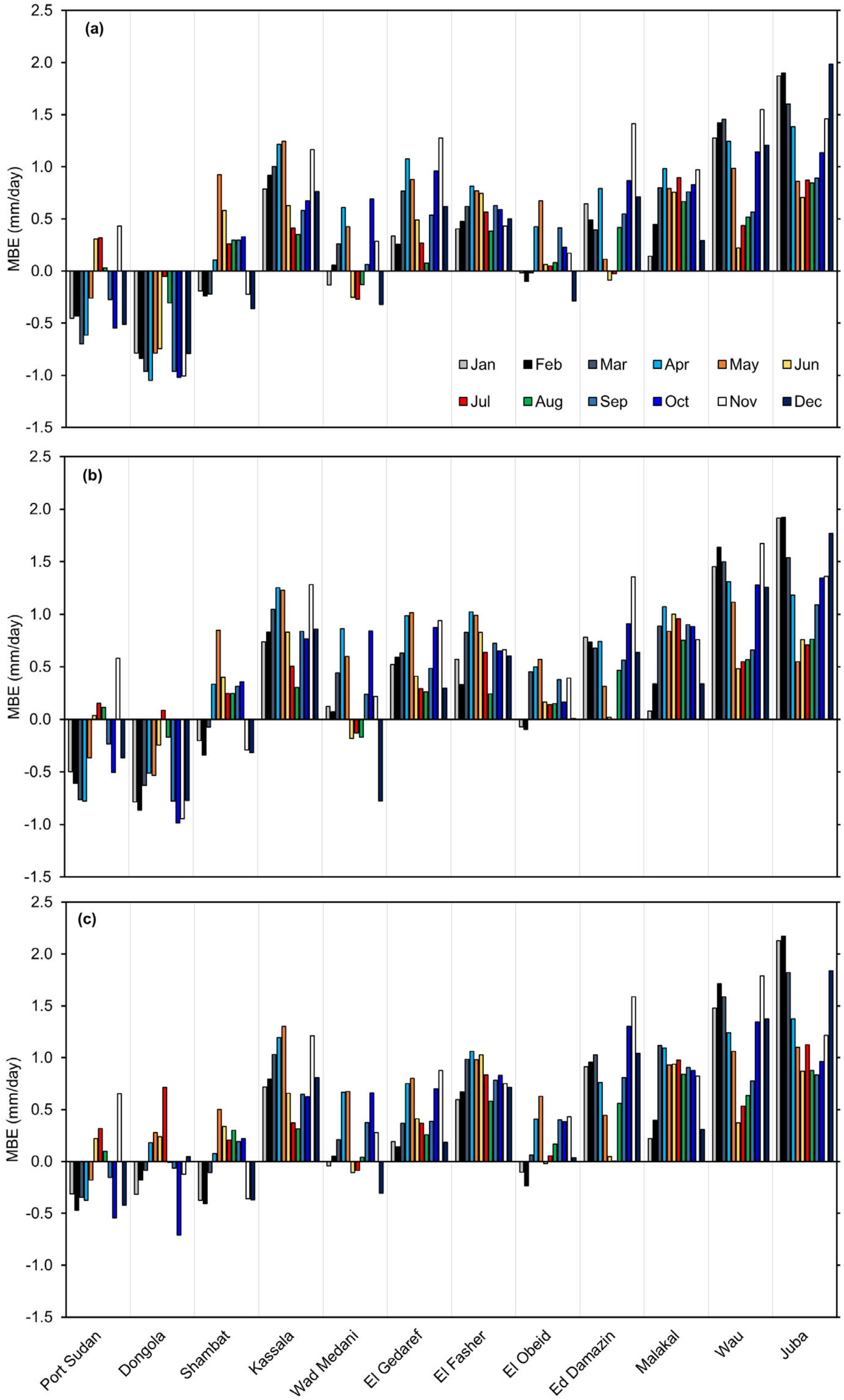

FIGURE 4 Station-by-station comparison of annual cycle of original mean biased error: (a) odd years' data within the common data period, (b) even years' data within the common data period and (c) data outside the common period. The stations are arranged in order of decreasing latitude.

from −0.506 mm/day at Dongola to 1.293 mm/day at Juba on average. Moreover, the MPE escalates approximately from −8% to 31% at the respective stations. Based on the R^2, HAR-85 formula is capable of explaining up to 87% of the variation in FAO-PM ET_o at Port Sudan, but only 14% of this variation is obtainable at Juba on average.

Figure 4 shows the station-by-station comparison of intra-annual MBE. Despite the salient overall similarity of MBE results between the three analysis periods in terms of existing over- and under-estimates, a look at the details reveals somewhat variations in the magnitudes at specific stations. These results evidence the influence of varying the study period on the performance of the HAR-85 formula. Such a variation is however less apparent between the odd (Figure 4a) and the even (Figure 4b) years than in the years outside the common period (Figure 4c).

4.1.2 | Study area-wide evaluation

Since the station-by-station evaluation carried out above exhibited latitude influence on the performance of HAR-85, it appears interesting to explore this influence on the scale of the entire study area by considering the data of the two countries together as one set. To this end, the best way would be to consider the evaluation results in a month-by-month manner that can also make a prominent exhibition of the seasonal performance of the formula. The eight performance indicators are depicted in Figure 5 for the 12 months using the common data period among the stations for each monthly evaluation. Broadly speaking, the annual cycles of the MBE, MABE, MPE and RMSE display double-hump pattern, peaking in April and November. The latter peak is higher than the former. The MAPE shows one clear peak in November despite high values in January to April. Contrary to this pattern, the R^2 and the slope are patterned with a single peak, specifically in September for the slope but in July or August for R^2 depending on the dataset used. The intercept is negative during the period May to September and positive otherwise, with November having the largest positive value whereas September indicates the largest negative value. Generally, the low errors occur during June to September. It is worth noting, as shown in Figure S1, that June to September is the rainy part of the year, November is the transitional month between the rainy season and the dry, cool season at the inland stations, whereas April is the hottest month of the year almost across both Sudan and South Sudan (Alvi & Elagib, 1996; Elagib, 2009a; Elagib & Mansell, 2000a). The above results suggest that the HAR-85 equation performs best in the wettest months, worse in the hottest month and worst in the month of transition between the rainy season and the dry, cool season. Furthermore, the bias associated with HAR-85 is indicative of overestimation throughout the year. Based on the average of performance indicators obtained using the odd and even years' data, the MBE ranges from 0.281 mm/day in August to 0.663 mm/day in November. The MPE ranges from 7% in June/August to ~17% in November. As indicated by R^2, the proportion of the variation in FAO-PM ET_o that is predictable from the HAR-85 ET_o varies from as low as 0.9% (November) to as high as 88% (July) on average.

4.1.3 | Factors influencing the bias error

Figure 3 shows broadly a characteristic latitudinal effect on the performance of the HAR-85 formula. To confirm this observation, the station-specific performance metrics are plotted versus the latitude (Figure 6a–g). Seven of the indicators are latitude-dependent, and this relation is essentially a second order polynomial regression. About 70% to 91% of the variations in these indicators are explainable by the latitude of the location, as demonstrated respectively by the slope and R^2. Conversely, the intercept did not exhibit a clear relation with latitude, but it can be expressed as a function of the slope (Figure 6h). In general, MBE inversely relates with latitude (Figure 6a). The role of latitude in deciding the performance of the HAR-85, as expressed by the bias error, on the monthly timescale for the entire study area is further presented in Tables S1 and S2. As noted earlier, Table S1 again puts forward an inverse relationship between the bias error and latitude. However, the latitudinal effect is in overall nonlinear (2nd order polynomial), as shown in Table S2. Expressing the relationship in a nonlinear form provides better results in terms of R^2 in few months, depending of the dataset under consideration. Comparing the R^2 for each set of data (odd or even) between the two tables, one can find no or little improvement during the dry, cool months of the year (January to March, November and December) and part of the wet months (June to August), but moderate improvement during the other part of the wet season (September and October). The nonlinearity presents the largest improvement in the hottest months (April and May). Unlike the latitude, the strength of the independent effect of the other geographical coordinates, that is, the longitude and altitude, on the performance is much lower, especially the longitude, compared to the latitude (Figure S2).

Figure 7 displays the dependency of the bias error on the monthly rainfall using the odd and even years' data within the common period and the data lying outside the common period. Generally, the bias error of HAR-85 in the three datasets reduces as monthly rainfall increases, with apparently maximum bias taking place at or near-zero rainfall. These results go in line with the results presented in Figure 5 which indicate higher errors occuring outside the rainy period June through October. The overall conclusion of this section is that the geographical coordinates and rainfall play an important role in determining the bias error of HAR-85 equation, a role thus deserves further investigation.

4.2 | Adjustment models

The above observations clearly showed seasonal variation in the deviation from or proximity to the FAO-PM method rendered by the HAR-85 formula in estimating ET_o. They also confirmed location (geographical coordinates) and rainfall effects on this deviation. Thus, exploring a relevant approach to adjust the latter formula seems justifiable. Using one to four independent variables, namely latitude, longitude, altitude and/or rainfall, the results of both yearly and seasonal analyses are given in Table 2 for candidate adjustment models and in Table S3 for non-candidate models. The portion of variance in the bias error that can be explained by the candidate yearly models ranges from 45.7% to 47.6%. It is estimated that 36.6% to 63.9% of the variations in the bias error are explainable by the seasonal models, with highest R^2 is obtained by the dry season model while the least R^2 characterizes the wet season model. Low R^2 for the wet season is expected in view of the high variability of climate during this season.

4.2.1 | Adjustment of bias in the HAR-85 formula

In this section, we present the results of testing the ability of the yearly and seasonal adjustment models in improving the estimates

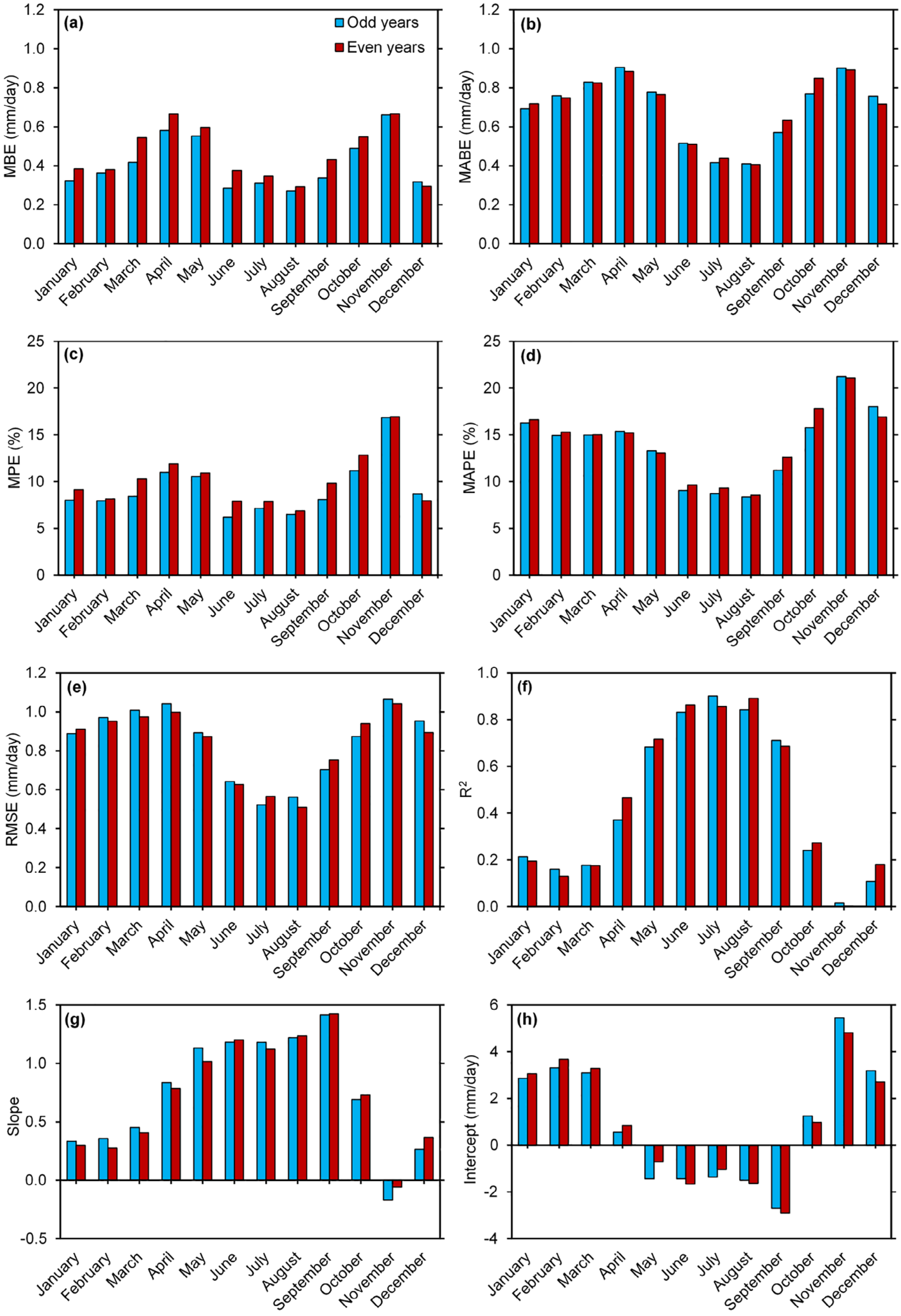

FIGURE 5 Month-specific comparison of performance indicators of HAR-85 formula between evaluations based on odd and even years' data.

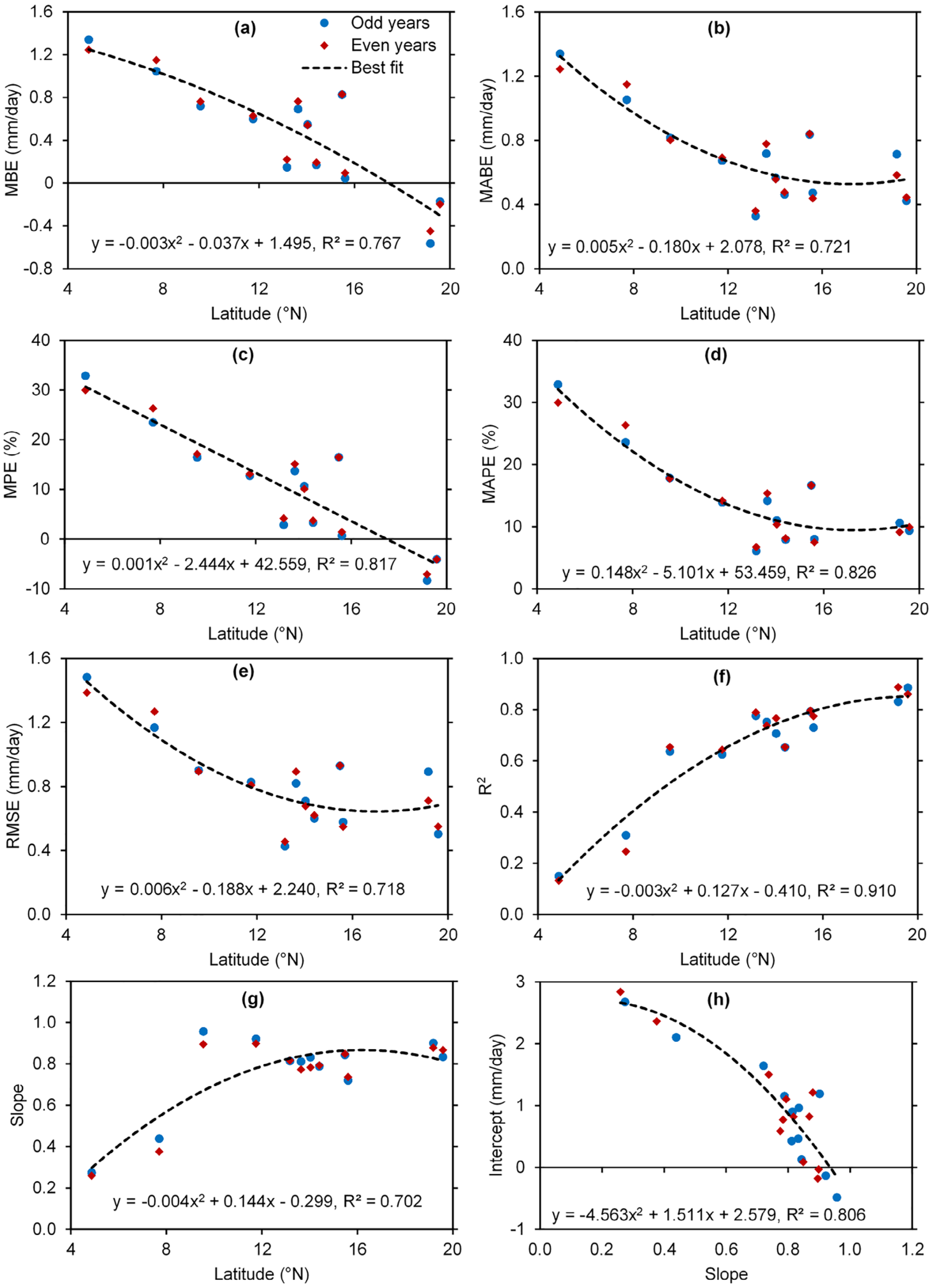

FIGURE 6 Latitudinal effect on the performance indicators (a–g) shown in Figure 3 and the correlation between the intercept and the slope (h).

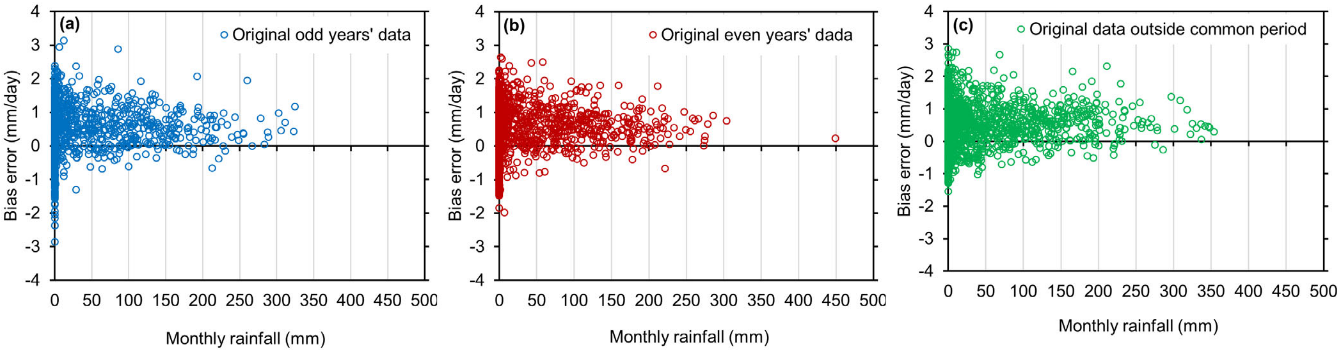

FIGURE 7 Effect of monthly rainfall on the bias error for the 12 stations using odd and even years' data within the common data period and data outside the common period.

made by the original HAR-85 equation. The corrected bias error is plotted against the monthly rainfall as shown in Figure 8. Comparing these figures with Figure 7, it is noticeable that ET_o estimates from the HAR-85 formula can be reliably improved as the amplitude of error is reduced. The new errors resulting from the bias-correction models now tend to take a normal distribution between over-and under-estimates. The even years' data have proven to be more adjustable at zero rainfall, thus presenting narrower ranges of magnitude than the model based on odd years' data. Also noticeable is that the adjustment models developed using the full common period's data (Figure 8c,f), that is, the final models, are capable of narrowing the error range that characterizes those odd or even years' data especially at zero rainfall. This improvement reveals despite the varying data size among the stations.

Figure 9 depicts the MBE values over January to December for all the stations following the correction of the HAR-85 formula using the different versions of candidate adjustment models (yearly and seasonal) in Table 2. To figure out the performance of the adjusted HAR-85 formula, we compared this validation figure with Figure 4 that presents the original MBE values. In overall, the annual cycle of the MBE displays considerable change in terms of magnitude and sign of error across the study area. Instead of the systematic overestimation, especially at the arid, semi-arid and dry sub-humid stations, the MBE after correction shows both over- and under-estimation. Few stations, however, reveal a turn from negative to positive MBE or vice versa following the correction, but to a lesser extent Dongola. An overview of the results presented in Figure 9 shows a shrinking range of MBE.

As for the year-round models, the MBE range narrowed from −1.050-1.982 mm/day (Figure 4a) to −0.869-0.897 mm/day (Figure 9a) for the odd years' data, from −0.984-1.923 mm/day (Figure 4b) to −1.175-1.074 mm/day (Figure 9b) for the even years' data and from −0.710-2.171 mm/day (Figure 4c) for data falling outside the common period to −0.797-1.197 mm/day (Figure 9c). Zooming in on the station scale, the worst performance of HAR-85 formula that is generally remarkable at Juba in the dry sub-humid zone is effectively moderated following the corrections. This improvement can be indicated by the following three examples (compare Figure 4a–c and Figure 9a–c). The correction implemented to the odd years' data changed the MBE from 0.706-1.982 mm/day to −0.623-0.507 mm/day. In the case of even years' data, the correction led to MBE of −0.707-0.397 mm/day instead of 0.549-1.923 mm/day. Using yearly common period's model with dataset outside the common period at this station, the MBE is found to alter from 0.833-2.171 mm/day to −0.449-0.671 mm/day.

A similar narrowing of the MBE range is noticeable in relation to the seasonal adjustment models (compare Figure 4a–c and Figure 9d–f). The MBE range for the odd and even years' data within the common period changed from −1.050-1.982 mm/day to −0.878-0.778 mm/day and from −0.984-1.923 mm/day to −1.000-0.945 mm/day, respectively. For the data falling outside the common period, the MBE range altered to −0.654-0.988 mm/day instead of −0.710-2.171 mm/day. On the station scale, the adjustment effectively improved the poorest performance of HAR-85 equation that is observed at Juba in the dry sub-humid zone. Such an improvement is indicated by a narrowed MBE of −0.430-0.370 mm/day instead of 0.706-1.982 mm/day in the odd years' dataset. In the case of even years' data, the MBE is found to alter from 0.549-1.923 mm/day to −0.805-0.322 mm/day. Finally, the correction implemented to the data outside the common period resulted in MBE of −0.402-0.588 mm/day in place of 0.833-2.171 mm/day.

Using the data outside the common period to validate the final adjustment models, the station-by-station scatter plots of FAO-PM versus HAR-85 ET_o (Figure S3) underscore the following observations. The adjustment narrowed the gap between the regression line and 1:1 line, reducing the notable overestimation prior to the correction. These results are prominent for Kassala, Wad Medani and El Fasher in the arid region and El Gedaref, Ed Damazin and Malakal in the semi-arid region. The results for the too dry stations (Dongola and Port Sudan) as well as the stations bordering this zone, that is, Shambat and El Obeid, seem to be unpromising. However, this latter observation indicates also that correction of HAR-85 formula may not be needed in view of the small errors exhibited by the original data for these stations (Figure 3).

TABLE 2 Candidate multiple linear adjustment models of bias errors as functions of geographical coordinates and/or rainfall for the entire study area and all the months using data of common period among all the stations. All coefficients of determination are significant at 0.0001 level

	Odd years' data (data size = 8 years × 12 stations × 12 months = 1152)				Even years' data (data size = 9 years × 12 stations × 12 months = 1296)				Common period's data (data size = 17 years × 12 stations × 12 months = 2448)			
	Variable	Regression coefficient	Significance level	R^2	Variable	Regression coefficient	Significance level	R^2	Variable	Regression coefficient	Significance level	R^2
Yearly	Model 4				Model 4				Model 4			
	Constant	−0.147	0.491	0.457	Constant	0.207	0.266	0.476	Constant	0.019	0.892	0.467
	Latitude	−0.125	0.0001		Latitude	−0.116	0.0001		Latitude	−0.119	0.0001	
	Longitude	0.058	0.0001		Longitude	0.044	0.0001		Longitude	0.051	0.0001	
	Altitude	0.001	0.0001		Altitude	0.001	0.0001		Altitude	0.001	0.0001	
	Rainfall	−0.002	0.0001		Rainfall	−0.002	0.0001		Rainfall	−0.002	0.0001	
Dry season	Model 4				Model 3				Model 3			
	Constant	−0.645	0.0899	0.614	Constant	−0.171	0.6016	0.639	Constant	−0.309	0.2089	0.623
	Latitude	−0.146	0.0001		Latitude	−0.148	0.0001		Latitude	−0.151	0.0001	
	Longitude	0.073	0.0001		Longitude	0.059	0.0001		Longitude	0.065	0.0001	
	Altitude	0.001	0.0001		Altitude	0.001	0.0001		Altitude	0.001	0.0001	
	Rainfall	0.011	0.0317									
Hot season	Model 3				Model 3				Model 3			
	Constant	−0.637	0.2045	0.427	Constant	0.228	0.5532	0.500	Constant	−0.179	0.5669	0.454
	Latitude	−0.118	0.0001		Latitude	−0.102	0.0001		Latitude	−0.109	0.0001	
	Longitude	0.073	0.0001		Longitude	0.042	0.0001		Longitude	0.057	0.0001	
	Altitude	0.001	0.0001		Altitude	0.001	0.0001		Altitude	0.001	0.0001	
Wet season	Model 4				Model 4				Model 4			
	Constant	0.658	0.0143	0.375	Constant	0.930	0.0002	0.366	Constant	0.803	0.0001	0.369
	Latitude	−0.095	0.0001		Latitude	−0.088	0.0001		Latitude	−0.091	0.0001	
	Longitude	0.024	0.0019		Longitude	0.016	0.0243		Longitude	0.020	0.0002	
	Altitude	0.001	0.0001		Altitude	0.001	0.0001		Altitude	0.001	0.0001	
	Rainfall	−0.002	0.0001		Rainfall	−0.002	0.0001		Rainfall	−0.002	0.0001	

Note: Units of variables: bias error is in mm/day; latitude is in °N; longitude is in °E; altitude is in meters above sea level; rainfall is in mm.

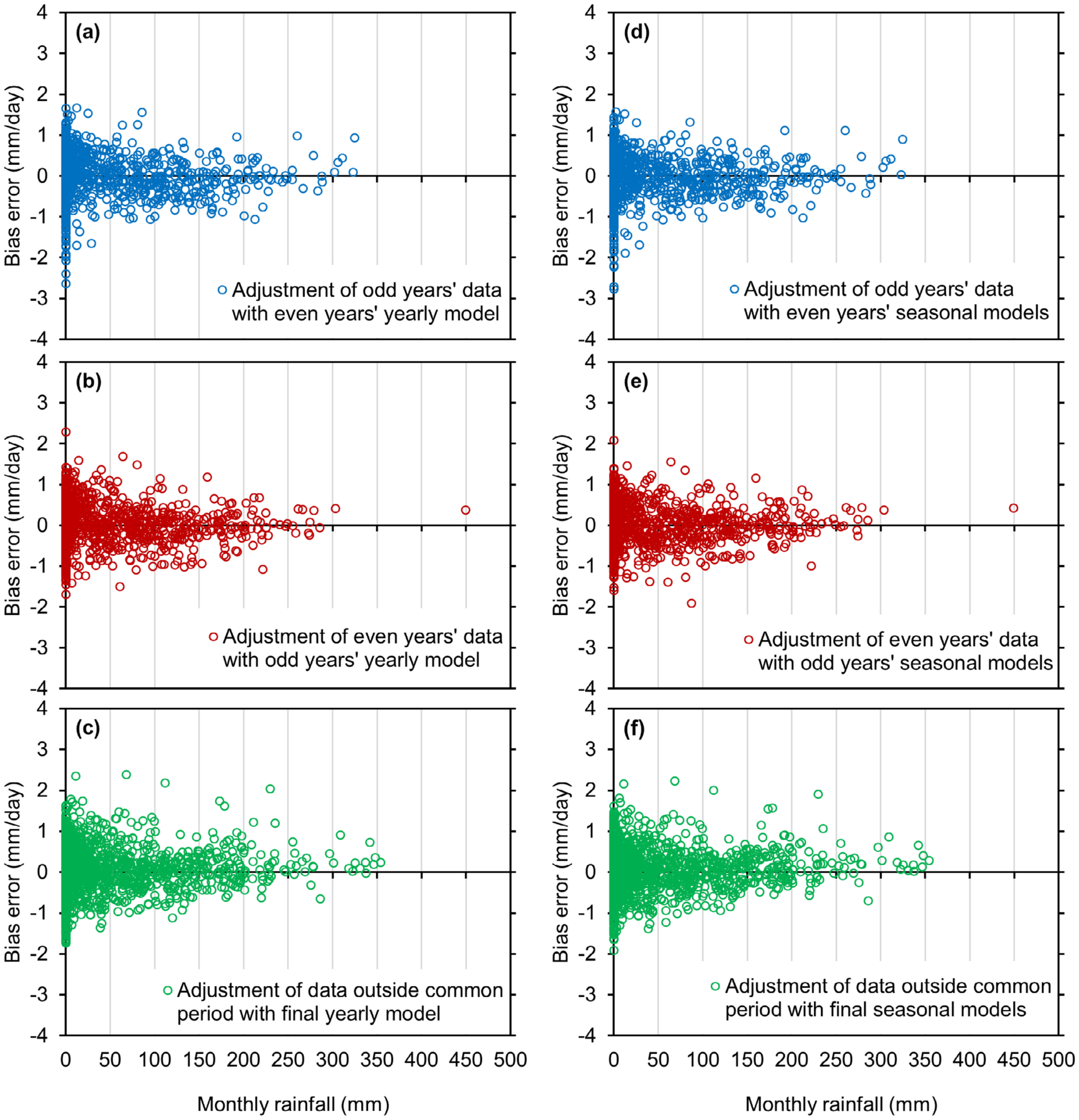

FIGURE 8 Bias error as a function of monthly rainfall using the 12 stations' data after adjusting the HAR-85 estimates with yearly (left) and seasonal (right) candidate models. The final models are the ones developed using the full common period's data.

4.2.2 | Final and recommended adjustment models

Due to the powerfulness of adjustments in improving ETo estimates, we infer that the original HAR-85 formula should be adjusted using either the year-round or seasonal candidate model(s) constructed from the full data of the common period. By overviewing Table 3, the original HAR-85 formula performs better than the adjustment models in all the seasons at Dongola in the hyper-arid zone. At Kassala and El Fasher in the arid zone and Ed Damazin in the semi-arid zone, the yearly model can be selected as the final model for all the seasons. All the three seasonal models are outperforming the yearly model at the two stations (Wau and Juba) located in the dry sub-humid region. The use of a couple or multiple final models (i.e., yearly, seasonal and/or origianl HAR-85) is necessary for the remainder stations. In the cases of stations requiring adjustment to the HAR-85 formula, the original absolute MBE is found to range from 0.166 to 2.171 mm/day. Conversely, the absolute MBE is only 0.011 to 0.400 mm/day when the original HAR-85 is performing sufficiently accurate. Among the final adjustment models, the yearly model can still be recommended for simplicity and general use across the two countries as it results in an error closer in magnitude to the error resulting from the seasonal final models (Figure 9).

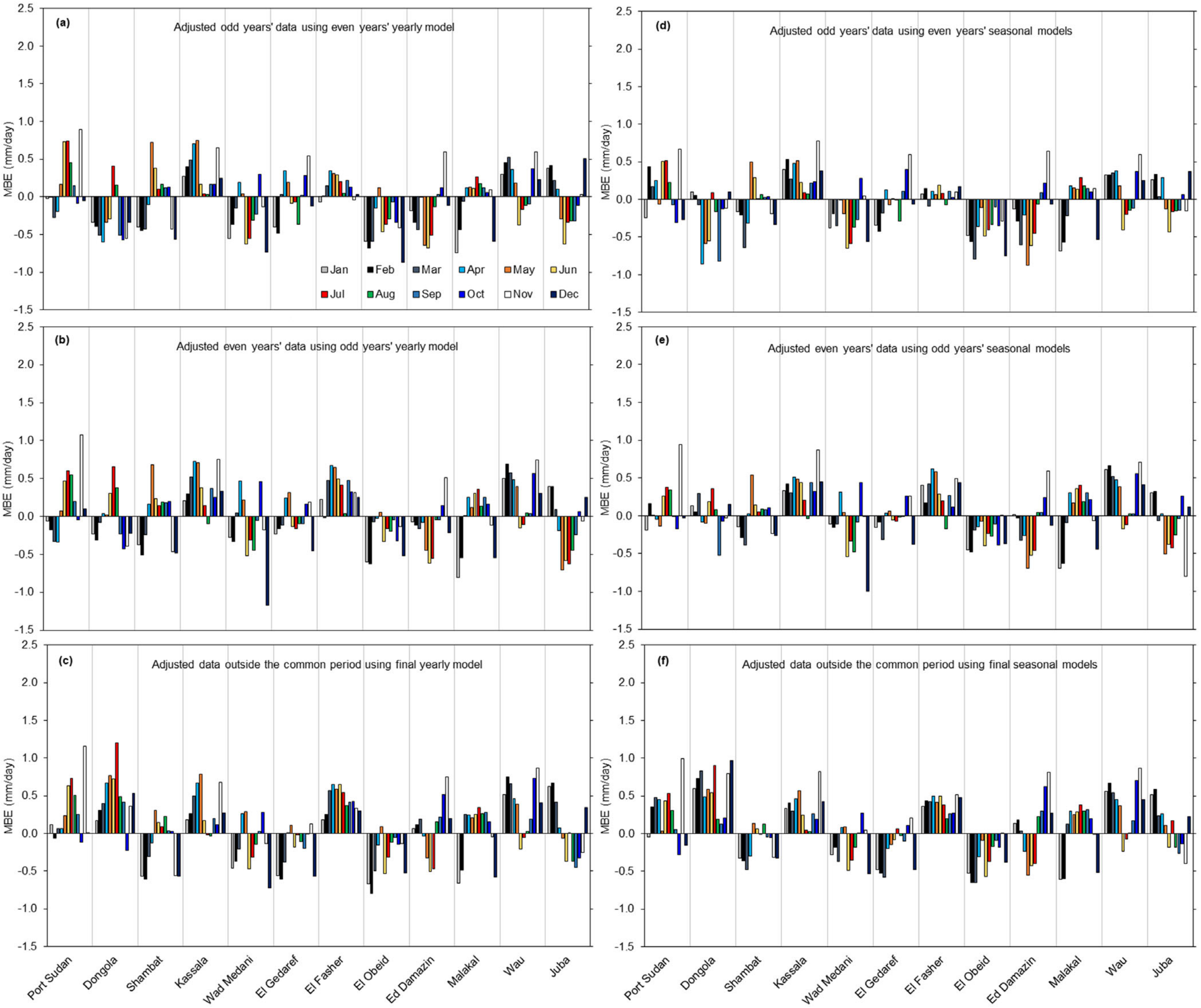

FIGURE 9 Validation of yearly (left) and seasonal (right) candidate models presented as station-by-station annual cycle of adjusted mean biased error. (a), (b), (d) and (e) were based on the data of the common period.

5 | DISCUSSION

5.1 | Interpretation of the over- and under-estimation results

Temesgen et al. (1999, 2005) indicated that high humidity conditions may result in an overestimation of ET_o by the Hargreaves method. On one hand, our results agree with their finding in that overestimation manifests in all climate zones except the hyper-arid and increases towards the more humid stations, that is, Wau and Juba. It is worth mentioning that South Sudan encompasses a huge swampy area, where the relative humidity is 50%–80% during at least half of the year (Alvi & Elagib, 1996; Mohamed et al., 2006). The performance on the scale of a month is also characterized by overestimation throughout the year though with less overestimation during the more humid months (wet season). On the other hand, the slight overestimation exhibited by the data for two arid stations, namely Shambat and Wad Medani, could be explained by the location of the two stations beside irrigated fields. Such fields experience local advection (oasis effect) leading to enhanced actual evapotranspiration resulting from the horizontal transfer of sensible heat (De Bruin & Lablans, 1998). Pelton et al. (1960) also stated that a temperature-based method 'does not account for either the lag of temperature behind radiation, which arises from the thermal storage of the soil, the effect of moisture availability in the region upon air temperature, or the large effect of warm and cool air advection on temperature than on heat exchange with the surface.'

The underestimation exhibited by the HAR-85 at the coastal station (Port Sudan) is in good agreement with results reported by several researchers (Aguilar & Polo, 2011; Amatya et al., 1995; Trajkovic & Kolakovic, 2009). These studies attributed the apparent underestimation to three factors as follows. First, the advective effect decreases the temperature range. Second, the effect of higher

TABLE 3 Season-specific final model in terms of reducing the MBE in the validation process of the common period's adjustment models using data outside the common period

Station	Dry season	Hot season	Wet season
Port Sudan	Yearly	HAR-85[a]	Yearly
Dongola	HAR-85[a]	HAR-85[a]	HAR-85[a]
Shambat	Dry season	HAR-85[a]	Wet season
Kassala	Yearly	Hot season/Yearly[b]	Yearly
Wad Medani	HAR-85[a]	Hot season	HAR-85[a]
El Gedaref	HAR-85[a]	Yearly	Wet season
El Fasher	Yearly	Hot season/Yearly[b]	Wet season/Yearly[b]
El Obeid	HAR-85[a]	Yearly	HAR-85[a]
Ed Damazin	Yearly	Yearly	Yearly
Malakal	HAR-85[a]	Hot season	Yearly
Wau	Dry season	Hot season	Wet season
Juba	Dry season	Hot season	Wet season

[a] Original HAR-85 performance is sufficiently adequate, showing satisfactory absolute MBE of 0.011–0.400 mm/day.

[b] Both yearly and specific season adjustment models perform nearly the same.

atmospheric moisture on the transmissivity results in increasing the attenuation of solar radiation at the surface. Finally, the ample humidity in the air hampers more evaporation in a coastal location. As regards the second factor, the coastal station (Port Sudan) does show lowest DTR in comparison to the other inland stations (Elagib, 2010).

The underestimation shown for Dongola in the hyper-arid zone and the overestimation found for El Obeid can be explained by the trends in the climate elements used in either method. During the full study period, results (not shown) obtained in the present study of annual mean temperature, DTR and HAR-85 ET_o indicated the following. There is no significant trend in mean temperature for any of the two stations whereas significant decreasing (increasing) DTR trend was observable for Dongola (El Obeid). Accordingly, Dongola (El Obeid) showed significant decreasing (increasing) trend in HAR-85 ET_o. Elagib and Mansell (2000b) reported significant decreasing trends in the annual FAO-PM ET_o only for Dongola during the study period. Although this trend was much faster than that found in the annual HAR-85 ET_o, the FAO-PM ET_o values did not fall below their counterparts.

5.2 | Effect of data period and split sampling on the results

The results presented in this study revealed the dependence of the performance of the HAR-85 equation on the time period considered for the evaluation. They also confirm robustness of using the independent datasets based on odd years, even years and full span of years to ensure the inclusion of a wide range of climate states for both the adjustment and validation process. Given the year-to-year variability of climate and for more comprehensiveness, Gavilán et al. (2006) recommended the use of time series of data of 10 years or more to improve the reliability of the proposed adjustments. The point of desirable long series of climatic data was also emphasized by Er-Raki et al. (2010). This guidance was pursued and implemented in the best possible way in our study (Section 3). At the station level of analysis, this guideline was well noted where the shortest length of data was 11 to 25 years for the analysis of either odd or even years. On the scale of monthly or entire-study area analysis, the timespan of the dataset was only possible to extend to 8 or 9 years in the evaluation -in odd or even years, respectively, or to 5–33 years in the evaluation using datasets for years outside the common period. Nevertheless, the final correction formulae were developed using 17-year long dataset. In addition to the above guideline, our analysis was uniquely (in such ET_o evaluations) undertaken based on exchanging odd and even years' datasets within the common period for adjustment and validation processes. This technique seems to explain a rationale that the entire range of climate variability within the study period was taken into account in both analytical processes. The dataset exchange strategy proved that HAR-85 can perform differently when distinct periods are considered in the study. Such an effect is demonstrated, for example, by the adjustment model derived from odd years' data for the dry season (Table 2). This model shows dependence of the bias error on latitude, longitude, altitude and rainfall during the odd years (Model 4) but only on the geographical coordinates (Model 3: latitude, longitude and altitude) during the even years. Using the full dataset of the common period, only the geographical location appears to have affected the HAR-85 performance.

5.3 | Limitations and opportunities of the present study

The present study focused on and tested one distinct ET_o model, that is, HAR-85. One limitation of the study is perhaps the existence of other simple models in the literature that might be more suitable for parts of the two countries under study but have not been studied herein. Nevertheless, there are a couple of advantages of HAR-85 model. The main advantage is that it requires as minimal input data as possible compared to the FAO-PM method. For most locations of the two countries, which extend across heterogeneous climates, the data needed to apply FAO-PM are often unavailable. The other advantage is that this temperature-based model involves three temperature parameters, namely maximum, minimum and DTR, commonly used to indicate climate change and warming of the air. In this context, these parameters were shown to change significantly in the two countries (Elagib, 2010; Elagib & Mansell, 2000a). Notwithstanding this advantage, frequent evaluation of the ET_o estimation methods against lysimeter is recommended to account for the climate change and global warming aspects (Azhar & Perera, 2011).

As indicated by Martínez-Cob and Tejero-Juste (2004), there is difficulty encountered in achieving a single universal adjustment of the empirical HAR-85 equation. In methodological strategies for improving the local parametric calibration of the HAR-85, Martí et al. (2015) found that an adjustment incorporating temperature range and geographical inputs, such as longitude and altitude, only involved a slight accuracy in comparison to models incorporating wind class. Our findings counteracted these results. Despite suggesting a fixed correction value for a given location such as Model 3 for the dry and hot seasons (Table 2), bias models relying on geographical coordinates only like these are found to be easy and reasonable adjustment approach. However, an adjustment model incorporating rainfall together with geographical coordinates (Model 4) can prove more credible due to its dynamic nature. This credibility is underpinned in view of the dependence of the bias error on the period of study and a changing climate. It is likely that the study area-wide, month-specific approach outlined in this research could be of particular interest elsewhere. The rationale behind this likelihood of interest stems not only from the success in dealing with the problem of finding acceptable alternative to the FAO-PM-based ET_o, but also from offering and establishing a desirable spatial and seasonal adjustment approach of the model instead of a station-by-station correction.

A final note that can be reported here is that some researchers raised concerns about the use of the FAO-PM method against which the performance of other methods can be benchmarked. For instance, Droogers and Allen (2002) concluded that this method is practical and accurate if accurate collection of weather data can be expected; however, concerns exists about its accuracy under arid conditions when employing meteorological data that originate from environments having insufficient water supply. Unwell-watered conditions do not support ET_o (Droogers & Allen, 2002). Martí et al. (2015) recommended, therefore, considering measured ET_o data to evaluate the performance of the models since soundness or falsity of calculated benchmark might not be assured. However, measured ET_o data remain more challenging in the first place than ensuring good quality meteorological observations.

6 | CONCLUSIONS

Because the use of the FAO-PM method for calculating ET_o is often restricted by lack of input variables, especially in developing countries, this paper examined the possibility for adjusting the HAR-85 formula based on a simple regression using readily available parameters. It can be concluded from the present study that this simple ET_o formula is not applicable in the majority of the climatic regions covered herein. It requires little, modest or considerable local adjustment depending on the geographical location and climatic conditions under which it is applied. While this method offers somewhat satisfactory results in hyper-arid and most arid areas, it manifests limited success in dry sub-humid zones. On average, the bias error reveals underestimation in the hyper-arid zone, but is characterized by notable overestimation in all other climates, that is, arid, semi-arid and dry sub-humid. Whereas the formula gives a better fit with FAO-PM in the wet season, it lacks correspondence during the dry parts of the year.

Despite being less suitable for use at least across a large part of the study area, the simplicity of HAR-85 formula and its demand for less data render promising application in the study area if suitable adjustment is made. Therefore, this study proposed an adjustment regression formula, which uses geographical coordinates (latitude, longitude and altitude) and/or rainfall, to correct the bias between HAR-85 and FAO-PM. Seasonal (dry, hot and wet) and year-round adjustment models were proposed to HAR-85 for use across the entire study area. For simplicity, the yearly adjustment model is still applicable without jeopardizing the accuracy gained through the seasonal models. Refining the HAR-85 method through these bias correction models hence represents a simple and a practical alternative to those approaches that require other data inputs, such as wind speed and/or relative humidity. Such additional data-intensive adjustments, as proposed in the literature elsewhere, might not be recordable at all weather stations or during all times in data-scarce regions, such as the current study area.

Under comparatively consistent geographical and climatic conditions, it is proposed that the adjustment models established herein for the HAR-85 error for two countries with a large areal extent is reasonably generic and usable elsewhere. Its suitability could be especially valid within a range of latitudes between 4° and 20° N and in hyper-arid to dry sub-humid climates. Alternatively, the simple adjustment approach conducted herein for correcting the HAR-85 bias is encouraging and practical to establish. We, therefore, recommend the application of this approach outside the ambit of the study area to obtain reliable ET_o under similar environments. This correction approach gives reliable results and helps overcome the basic obstacle to using the FAO-PM method.

The findings of the present study provide information for hydrological, agricultural and ecological planning and policymaking. This information is particularly useful with the background of the study area that is characterized by high losses of the Nile water to evaporation and seepage (Alvi & Elagib, 1996), low water use efficiency of its irrigated agricultural schemes (Al Zayed et al., 2015; Al Zayed & Elagib, 2017) and ecohydrological challenges (Babker et al., 2020). It is useful in the agriculture sector for quantifying the crop water requirements, defining the irrigation scheduling and assessing the water use efficiency.

The study demonstrated that the factors underlying the bias of HAR-85 can change when different data periods or even odd and even years within the same period are considered. Climate change will have significant impact on weather variables, such as rainfall and/or temperatures. Care should therefore be considered to revisit the performance evaluation over time to ensure the applicability of the adjustment formula. This step is important since climate change is also expected to significantly impact irrigation management.

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DATA AVAILABILITY STATEMENT

The original meteorological data used to calculate ETo were acquired from Sudan Meteorological Authority. However, the FAO-PM ETo data used in this study were those used in Elagib and Mansell (2000b) and Al Zayed et al. (2015). HAR-85 ETo were mostly obtained by Elagib (2009a), partly from Elagib (2014) and partially calculated in the present work.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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