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DATA NOTE

REVISED CMIP6-based global estimates of future aridity index and potential evapotranspiration for 2021-2060

[version 4; peer review: 3 approved]

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Abstract

The “Future_Global_AI_PET Database” provides high-resolution (30 arc-seconds) average annual and monthly global estimates of potential evapotranspiration (PET) and aridity index (AI) for 22 CMIP6 Earth System Models for two future (2021–2041; 2041–2060) and two historical (1960–1990; 1970–2000) time periods, for each of four shared socio-economic pathways (SSP). Three multimodel ensemble averages are also provided (All; Majority Consensus, High Risk) with different level of risks linked to climate model uncertainty. An overview of the methodological approach, geospatial implementation and a technical evaluation of the results is provided. Historical results were compared for technical validation with weather station data (*PET:* r^2 = 0.*72; AI:* r^2 = *0.91*) and the CRU_TS v 4.04 dataset (*PET:* r^2 = 0.*67;* AI: r^2 = 0.*80*). Within the context of projected significant change in the near- and medium-term, the “Future_Global_AI_PET Database” provides a set of data projections and tools available for a variety of scientific and practical applications, illustrating trends and magnitude of predicted climatic and eco-hydrological impacts on terrestrial ecosystems. The Future_Global_AI_PET Database is archived in the ScienceDB repository and available online at: https://doi.org/10.57760/sciencedb.nbsdc.00086

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REVISED **Amendments from Version 3**

*Corrected: spelling - Penman-Monteith

*Corrected Reference: Wang *et al.*, 2018, was incorrect,

Should be:

Šimůnek, J., M. Th. van Genuchten and M. Šejna, The HYDRUS-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media, Version 3.0, HYDRUS Software Series 1, Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, 2005.

*Added this statement to Methods: "After evaluation, 4242 stations were used for the spreadsheet analysis, and a subset of data points common among all geospatial datasets created, which came out to 3842 stations."

*Corrected this statement in Methods: "Based upon the distribution of the various scenarios along their projected temperature and precipitation estimates *for the 2021-2040 future time period* (Figure 3 & Figure 4), three multi-model ensembles, each articulated by their four..."

Any further responses from the reviewers can be found at the end of the article

Introduction

Potential evapotranspiration (PET) characterizes the atmosphere's capacity to remove water through evapotranspiration (ET). Evaporation and transpiration processes collectively transfer water from the Earth's surface to the atmosphere (Allen *et al.*, 1998; Jensen & Allen, 2016) with rates determined by solar radiation, air temperature, relative humidity (specifically, vapor pressure deficit), wind speed (Pandey *et al.*, 2017; Zotarelli *et al.*, 2018), as well as the distinctive traits of vegetation, or crops and agricultural practices (Jensen & Allen, 2016). Estimates of PET have been widely used across diverse scientific fields and practical domains (Hargreaves, 1994a; Zomer *et al.*, 2022), with PET estimates and related indices playing a crucial role in agricultural and natural resource management with demonstrated utility on scales from individual farms to regional and global (Anwar *et al.*, 2021; Basarin *et al.*, 2020; Itenfisu *et al.*, 2003; Valipour *et al.*, 2020). While potential evapotranspiration (PET) reflects potential atmospheric water demand across varied vegetation types, useful in broader ecosystem and hydrological studies, reference evapotranspiration (ET_0) estimates the effective water use from a well-watered reference crop, and as such, is particularly useful for agriculture and irrigation management.

In an era of rapid environmental and climatic transformations, PET estimates, along with their related indices, assume a pivotal role as direct and critical measures, as well as predictive tools, for gauging the trajectory, direction, and extent of climatic variations and their ramifications for terrestrial, and particularly agricultural and natural ecosystems. As an example, indices relying on PET estimates include the Standardized Precipitation Evapotranspiration Index (SPEI), Palmer Drought Severity Index (PDSI), Crop Water Stress Index (CWSI), Water Deficit Index (WDI), Evaporative Stress Index (ESI), and the Aridity Index (AI) described in this paper, Indices like the SPEI, AI, PDSI, CWSI, WDI, ESI and the AI incorporate PET to understand and evaluate water availability, climate impacts, and drought. Given the current global climate emergency, as reported in recently released findings of the latest Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2019; IPCC, 2021; IPCC, 2022), and other more dire, increasingly urgent assessments (Forster *et al.*, 2023; Hansen *et al.*, 2023), such estimates and the projection of their trajectory and future trends in the near- and medium-term, not only hold implications for agricultural production, food security, and sustainable development, biodiversity and conservation, but ultimately, the well-being of human civilization.

An established approach employed to evaluate aridity status and changes involves the use of the aridity index (AI), which describes the ratio of precipitation to PET. Aridity indices (Arora, 2002; Greve *et al.*, 2019; Nastos *et al.*, 2013) furnish a means to gauge moisture availability for plant growth, generally of specific reference crops or specific vegetation types (Allen *et al.*, 1998; Itenfisu *et al.*, 2003; Walter *et al.*, 2001). By consolidating the complex concept of aridity into a single numerical value, the utilization of aridity indices enables both spatial and temporal comparisons. The AI serves as proxy for a comprehensive evaluation of a set of hydro-climatological and hydro-ecological variables to determine historical, recent conditions and projected changes in hydrological cycles at specified future times and time scales, notably soil moisture availability. Application of an AI to historical climate datasets can establish crucial baselines for monitoring and assessing the impact and consequences of climatic change on hydrological cycles. Both PET and AI regularly serve as inputs for various operational decision-making processes, including irrigation management, crop cultivation practices, and the anticipation of drought and flood, with great value for agricultural production and water resource governance (Zhou *et al.*, 2020). These indices provide policy guidance across various sectors beyond agricultural and natural resource management, with significant implications for meeting the various Sustainable Development Goals, several of which are directly water related.

A previous initial version, the "Global Aridity Index and PET Database" (Global-AI_PET_v1) (Trabucco & Zomer, 2008), based on the historical global climatic dataset WorldClim v1.4 (Hijmans *et al.*, 2005: available at http://WorldClim.org), and calculated using the Hargreaves equation (Hargreaves, 1994b) for the averaged time period 1960–1990, has been available online since 2009 (Trabucco & Zomer, 2008; Trabucco *et al.*, 2008; Zomer *et al.*, 2006; Zomer *et al.*, 2008). A subsequent version, the "Global Aridity Index and Potential Evapotranspiration (ET_0) Climate Database" - Global-AI_PET_v2 (Trabucco & Zomer, 2019) - implementing a Penman-Monteith equation and based on the WorldClim 2.0 (Hijmans *et al.*, 2005) for the averaged period 1970–2000, has been available online since 2019, with an updated version - Global-AI_PET_v3 (Zomer *et al.*, 2022) - based on the WorldClim v2.1 historical dataset available since 2022. These datasets have been shown to have wide utility across a wide range of disciplines and have been downloaded and cited numerous times, and are fully discussed in Zomer *et al.*, 2022. Both have been used in this study as comparative references.

A set of future projections of global PET and AI (Figure 1) were produced to construct the Global-Future_AI_PET Database

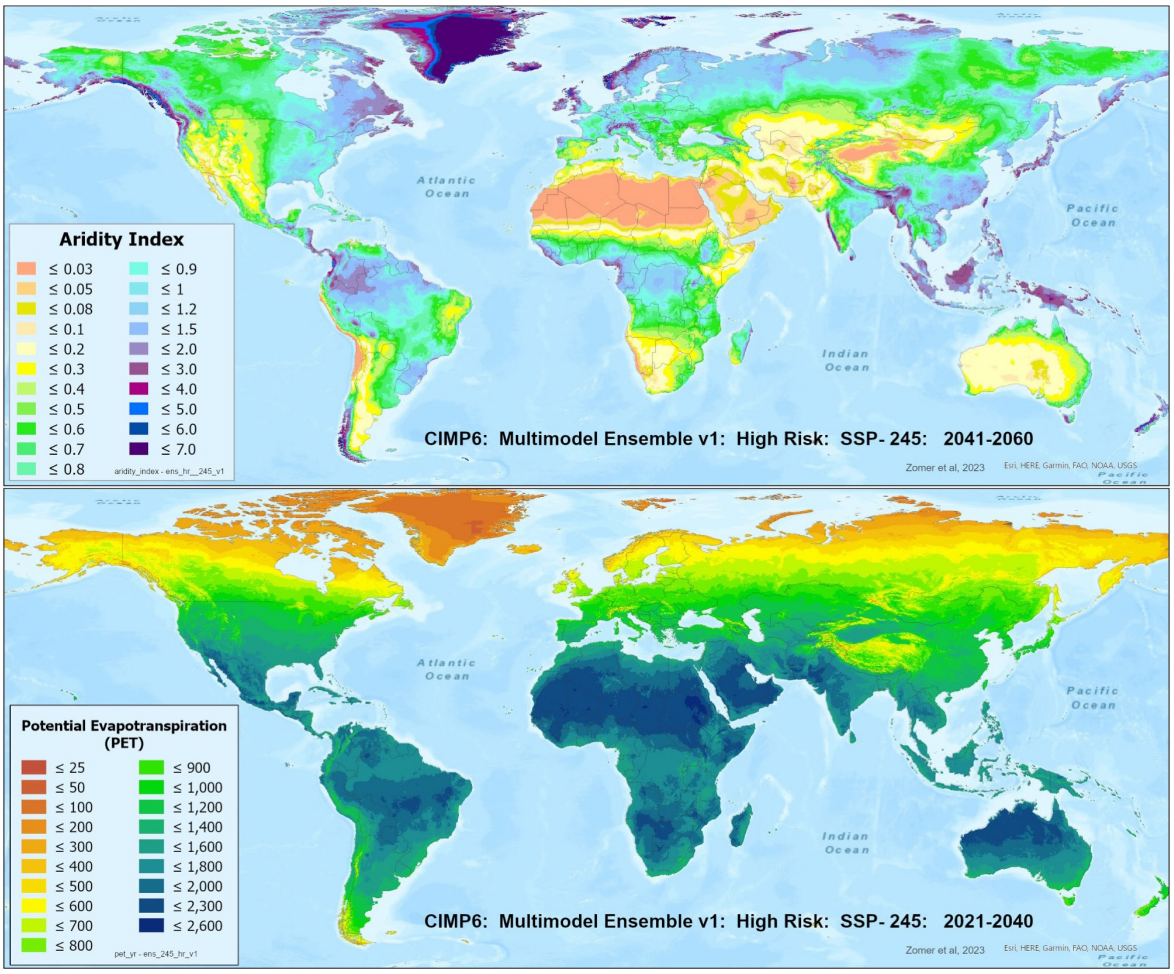


Figure 1. Global PET and Aridity Index. Global PET and Aridity Index calculated using the Hargreaves equation for the entire globe at 1 km spatial resolution, showing an example using a averaged multimodel ensemble of future projections of CMIP6 ESM for two time periods.

(Zomer & Trabucco, 2024) based on 22 Coupled Inter-Comparison Modeling Project – Phase 6 (CMIP6: (Eyring *et al.*, 2016)) Earth System Models (ESM). Due to a continuing lack of high resolution downscaled CMIP6 future projection data for several climate variables needed to parameterize a full implementation of the Penman-Monteith equation, and a desire to maintain continuity with the previously used WorldClim (Fick & Hijmans, 2017) datasets (reportedly among the most widely used climatic datasets for environmental, biogeographical or ecological analysis (Bobrowski *et al.*, 2021)), Hargreaves equation for calculating PET, was applied to the CMIP6 ESM data. This maintains a similar approach and methodology as used to develop the Global-AI_PET Database v1 (Trabucco & Zomer, 2008) Using bias-corrected downscaled climatic parameters (i.e., minimum / maximum temperature, and precipitation), derived from interpolation of weather station data (30 arc seconds resolution), and provided by WorldClim.org, each ESM model projection was evaluated across four emission scenarios, or *Shared Socio-Economic Pathways* (SSP 126; 245; 370; 585). In total there are 168 ESM/SSP scenario combinations in the database, as there are a few exceptions due to missing data (Table 1). Additionally, three multimodel ensemble averages have been calculated (for each of the respective SSP): an ensemble including all the available models, a majority consensus ensemble and an ensemble outlining a high risk (more extreme) scenario. In addition, PET and AI have been calculated as 30-years average for two historical time periods (1960–1990; 1970–2000). The Future_Global_AI_PET Database (Zomer & Trabucco, 2024) described in this paper is archived and available online from the Science Data Bank (ScienceDB) at: https://doi.org/10.57760/sciencedb.nbsdc.00086.

Methods

Estimating potential evapotranspiration

Among the various equations employed for estimating PET (Droogers & Allen, 2002; Hadria *et al.*, 2021; Hargreaves, 1994a; Hargreaves & Samani, 1985; Itenfisu *et al.*, 2003; McMahon *et al.*, 2016; Srdić *et al.*, 2023; Sutapa *et al.*, 2020), the Penman-Monteith equation and methodology outlined in the Food and Agriculture Organization FAO-56 (Allen *et al.*, 1998) guidelines is widely recognized as the standard method.

Table 1. Available datasets in the *Future_Global_AI_PET Database*. Available datasets in the *Future_Global_AI_PET Database,* including two historical datasets, 22 ESM models calculated for each of their respective SSP, for two time periods, and 3 averaged multimodel ensembles.

Historical Datasets											
WorldClim 1.4 (1960–1990)									**ESMs included within Ensemble**		
WorldClim 2.1 (1970–2000)											
Earth System Models (ESM)	**Year: 2021–2040**				**Year: 2041–2060**				**MultiModel Ensemble**		
SSP Scenario:	**126**	**245**	**370**	**585**	**126**	**245**	**370**	**585**	**All**	**Consensus**	**High-Risk**
ACCESS-CM2	X	X	X	X	X	X	X	X	X		X
ACCESS-ESM1-5	X	X	X	X	X	X	X	X	X	X	
CanESM5	X	X	X	X	X	X	X	X	X		X
CanESM5-CanOE	X	X	X	X	X	X	X	X	X		X
CMCC-ESM2	X	X	X	X	X	X	X	X	X	X	
CNRM-CM6-1	X	X	X	X	X	X	X	X	X	X	
CNRM-CM6-1-HR	X	X	X	X	X	X	X	X	X	X	
CNRM-ESM2-1	X	X	X	X	X	X	X	X	X	X	
FIO-ESM-2-0	X	X		X	X	X		X	X		
GFDL-ESM4	X		X		X		X		X		
GISS-E2-1-G	X	X	X	X	X	X	X	X	X	X	
GISS-E2-1-H	X	X	X	X	X	X	X	X	X	X	
HadGEM3-GC31-LL	X	X		X	X	X		X	X		X
INM-CM4-8	X	X	X	X	X	X	X	X	X	X	
INM-CM5-0	X	X	X	X	X	X	X	X	X	X	
IPSL-CM6A-LR	X	X	X	X	X	X	X	X	X	X	
MIROC-ES2L	X	X	X	X	X	X	X	X	X	X	
MIROC6	X	X	X	X	X	X	X	X	X	X	
MPI-ESM1-2-HR	X	X	X	X	X	X	X	X	X	X	
MPI-ESM1-2-LR	X	X	X	X	X	X	X	X	X	X	
MRI-ESM2-0	X	X	X	X	X	X	X	X	X	X	
UKESM1-0-LL	X	X	X	X	X	X	X	X	X		X
MultiModlel_Ensemble									**No. of ESM in Ensemble**		
All	X	X	X	X	X	X	X	X			
Consensus	X	X	X	X	X	X	X	X	20 – 22	15	4 – 5
High-Risk	X	X	X	X	X	X	X	X			

FAO-56 defines and provides guidance on calculating reference evapotranspiration (ET_0), that is, the evapotranspiration (ET) of a reference crop, rather than defining potential evapotranspiration (PET) directly. FAO-56 presents a standard method to estimate ET_0, which is widely accepted as a reference standard, and often closely related to PET in practice. In FAO-56, the ET_0 is calculated using the Penman-Monteith equation, which takes into account factors like temperature, relative humidity, wind speed, and solar radiation. While ET_0 is a measure of the evapotranspiration rate from a reference crop under optimal conditions, PET generally represents the water demand of vegetation if water is freely available. Though not synonymous,

ET_0 from FAO-56 is widely used as an estimate for PET, particularly in agricultural and environmental applications.

FAO-56 defined the ET of a reference crop (ET_0) under optimal conditions. Specifically, it assumes a reference crop characterized by well-watered grass with a uniform height of 12 centimeters, a fixed surface resistance of 70 seconds per meter, and an albedo of 0.231. More generally, ET_0 quantifies the rate at which readily available soil water evaporates from specified vegetated surfaces comprised of dense, actively growing vegetation with prescribed height and surface resistance, not limited by soil water availability and encompassing an expanse of at least 100 sq. meters of similar or identical vegetation types. ET_0 serves as a fundamental hydrological variable with utility in various research domains, notably related to hydrologic water balance, simulation of crop yield, management of irrigation systems, and water resources management. ET_0 values obtained from different locations or seasons are comparable as they pertain to evapotranspiration from the same reference surface enabling researchers and practitioners to evaluate atmospheric evaporative demand independent of specific crop characteristics, crop development stages, management practices, or water availability (Itenfisu *et al.*, 2003; Zotarelli *et al.*, 2018). Climatic parameters and crop-specific resistance coefficients determined for the reference vegetation are the principal factors influencing ET_0 estimation (Jensen & Allen, 2016). As such, additional crop-specific coefficients (Kc) and ET_0 can, in turn, be employed to derive ET estimates for specific crops (ETc).

The International Commission for Irrigation and Drainage (ICID) (Doorebos & Pruitt, 1977; Hargreaves, 1994b) and the Food and Agriculture Organization of the United Nations - FAO (Allen *et al.*, 1998) designated the Penman-Monteith (PM) method as a standard method of computing ET_0 from climatic data and designated it as the reference for evaluating other methods. A study of ET_0 equations using lysimeter ET and synoptic climatic data by European Commission's Joint Research Centre (Choisnel *et al.*, 1992) compared twelve equations using Penman-Monteith (Allen *et al.*, 1998) as the reference standard. The results from the PM equation were compared with nine equations that are simpler and require less data than the data intensive requirements of the PM equations. The Hargreaves (Hargreaves, 1994b) equation demonstrated the nearest results to the classic PM (Droogers & Allen, 2002; Itenfisu *et al.*, 2003). The Hargreaves method with substantially less data requirements, i.e., requiring only measured values of maximum and minimum temperatures and precipitation, was recommended for more general use and therefore is considered more appropriately applicable to data scarce regions and situations (Droogers & Allen, 2002). For the purposes of this paper, to maintain clarity, we refer to reference evapotranspiration calculated using the Penman-Monteith as "ET_0" and calculations using the Hargreaves equation as "PET".

To meet the objectives of a global spatial analysis at the desired very high spatial resolution (30 arc seconds or ~1 km) with available climate variables (temperature and precipitation), in the preparation of the previously released first version of the *Global-AI_PET_v1* (Trabucco *et al.*, 2008; Zomer *et al.*, 2006), four different temperature-based methods of calculating PET were compared with the Penman-Monteith method for calculating ET_0, and tested to determine which equation performed the best for the objectives of that analysis (Figure 2; Table 2): Thornthwaite (Thornthwaite, 1948), Thornthwaite modified by Holland (Holland, 1978), Hargreaves (Hargreaves, 1994a), Hargreaves Modified by Droogers and Allen (Droogers & Allen, 2002), and the FAO Global Penman–Monteith Spatial Dataset (Allen *et al.*, 1998).

These are briefly described below:

Thornthwaite equation (Thornthwaite, 1948)

$$PET = 16\left(\frac{L}{12}\right)\left(\frac{N}{30}\right)\left(\frac{10T_d}{I}\right)^{\propto} \quad (1)$$

Where:

PET is the estimated potential evapotranspiration (mm/month)

T_d is the average daily temperature (degrees Celsius; if this is negative, use 0) of the month being calculated

N is the number of days in the month being calculated

L is the average day length (hours) of the month being calculated

$\propto = (6.75 * 10^{-7})\, I^3 - (7.71 * 10^{-5})\, I^2 + (1.792 * 10^{-2})\, I + 0.49239$

$I = \sum_{i=1}^{12}\left(\frac{T_{m_i}}{5}\right)^{1.54}$ is a heat index based on the 12 monthly mean temperatures.

Thornthwaite modified by Holland (Gordon *et al.*, 2005; Holland, 1978):

This equation requires only one climatic input variable (Celsius temperature *T*) and it has been suggested that Thornthwaite-based methods are as good as more refined methods when dealing with monthly data as compared with more detailed daily data (27).

$$PET = 1.2 * 10^9 * e[-4.62 * 10^3 / (T + 273.15)] \quad (2)$$

Modified Hargreaves (Droogers & Allen, 2002)

$$ET_0 = 0.0013 \cdot 0.408RA \cdot (Tavg + 17.0) \cdot (T\,D - 0.0123P)0.76 \quad (3)$$

Where:

RA is extraterrestrial radiation expressed in (MJ m−2 d−1),

*T*avg is average daily temperature (C°)

TD (C°) is the temperature range

P is precipitation in mm per month

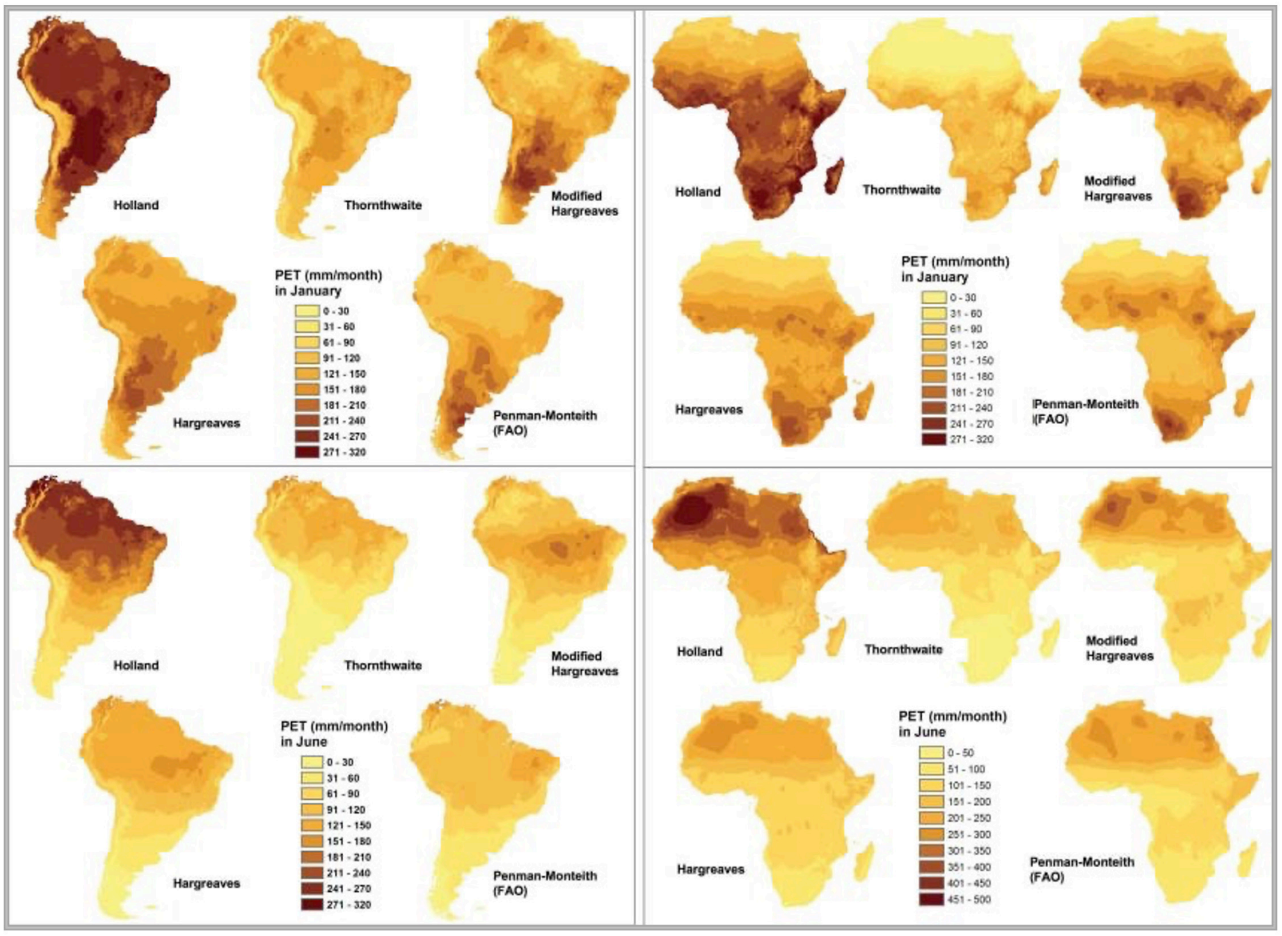


Figure 2. Comparison of five different methods of calculating PET. Comparison of four different temperature-based methods of calculating PET (Thornthwaite, Thornthwaite modified by Holland, Hargreaves, Hargreaves Modified by Droogers and Allen), against the reference FAO Global Penman–Monteith.

Table 2. Comparison of four different temperature-based methods of calculating PET (Zomer *et al.*, 2006). Five different methods of calculating PET were tested to verify which performed the best for the objectives of this analysis: Thornthwaite (Thornthwaite, 1948), Thornthwaite modified by Holland (Holland, 1978), Hargreaves (Hargreaves *et al.*, 1985), Hargreaves modified by Droogers (Droogers & Allen, 2002), and the FAO Global Penman-Monteith Dataset (Allen *et al.*, 1998). Results of the comparison are given as the mean difference (Mean Diff) between Penman-Monteith estimates based on observed weather station data and predicted estimates using the various different methods, and their standard deviations (Std Dev). Source: (Trabucco *et al.*, 2008).

		Mean Difference (mm) and Standard Deviation (mm) between Observed and Predicted Values:									
		Holland (Thornthwaite)		Thornthwaite		Hargreaves		Modified Hargreaves		Penman-Monteith FAO	
Region	**Month**	**Mean Diff**	***Std Dev***	**Mean Diff**	***Std Dev***	**Mean Diff**	***Std Dev***	**Mean Diff**	***Std Dev***	**Mean Diff**	***Std Dev***
Africa											
	January	71.8	*40.2*	41.6	*33.3*	22.3	*16.1*	24.8	*20.1*	11.1	*12.6*
	July	84.4	*41.7*	32.1	*23.7*	20.0	*19.3*	21.1	*19.3*	12.7	*16.0*
South America											
	January	69.9	*43.6*	50.5	*32.9*	38.2	*19.2*	41.6	*26.0*	34.9	*26.7*
	July	67.3	*35.9*	37.2	*24.7*	27.2	*14*	30.4	*20.1*	24.3	*15.1*
Resolution		1 km		1 km		1 km		1 km		20 km	

FAO 56 Penman–Monteith equation (Allen *et al.*, 1998)

The FAO-56 Penman-Monteith form of the combination equation to estimate ET_0 is calculated as:

$$ETo = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad (4)$$

Where

ET_0 is the evapotranspiration for reference crop, as mm day^{-1}

R_n is the net radiation at the crop surface, as MJ m^{-2} day^{-1}

G is the soil heat flux density, as MJ m^{-2} day^{-1}

c_p is the specific heat of dry air

p_a is the air density at constant pressure

e_s is the saturation vapour pressure, as *kPa*

e_a is the actual vapour pressure, as *kPa*

e_s - e_a is the saturation vapour pressure deficit, as *kPa*

Δ is the slope vapour pressure curve, as *kPa* °C^{-1}

γ is the psychrometric constant, as *kPa* °C^{-1}

r_s is the bulk surface resistance, as m s^{-1}

r_a is the aerodynamic resistance, as m s^{-1}

Values for PET calculated using each of the above five methods were compared to PET values for specific weather stations calculated using historical weather station data (n = 2288). ET_0 values were calculated using the more complex Penman–Monteith model applied on direct observations of the various climatic parameters obtained from the FAOCLIM (FAO and (SDRN), 2001) climate station dataset (covering the time period: 1960–1990). Based on the results of the comparative validation, the Hargreaves model was confirmed to be the best fit to model PET globally with the available data at the time and chosen for the implementation of the *Global-AI_PET_v1*. The Hargreaves method has been shown to perform well compared to the PM method, but required less parameterization, and had significantly lower sensitivity to error in climatic inputs (Allen *et al.*, 1998; Droogers & Allen, 2002; Jensen *et al.*, 1997; Pimentel *et al.*, 2023). Although the release of the *WorldClim v2.1* allowed for the implementation of the PM equation and the development of the *Global-AI_PET_v3*, the currently available downscaled CMIP6 projections (available from *WorldClim*.org) do not provide the full set of climate variables required to implement the PM equation at this resolution.

Hargreaves equation

The Hargreaves methodology (Hargreaves, 1994b; Hargreaves & Samani, 1985; Jensen & Allen, 2016; Jensen *et al.*, 1997; Šimůnek *et al.*, 2005) uses only mean monthly temperature (T_{mean}), mean monthly temperature range (*TD*) and extraterrestrial radiation (*RA*, radiation on top of the atmosphere) to calculate PET, as shown below:

$$PET = 0.0023 * R_a * (T_{mean} + 17.8) * TD^{0.5} \quad (5)$$

where R_a is extraterrestrial radiation at the top of the atmosphere, TD is the difference between mean maximum temperatures and mean minimum temperatures *(T_{max} - T_{min}), and T_{mean} is equal to T_{max} + T_{min}* divided by 2. *PET is* multiplied by number of days in each month to give the monthly total (mm/month).

Extraterrestrial radiation, R_a, is calculated as follows (Jensen *et al.*, 1997; Jensen & Allen, 2016; Šimůnek *et al.*, 2005):

$$R_a = \frac{0.408 G_{sc}}{\pi} d_r(\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s) \quad (6)$$

Where: R_a is in mm/day

G_{sc} is the solar constant [MJ m^{-2}day^{-1}] (117.5 MJ m^{-2}day^{-1}),

φ is the latitude [radians],

ω_s is the sunset hour angle [radians],

d_r is the relative distance between Earth and Sun

δ is the solar declination [rad].

The last three variables are calculated as follows:

$$\omega_s = \arccos(-\tan\varphi \tan\delta) \quad (7)$$

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \quad (8)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (9)$$

Where: J is the Julian Day, or number of the day in the year.

The Hargreaves equation was implemented globally on a per grid cell basis at 30 arc seconds resolution (~ 1km2 at the equator), in ArcGIS (v11.1) using Python v3.2 (see code availability section) to estimate PET and derive an AI using an ensemble of future projections provided by the CMIP6 collaboration (Eyring *et al.*, 2016). The data to parametrize the equation were obtained from the WorldClim.org online data repository (Fick & Hijmans, 2017), which provides bias-corrected downscaled monthly values of minimum temperature, maximum temperature, and precipitation for 22 CMIP6 Earth System Models (ESMs), for each of four SSP: 126, 245, 370 and 585.

PET and AI were estimated for two historical periods, WorldClim 1.4 (1960–1990) and WorldClim 2.1 (1970–2000), representing on average a decades' change, by applying the Hargreaves methodology described above. Similarly, PET and AI were

estimated for two future time periods, namely 2021–2040 and 2041–2060, for each of the 22 models across their respective four SSP scenarios (126, 245, 370,585).

Aridity Index

The aridity index (AI) is expressed as the ratio of precipitation over PET (or ET_0). The AI quantifies water availability for plant growth based on the ratio of precipitation to PET (or ET_0) and is a measure of available precipitation relative to water demand for plant growth (Arora, 2002; Derdous *et al.*, 2020; Girvetz & Zganjar, 2014).

The AI for the averaged time periods has been calculated on a per grid cell basis, as:

$$AI = MA_Prec/MA_PET \quad (10)$$

where:

AI = Aridity Index

MA_Prec = Mean Annual Precipitation

MA_PET = Mean Annual PET

Using the mean annual precipitation (*MA_Prec*) values obtained from the CMIP6 downscaled climate projections, and the PET (*MA_PET*) datasets estimated as monthly averages by the method described above and aggregated at yearly scale. The *AI* algorithm was implemented on a per grid cell basis. Using this formulation, *AI* values are unitless, increasing with more humid condition and decreasing with more arid conditions.

As a general reference, the climate classification scheme for AI values provided by UNEP (UNEP, 1997) provides an insight into the climatic significance of the range of moisture availability conditions described by the AI (Table 3). Higher values of the AI, primarily evident in the colder and arctic regions, are considered not interpretable in terms of plant growth as per the original intent of the aridity index measure.

Multi-model ensembles

Based upon the distribution of the various scenarios along their projected temperature and precipitation estimates for the 2021–2040 future time period (Figure 3 & Figure 4), three multi-model ensembles, each articulated by their four respective SSPs, were identified (Table 1).

- **All Models:** includes all of the 22 ESM, as available within a particular SSP.
- **High Risk:** includes 5 ESM identified as projecting the highest increases in temperature and precipitation and lying outside and significantly higher than the majority of estimates.
- Majority **Consensus**: includes 15 ESM, that is, all available ESM excluding the ESM in the "High Risk" category, and those missing data across all of the 4 SSP. Further herein referred to as the "Consensus" category.

The three parameters of monthly minimum temperature, monthly maximum temperature and monthly precipitation for ESM's included within each of these ensembles were averaged for each of their respective SSPs. These averaged parameters were then used to calculate average PET and AI for each ensemble category as per the above methodology.

In general, there was found to be a high level of agreement amongst the ESM included within each of the respective averaged multimodel ensembles (Table 4), however, as illustrated in Figure 5, with significant variability across regions (See Extended Materials for regional results). Agreement was fairly high for the basic parameters of annual average temperature and annual average precipitation with all values below 5%, indicating very low variability relative to the mean, suggesting strong consistency or agreement. Somewhat less for annual averaged PET and AI, which is slightly increased in the 2041–2060 time period. To compensate for negative values, the coefficient of variation (CoV) for mean annual temperature was calculated by adding 33 degrees to the annual temperature value.

An overview of the distribution of the global average annual temperature and average annual precipitation projected by the various ensembles, as articulated to each SSP (Figure 6) illustrates that all models indicate global trends of increasing precipitation and increasing temperature in the near-term, more so by the 2041–2060 time period. However, when considering the projected global increase in PET (Figure 7), there emerges a distinct and significant drying trend indicated by decreasing AI values, both in the near-term, and again, more so by 2041–2060. There is, however, significant variability shown among regions (See Extended Data for tabular and regional descriptive statistics).

Table 3. Climate classification scheme for AI values. Climate classification scheme for AI values (UNEP, 1997).

Aridity Index Value	Climate Class
< 0.03	Hyper-Arid
0.03 – 0.2	Arid
0.2 – 0.5	Semi-Arid
0.5 – 0.65	Dry Sub-Humid
> 0.65	Humid

Technical validation

The global estimations of PET (Hargreaves method) and ET_0 (Penmen-Monteith), and their respective AI derived from these, were evaluated against the FAO "CLIMWAT 2.0 for CROPWAT" (Muñoz & Greiser, 2006) global climate database using long-term monthly mean values of climatic parameters derived from weather station data, roughly covering the period of 1971–2000, concurrent with the temporal coverage of the WorldClim version 2.1 database (Fick & Hijmans, 2017;

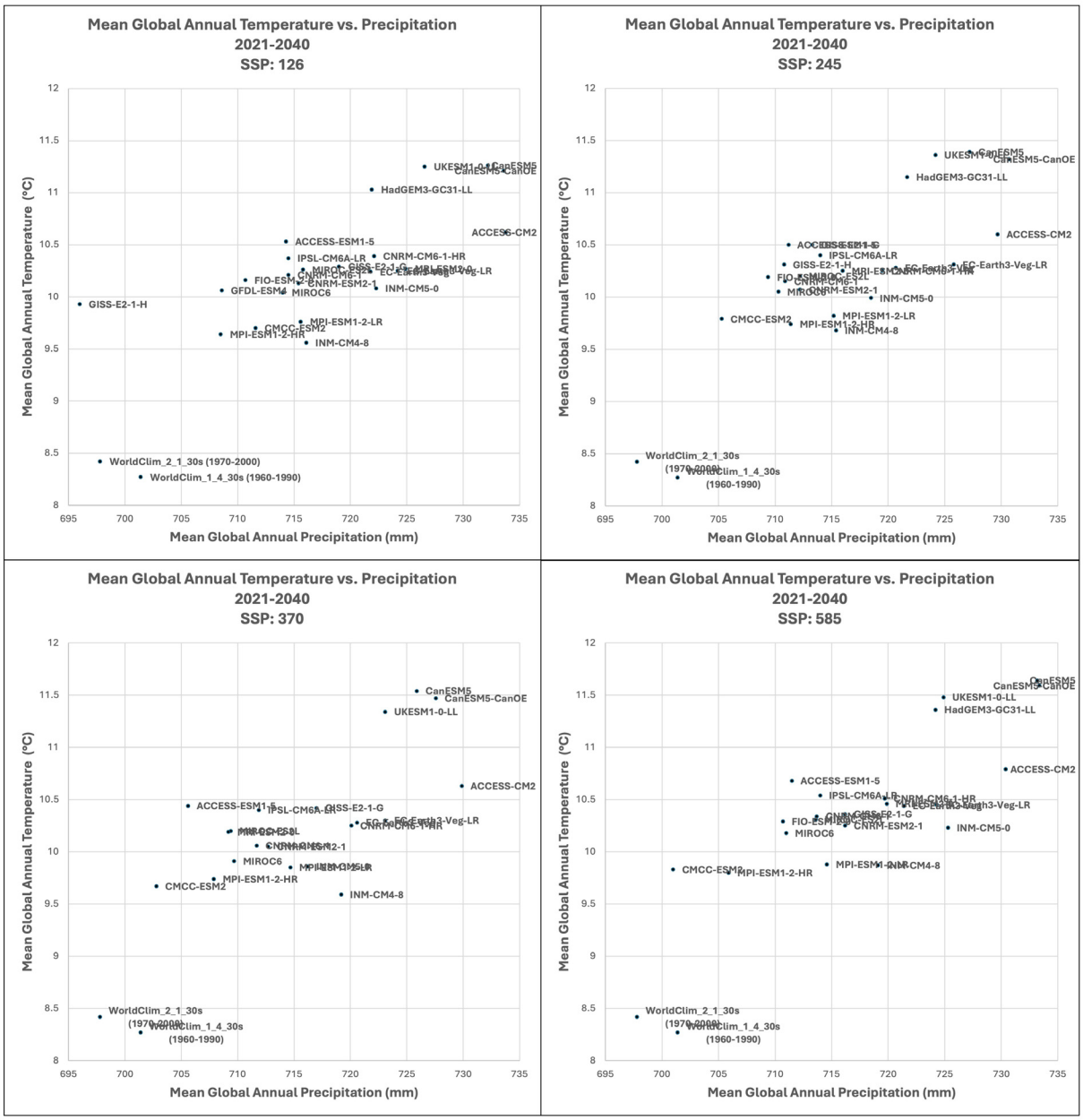


Figure 3. Distribution of 22 CMIP6 Earth System Models along temperature and precipitation gradients (2021–2040). Distribution of average global mean annual temperature and mean annual precipitation of 22 CMIP6 ESM for four SSP for the time period 2021–2040.

Zomer *et al.*, 2022). CLIMWAT 2.0 provides observed agro-climatic data of over 5000 stations distributed worldwide (Figure 8), including monthly averages for seven climatic parameters, namely maximum temperature, minimum temperature, relative humidity, wind speed, sunshine hours, radiation balance and ET_0 calculated according to the Penman-Monteith method, as well as the coordinates and altitude of the station. After evaluation, 4242 stations were used for the spreadsheet analysis, and a subset of data points common among all geospatial datasets created, which came out to 3842 stations.

Input parameters for validation were extracted from each of the two historical geospatial datasets by sampling of the gridded data at the weather station coordinates and were compared with the values from the weather station data to evaluate the accuracy and overlap of the CLIMWAT and WorldClim datasets,

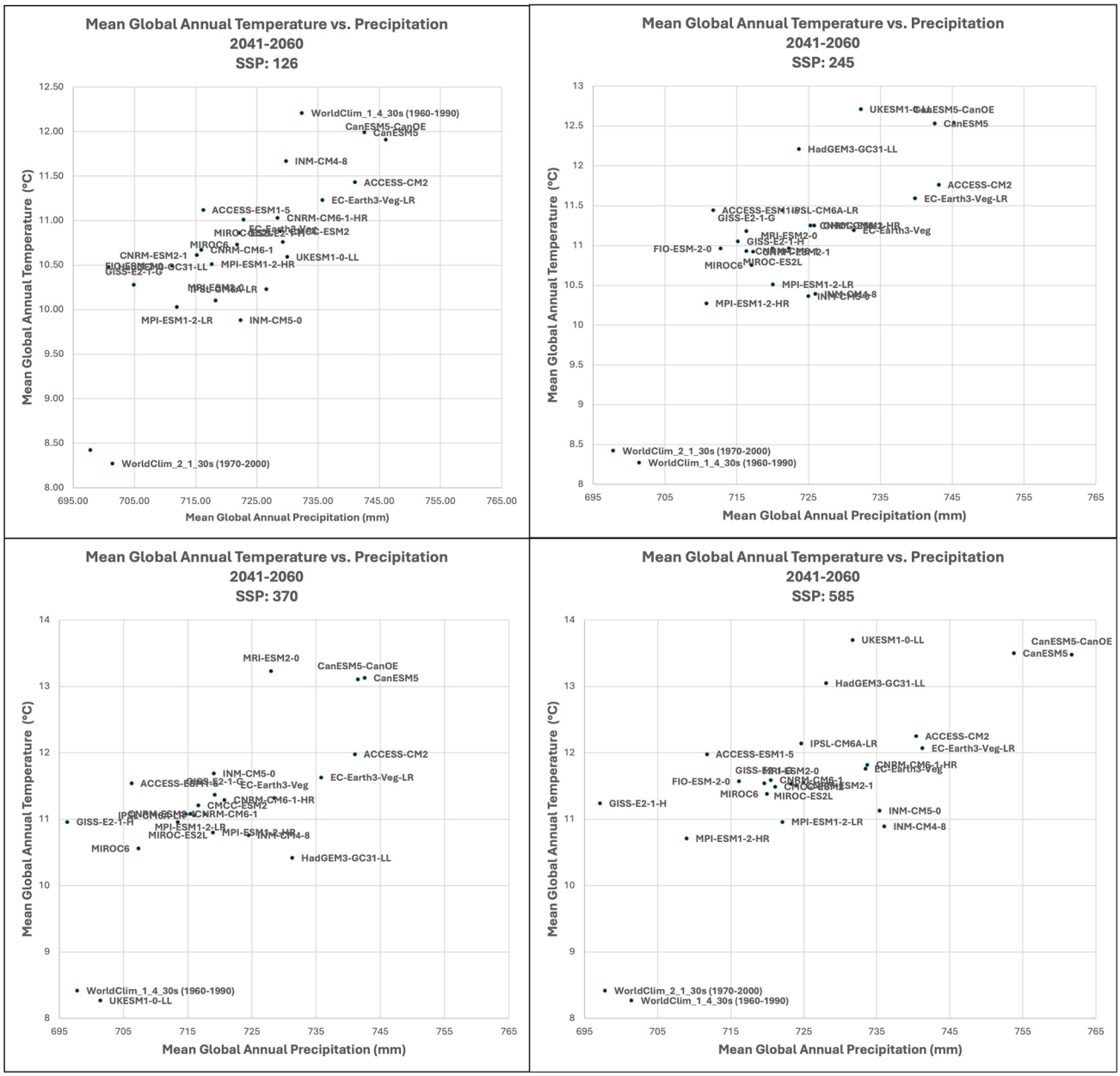


Figure 4. Distribution of 22 CMIP6 Earth System Models along temperature and precipitation gradients (2041–2060). Distribution of average global mean annual temperature and mean annual precipitation of 22 CMIP6 ESM for four SSP for the time period 2041–2060.

and the suitability of using the CLIMWAT to evaluate the performance of the PET spatial estimation. An assessment of the input parameters from the WorldClim datasets showed high levels of correspondence when compared to the CLIMWAT data (Zomer *et al.*, 2022) that the CLIMWAT was considered an appropriate dataset available for evaluating the accuracy of the PET and AI estimation algorithms.

The previously developed dataset, Global-AI_PET_v3 (Zomer *et al.*, 2022), based upon WorldClim v. 2.1 and calculated using the Penman-Monteith equation was used as a comparative standard, with the assumption that the full implementation of the Penman-Monteith, it being the standard, would provide the more robust results. PET estimates were tested and compared both using the Hargreaves and the Penman-Monteith equations with CLIMWAT provided parameters from 4242 weather stations to parameterize the estimation algorithm (Table 5; Figure 9). The calculated values for the Hargreaves equation were shown to have a moderate level of correspondence (r^2 = 0.68) with a fairly high standard error (346 mm). As expected, the Penman-Monteith results were highly accurate (r^2 = 0.99; standard error = 36mm), as they replicated the

Table 4. Coefficient of variation of ensemble averages. Coefficient of variation showing agreement amongst CMIP_6 Earth System Models (ESM) included with each of three averaged multimodel ensembles, as articulated for each of four shared socio-economic pathways (SSP: Scenario).

MultiModel Ensemble		Coefficient of Variation (%)			
		2021–2040			
	Scenario	tmean_yr	prec_yr	pet_yr	aridity_index
All	126	2.08	4.24	2.95	5.30
	245	2.21	4.42	3.19	5.68
	370	2.49	4.96	3.48	6.36
	585	2.56	5.32	3.85	7.07
	Ensemble average:	**2.34**	**4.74**	**3.37**	**6.10**
Consensus	126	1.44	3.64	2.37	4.75
	245	1.44	3.65	2.37	4.83
	370	1.36	3.85	2.33	5.12
	585	1.48	4.31	2.61	5.73
	Ensemble average:	**1.43**	**3.86**	**2.42**	**5.11**
High Risk	126	1.09	2.63	1.71	3.72
	245	1.17	2.68	1.75	3.80
	370	1.30	2.61	1.69	3.58
	585	1.22	2.88	1.71	3.91
	Ensemble average:	**1.20**	**2.70**	**1.72**	**3.75**
MultiModel		2041–2060			
Ensemble	Scenario	tmean_yr	prec_yr	pet_yr	aridity_index
All	126	2.08	4.19	2.94	5.24
	245	2.21	4.42	3.19	5.67
	370	2.49	4.00	2.42	5.18
	585	2.56	4.45	2.69	5.78
	Ensemble average:	**2.34**	**4.27**	**2.81**	**5.47**
Consensus	126	1.44	3.70	2.41	4.70
	245	1.44	3.82	2.46	4.90
	370	1.36	4.03	2.44	5.19
	585	1.48	4.49	2.71	5.79
	Ensemble average:	**1.43**	**4.01**	**2.51**	**5.15**
High_Risk	126	1.25	3.18	2.17	4.67
	245	1.34	3.47	2.40	5.14
	370	1.72	3.78	2.80	5.66
	585	1.76	4.32	3.04	6.42
	Ensemble average:	**1.52**	**3.69**	**2.60**	**5.47**

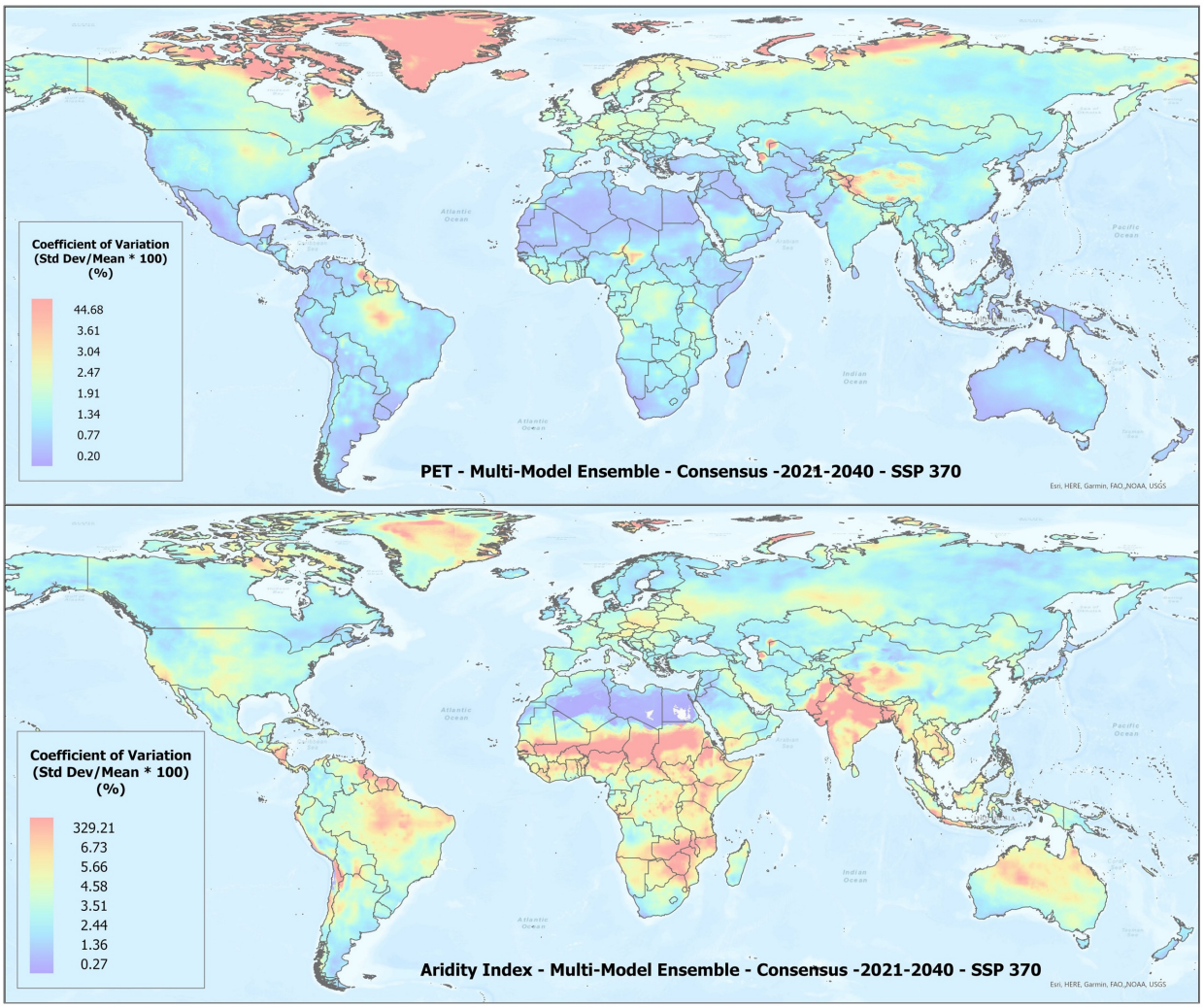


Figure 5. Example of spatial variation of Coefficient of Variation (CoV) of PET and Aridity Index. Coefficient of variation of PET and Aridity Index as shown for the "Consensus" multimodel ensemble average, SPP 370 scenario, shown here to illustrate variation in agreement across the various global regions.

CLIMWAT weather station reported results, i.e., using the same equation, confirming the relative accuracy of the dataset and its fitness for use as a comparative standard. The algorithm was then implemented geospatially on a per grid cell basis to produce global geospatial datasets calculated based upon the Hargreaves equation for the two historical time periods (WorldClim 1.4 – 1960–1990; WorldClim 2.1 – 1970–2000) and tested against the CLIMWAT ET_0 estimates from 3842 weather stations (i.e. all weather stations with useable data across all of the compared datasets). Although the results showed a higher level of accuracy (r^2 = 0.85) for the Penman-Monteith calculated dataset (Global_ET_0_v3), the relatively (or moderately) high accuracy (r^2 = 0.72) attained by the Hargreaves implementation of the algorithm maybe considered sufficient for use within many modeling and other efforts, however, with caveats in light of the variability associated with both the input data and accuracy of the estimation algorithm when applied globally. In particular, local estimates may have high variability associated with steep elevation gradients and heterogenous terrain, and/or low levels of accuracy at the grid cell level in certain regions due to interpolation of scattered or less dense weather station data. There is significant potential for error associated with both the interpolated and downscaled global input data and the application of the Hargreaves methodology (or Penman-Monteith for that matter) when implemented globally. It has been noted that the Hargreaves equation tends to under-estimate ET_o under high wind conditions (> 3m/s) and to over-estimate under conditions of high relative humidity (Richards, 2015).

There were significant differences between the Hargreaves (PET_WC_2.1) and Penman-Monteith (Global_ET0_v3) versions of the global implementation (r^2 = 0.67). PET_WC_2.1 using the Hargreaves methodology appeared to systematically underestimate higher PET values. Most of these higher values were generally outside of the prescribed realm of validity for the PET estimates related to plant growth or agricultural activities, and mostly found in the higher latitudes and arctic

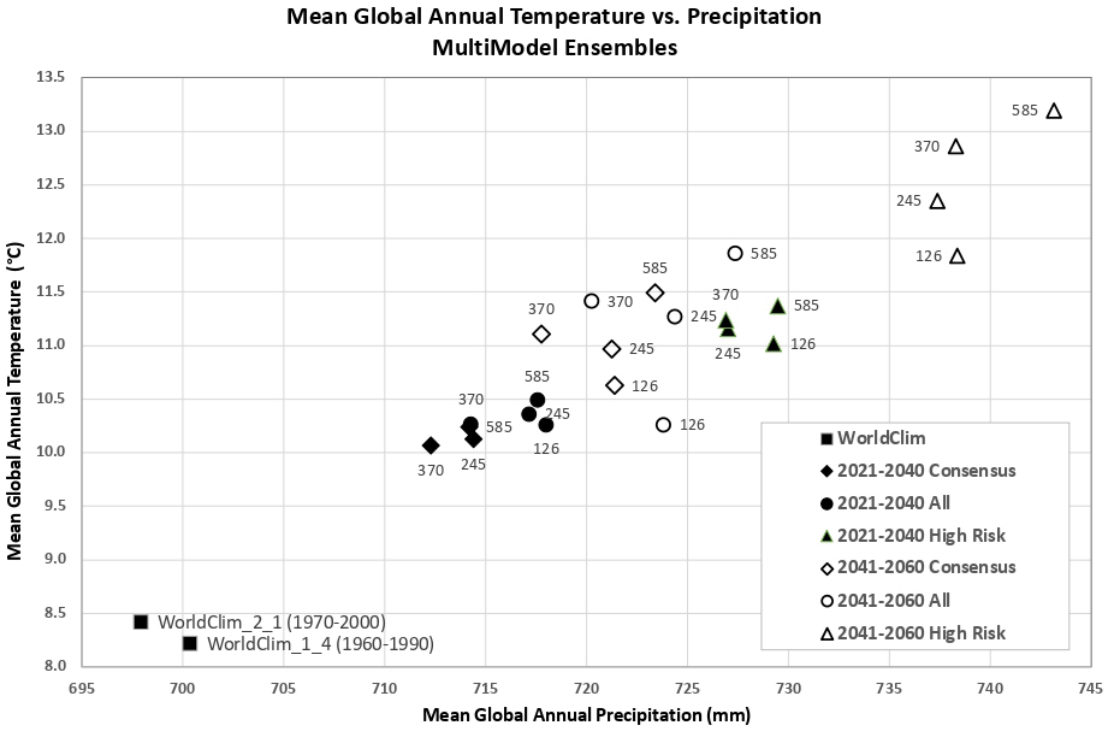


Figure 6. Distribution of historical and projected global averaged annual temperature and annual precipitation. Distribution of historical and projected global averaged annual temperature (°C) and annual precipitation (mm) of three averaged multimodel ensembles, across four shared socio-economic pathways (SSP: 126; 245; 370; 585).

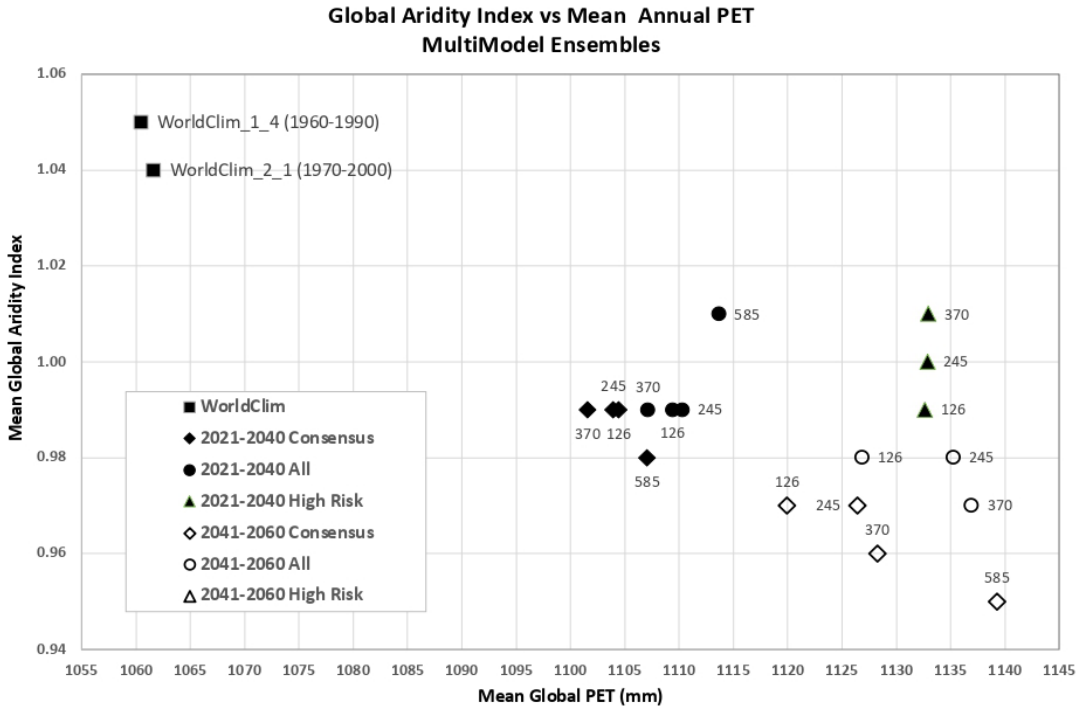


Figure 7. Distribution of historical and projected global averaged PET and Aridity Index. Distribution of historical and projected global averaged PET (mm) and the aridity index (AI) of three averaged multimodel ensembles, across four shared socio-economic pathways (SSP: 126; 245; 370; 585). Higher AI values indicate wetter conditions, lower values indicate drier conditions.

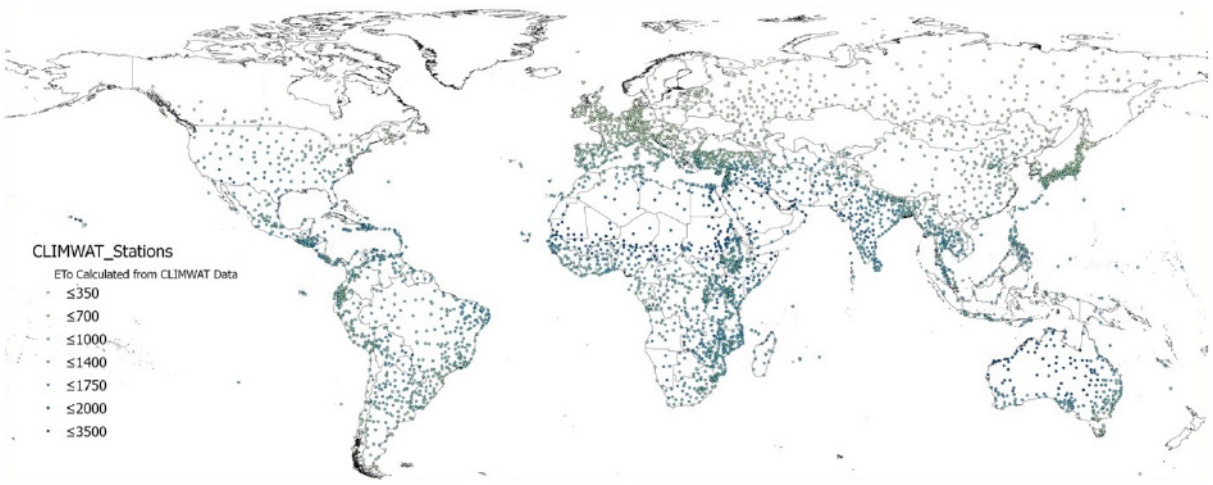


Figure 8. Location of weather stations included in the FAO CLIMWAT dataset. Location of weather stations included in the FAO CLIMWAT dataset, showing ET0_CLIMWAT values for Penman-Monteith Reference Evapotranspiration (ET0) (Muñoz & Greiser, 2006).

Table 5. Summary Table of Technical Validation Results.

Regression	R Square	Standard Error	Bias
Potential Evapotranspiration_ETo			
PET_CLIMWAT_XLS vs ET_0_CLIMWAT	0.680	345	586.30
ET_0_CLIMWAT_XLS vs ET_0_CLIMWAT	0.99	36	-53.71
PET_WC_1.4 vs ETo_CLIMWAT	0.72	221	-132.65
PET_WC_2.1 vs ET_0_CLIMWAT	0.76	212	-128.90
Global_ET_0_v3 vs ET_0_CLIMWAT	0.85	219	-389.38
PET_WC_2.1 vs Global_ET_0_v3	0.67	238	-262.12
Global_ET_0_v3 vs ET_0_CRU_TS	0.89	136	-408.12
Aridity Index			
AI_WC_1.4 vs AI_CLIMWAT	0.91	0.16	0.14
AI_WC_2.1 vs AI_CLIMWAT	0.88	0.18	0.14
Global_AI_v3 vs AI_CLIMWAT	0.90	0.17	0.21
AI_WC_2.1 vs Global_AI_v3	0.89	0.18	0.07
AI_CLIMWAT vs AI_CRU_TS	0.77	0.33	-0.02
AI_WC_2.1 vs AI_CRU_TS	0.79	0.26	-0.16
Global_AI_v3 vs AI_CRU_TS	0.83	0.22	-0.23

** Evaluated datasets	Description
PET (ET_0)	
ET_0_ClimWat	ET_0 as reported by CLIMWAT station data
ET_0_ClimWat_XLS	ET_0 calculated using estimation algorithm parameterized with CLIMWAT station data
ET_0_CRU_TS	ET_0 extracted from CRU_TS PET grid
PET_WC_1.4	PET calculated using WC_1.4 1960 - 1990 (Modified Hargreaves-Thornton)
PET_WC_2.1	PET calculated using WC_2.1 - 1970 - 2000 (Modified Hargreaves-Thornton)
Global_ET_0_v3	ET_0 calculated using WC_2.1 - 1970 - 2000 (Penman-Monteith)
Aridity Index (AI)	
AI_ClimWat	AI calculated using parameters from CLIMWAT station data - 1960-1990 (Penman-Monteith)
AI_CRU_TS	AI calculated using ET_0_CRU_TS - 1970-2000 (Penman-Monteith)
AI_WC_1.4	AI calculated using WC_1.4 - 1990 - 2000 (Modified Hargreaves-Thornton)
AI_WC_2.1	AI calculated using WC_2.1 - 1970 - 2000 (Modified Hargreaves-Thornton)
Global_AI_v3	AI calculated using WC_2.1 - 1970 - 2000 (Penman-Monteith)

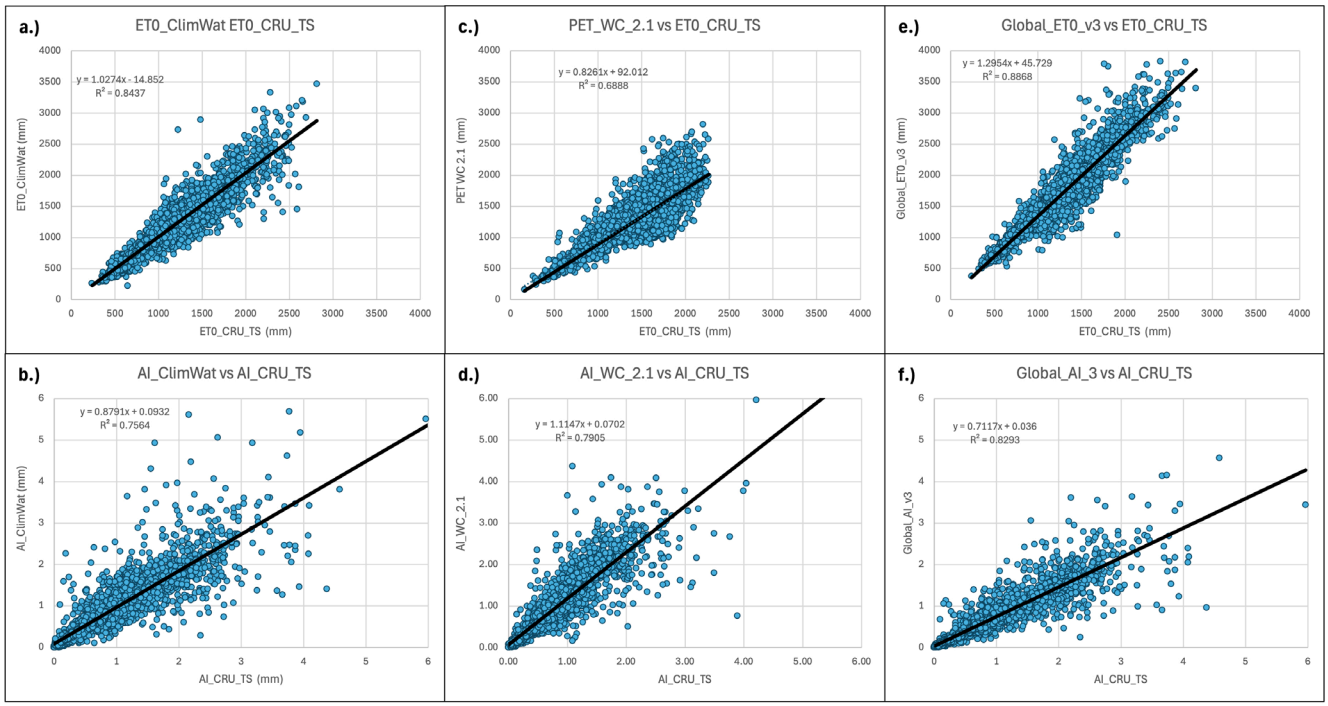


Figure 9. Validation and comparison of input data used in the analysis and results. Validation and comparison of: **a**.) PET (Hargreaves) calculated from the CLIMWAT (Muñoz & Greiser, 2006) weather station data versus the CLIMWAT reported ET_0 (Penman-Monteith); **b**.) ET_0 (Penman-Monteith) calculated from the CLIMWAT weather station data versus the CLIMWAT reported ET_0 (Penman-Monteith); **c**.) PET Hargreaves (WorldClim 2.1) versus CLIMWAT reported ET_0 (Penman-Monteith); **d**.) Aridity Index ((WorldClim 2.1) versus Aridity Index calculated from CLIMWAT weather station data and reported ET_0 (Penman-Monteith); **e**.) PET (Hargreaves) versus Global ET_0 – Version 3 ET_0 (Penman-Monteith).

regions. However, the AI estimates based on the AI_WC_2.1 analysis, when compared to AI estimates based on parameters provided by the CLIMWAT weather station data (Table 5; Figure 9e), showed a high level of correspondence (r^2 = 0.91), statistically the same as that from the Global-AI_PET_v3 estimates (r^2 = 0.90).

Similarly, the estimations of the Hargreaves PET (PET_WC_2.1) and ET_0 (Global_ET_0_v3) were evaluated against the ET_0 dataset provided by the CRU_TS (Climatic Research Unit gridded Time Series version 4.05) (Harris *et al.*, 2020). The CRU_TS is a widely used climate dataset on a 0.5° latitude by 0.5° longitude grid over all land domains of the world except Antarctica. It is derived by the interpolation of monthly climate anomalies from extensive networks of weather station observations. PET values are provided in the CRU_TS dataset, calculated based upon the Penman-Monteith formula (Droogers & Allen, 2002; Zomer *et al.*, 2022; Zotarelli *et al.*, 2018), using the CRU_TS gridded values of mean temperature, vapour pressure, cloud cover and wind field. For our comparison, we averaged the CRU_TS monthly values for PET from 1971–2000 to obtain a global coverage of average annual PET for that time period. The same CLIMWAT meteorological stations used in previous comparisons were used as sample points for the comparison with both the PET and ET_0 datasets, and the CLIMWAT ET_0 was also compared with the CRU_TS PET (ET_0_CRU_TS) dataset (r^2 = 0.84) to assess general congruence among the datasets (Table 5; Figure 10). Results showed a moderate level of agreement (r^2 = 0.68) between the ET_0_CRU_TS and Hargreaves (PET_WC_2.1) data, with a significantly higher level of agreement, as expected, for the Penman-Monteith ((Global_ET_0_v3: r^2 = 0.89)) results. However, both the Hargreaves and the Penman-Monteith calculated aridity indices showed high correspondence to each other and to the CLIMWAT and CRU_TS results. The CRU_TS precipitation data for the 1971–2000 time period was similarly averaged and used to calculate an AI based upon the CRU_TS dataset and compared to both the PET_WC_2.1 and the Global_AI_v3. The Hargreaves calculated geospatial aridity index dataset (AI_WC_2.1) showed high correspondence (r^2= 0.88) with the aridity index results calculated from the CLIMWAT station data (AI_CLIMWAT), only slightly less than the Global_AI_v3 (r^2 = 0.90). Both the AI_WC_2.1 and Global_AI_3 performed well (respectively r^2 = 0.79 and r^2 = 0.83) against the CRU_TS calculated AI (AI_CRU_TS).

Among other factors, the significant and specific influence of relative humidity and wind speed lead to particular deviations of results across broad climate regions between Hargreaves and Penman-Monteith model results (Allen *et al.*, 1998). This

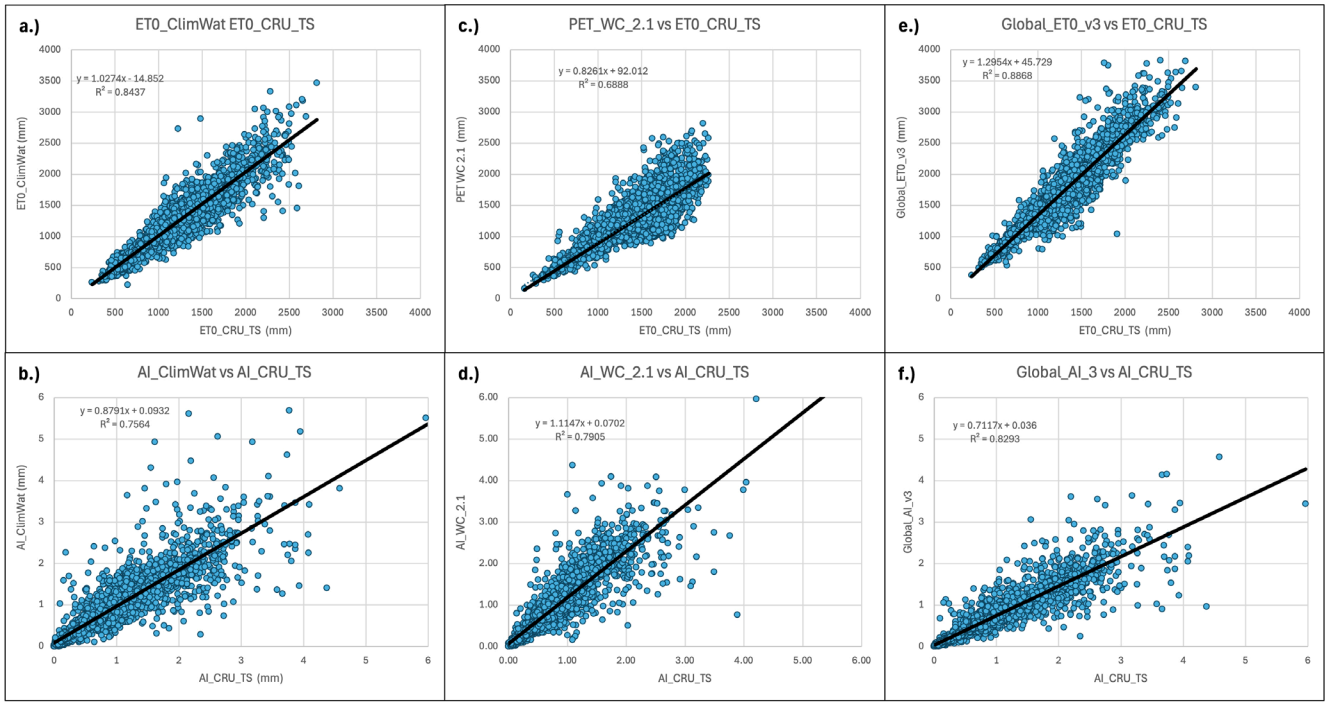


Figure 10. Validation and comparison of Hargreaves PET and Aridity Index vs. CRU_TS dataset. Validation and comparison of results for the PET (Hargreaves) and the Aridity Index datasets with the CRU_TS (Harris *et al.*, 2020) dataset.

uncertainty has led to several successful attempts (Aschonitis *et al.*, 2017; Tegos *et al.*, 2017) to provide calibration and correction factors map for Hargreaves estimates, based on parametric regression between Hargreaves PET and PM ET0 monthly values for historical condition, that can close the gap between results from Hargreaves and PM methods. While recognizing the value of such efforts, expansion on the use of these parametric corrections have still been quite limited on future projections, This would require at any site not basic changes in correlation between temperature (used in Hargreaves equations) with the others variables (RH, wind speed, solar radiation) additionally used in the Penman-Monteith equation, to maintain relative divergence between Hargreaves and Penman-Monteith values steady (and in turn correction coefficients) from historical to future conditions.

It is the authors conclusion given the high levels of uncertainty (Wang *et al.*, 2015) and the variability associated with future projections and interpolated climate datasets in general, that these results can provide meaningful inputs and useful insights regarding both trends and magnitude of change, but of course, should be used keeping in mind this uncertainty.

Usage notes

The geospatial datasets are provided online in GeoTIFF (.tif) format, in geographic coordinates; datum and spheroid are WGS84; spatial units are decimal degrees. The spatial resolution is 30 arc-seconds or 0.008333 degrees (approximately 1 km^2 at the equator). The PET values are defined as total mm of PET per month or per year. The Aridity Index values are unitless.

Although considered sufficient for use within many modeling and other scientific efforts, we highlight the earlier caveats showing the variability associated with both the input data and accuracy of the estimation algorithm when applied globally. As stated, local or even regional estimates may have high variability associated with steep elevation gradients and heterogenous terrain, and/or low levels of accuracy at the grid cell level due to interpolation of scattered or less dense weather station data, with significant potential for error associated with both the global input data (Navarro *et al.*, 2024) and the application of the Hargreaves methodology (Wang *et al.*, 2015) when implemented globally across a wide spectrum of environmental, geophysical, and bioclimatic conditions. As such, while useful for identifying and determining change, we urge caution in use of these datasets. Likewise, the aridity index, and the Hargreaves equation, are geared toward ascertaining moisture available for crop or other plant growth, and as such may not be designed for biomes and bioclimates beyond the reasonable temperature limits of seasonal agriculture. Aridity Index provides estimate on annual temporal scale, while other methods (e.g. SPEI, PSDI) can be further implemented using these PET and WorldClim datasets to derive other specific agrometeorological drought indicators at monthly and seasonal scale (Tegos *et al.*, 2023; Vicente-Serrano *et al.*, 2010). Some very high values of Aridity Index, primarily found in the highest latitudes and arctic regions, although remaining in the dataset, are considered uninterpretable.

Ethics and consent

Ethical approval and consent were not required.

Data availability

The Future_Global_AI_PET data layers have been processed and finalized for distribution online as GEO-TIFFs. These datasets have been zipped (.zip) into monthly series or their respective annual layers, by each combination of climate model and SSP scenario.

The Future_Global_AI_PET Database is archived and available online from the Science Data Bank (ScienceDB, at https://doi.org/10.57760/sciencedb.nbsdc.00086 (Zomer & Trabucco, 2024).

The "Future_Global_AI_PET Database" provides a set of high-resolution (30 arc-seconds) global raster datasets of average monthly and annual potential evapotransipation (PET) and annual aridity index (AI) for two historical (1960–1990; 1970–2000) and two future (2021–2040; 2041–2060) time periods for each of 25 CMIP6 Earth System Models across four emission scenarios (SSP: 126, 245, 370, 585). The database also includes three averaged multi-model ensembles produced for each of these four emission scenarios. There are a total of 389 files online, including a detailed Readme file, comprising 389 GB of data.

The Future_Global_AI_PET data layers have been processed and finalized for distribution online as GEO-TIFFs. These datasets have been zipped (.zip) into monthly series or their respective annual layers, by each combination of climate model and SSP scenario. The Future_Global_AI_PET Database is archived and available online from the Science Data Bank (ScienceDB), at https://doi.org/10.57760/sciencedb.nbsdc.00086 (Zomer & Trabucco, 2024).

Supplementary tables and figures are available online on the Figshare Data Repository as "Extended Data: CMIP6-Based Global Estimates of Future Aridity Index and Potential Evapotranspiration for 2021–2060" at https://doi.org/10.6084/m9.figshare.26095363 (Zomer *et al.*, 2024). These are available under a CC-BY 4.0 license in one file (Global Future AI_PET - SM_Tables v1) containing supplementary tables and a figure including:

- Global Mean Annual Climatic Parameters for All Included CMIP_6 ESM
- Mean Annual Climatic Parameters for all Multi-model Ensembles by Region
- Coefficient of Variation for all Multi-model Ensembles by Region
- Map of Global Regions used in the Regional Analysis

Code availability

The algorithm used to calculate PET and AI was coded in Python 3.2 and uses the ArcPy (ArcGIS) package. It is available under a Apache 2.0 license on Figshare at this link below:

https://figshare.com/articles/software/Global_Future_PET_AI_Algorithm_Code_Python_-_Calculate_PET_AI/24978666

Author contributions

Research design: R.Z.; A.T.; Equation development: A.T.; R.Z.; AML Programming: A.T.; Python programming: R.Z.; Statistical analysis: R.Z., J.X., A.T.; Writing: R.Z., J.X., A.T. DS; Tables and Figures: R.Z.; Financial Support: R.Z., A.T.; J.X.; D.S.

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Open Peer Review

Current Peer Review Status: ✔ ✔ ✔

Version 4

Reviewer Report 23 May 2025

https://doi.org/10.21956/openreseurope.22030.r54138

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✔ **Vassilis Aschonitis**
Hellenic Agricultural Organization, Soil and Water Resources Institute, Thessaloniki, Greece

no new comments

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: agrometeorology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 3

Reviewer Report 27 March 2025

https://doi.org/10.21956/openreseurope.21447.r51854

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✔ **Louise Crochemore**
[1] nstitute of Environmental Geosciences - CNRS, INRAE, IRD, Grenoble-INP, Université Grenoble Alpes, Grenoble, France
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We thank the authors for their thorough answers, and do acknowledge that this is a data note and

not a research article. As such, our points were well addressed. Here are a few remaining recommendations:
- Please check again the spelling of Penman-Monteith throughout the paper.
- The reference to Wang et al. (2018) for extraterrestrial radiation still seems erroneous. Please check. Neither the words "radiation" nor "extraterrestrial" appear in this article. The article seems to rather focus on transfers in porous media. Wang X, et al., (Ref 1)
- The information mentioned by the authors on the choice of the High risk scenarios would be useful to add to the note.
- Similarly, the information on why the number of CLIMWAT stations varies throughout the note is useful. Consider adding it at the beginning of the Technical validation.

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Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 01 May 2025

Robert Zomer

Thanks again to the Reviewers for greatly improving the manuscript... we have gone back and now addressed final points: 1.) Corrected Spellin: Penman-Monteith (2 instances found)

2.) Corrected Reference: Yes, .. the Wang et al., 2018, was incorrect,.. mislabelled in our bibliographic software. Correction citation is:
Šimůnek, J., M. Th. van Genuchten and M. Šejna, The HYDRUS-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media, Version 3.0, HYDRUS Software Series 1, Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, 2005.

3.) Added this statement to Methods: "After evaluation, 4242 stations were used for the spreadsheet analysis, and a subset of data points common among all geospatial datasets created, which came out to 3842 stations."

4.) Corrected this statement in Methods: " Based upon the distribution of the various scenarios along their projected temperature and precipitation estimates *for the 2021-2040 future time period* (Figure 3 & Figure 4), three multi-model ensembles, each articulated by their four..."

Competing Interests: No competing interests were disclosed.

Version 2

Reviewer Report 08 February 2025

https://doi.org/10.21956/openreseurope.21154.r50881

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Aristoteles Tegos
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The authors have taken on board my comments and the manuscript has been substantially improved.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Potential Evapotranspiration expert. Water Resources Management and hydrology epxert.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 07 February 2025

https://doi.org/10.21956/openreseurope.21154.r50879

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Vassilis Aschonitis
[1] Hellenic Agricultural Organization, Soil and Water Resources Institute, Thessaloniki, Greece
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I think the authors improved the document. Just some minor corrections:
1. Check the numbering of equations
2. The coefficient in Hargreaves equation is 0.0023 and not 0.023.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Hydrology, Hydroclimatology, Soil Science, Environmental Modelling

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 27 September 2024

https://doi.org/10.21956/openreseurope.19576.r43858

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Aristoteles Tegos
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The manuscript presents a high-resolution average annual and monthly global estimates of potential evapotranspiration (PET) and aridity index (AI) for 22 CMIP6 Earth System Models for two future (2021-2041; 2041-2060) and two historical (1960-1990; 1970–2000) time periods. The paper is well written but needs several modifications to include recent scientific findings.
My main concern is the lack of the discussion for the required local calibration of Hargreaves model which has been already proved to be necessary given the physical complexity of PET phenomenon (Tabari and Talaee 2011(Ref 1), Haslinger and Bartsc 2016 (Ref 2)). The same, using the same global database, has been highlighted by Tegos et al. 2017 (Ref 3) where the local calibration of temperature-base or simplified extraterrestrial are irreplaceable for improving the performance of simplified PET approaches (also Tegos et al 2015 (Ref 4)). I would recommend further discussion on that in order to provide limitations of the current dataset and also future improvements especially in geographic where temperature-radiation approaches are failed to provide reliable PET estimates such as Amazonios etc (Tegos et al .2017 (Ref 5))

Among the various equations employed for estimating PET. Suggest to add as citation the paper which presents a detailed review of PET model (McMahon et al 2016).

The Hargreaves (Hargreaves, 1994b) equation demonstrated the nearest results to the classic PM (Droogers & Allen, 2002; Itenfisu et al., 2003). The Hargreaves method with substantially less data requirements, i.e., requiring only measured values of maximum and minimum temperatures and precipitation, was recommended for more general use and therefore is considered more appropriately applicable to data scarce regions and situations (Droogers & Allen, 2002). For the purposes of this paper, to maintain clarity, we refer to reference evapotranspiration calculated using the Penman-Monteith as "ET_0" and calculations using the Hargreaves equation as "PET". Please refer to my above

comment on the historical criticism of the uncalibrated Hargreaves model. The txt must provide more details in the point.
There is a need for additional discussion of Aridity index (Vicente-Serrano et al. 2010 (Ref 6)). The original index was based on the use of the PET Thornthwaite model however recent a research has been criticized the use Thornthwaite model for assessing aridity severity (Tegos et al. 2023 (Ref 7)) and other PET models are recommended.

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Is the rationale for creating the dataset(s) clearly described?

Partly

Are the protocols appropriate and is the work technically sound?

Partly

Are sufficient details of methods and materials provided to allow replication by others?

Partly

Are the datasets clearly presented in a useable and accessible format?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Potential Evapotranspiration expert. Water Resources Management and hydrology epxert.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 29 Jan 2025

Robert Zomer

Reviewer Report - 3 2 Views
Approved with reservations
27 Sep 2024 VERSION 1
Aristoteles Tegos, National Technical University Athens, Athens, Greece

Reviewer Comments:
The manuscript presents a high-resolution average annual and monthly global estimates of potential evapotranspiration (PET) and aridity index (AI) for 22 CMIP6 Earth System Models for two future (2021-2041; 2041-2060) and two historical (1960-1990; 1970–2000) time periods. The paper is well written but needs several modifications to include recent scientific findings.
My main concern is the lack of the discussion for the required local calibration of Hargreaves model which has been already proved to be necessary given the physical complexity of PET phenomenon (Tabari and Talaee 2011(Ref 1), Haslinger and Bartsc 2016 (Ref 2)). The same, using the same global database, has been highlighted by Tegos et al. 2017 (Ref 3) where the local calibration of temperature-base or simplified extraterrestrial are irreplaceable for improving the performance of simplified PET approaches (also Tegos et al 2015 (Ref 4)). I would recommend further discussion on that in order to provide limitations of the current dataset and also future improvements especially in geographic where temperature-radiation approaches are failed to provide reliable PET estimates such as Amazonios etc (Tegos et al .2017 (Ref 5)).

Author Response:
We do reckon the added value of parametric corrections for the Hargreaves equations, in order to reduce gap with PM Monteith and especially some specific climate broader areas. The global database of corrected parametric equations for the Hargreaves eq (Tegos et al. 2017) can provide valuable information to improve accuracy of the Hargreaves method in such regions. Tegos et al. (2017) provide a spatial distribution of corrected parametric coefficients, based on regression between Hargreaves PET and PM ET0 monthly values for historical periods (based on historical observation available from CLIMWAT 2.0 database). As mentioned also by the first reviewer, several studies have tested calibration of Hargraves for current climate conditions. While recognizing the value of such efforts, we can not yet assume that such parametric regression (and thereafter the parameter correction) hold steady at same location in the far future (up to 2060). This would imply at any site not basic changes in the correlation between temperature (used in Hargreaves equations) with the others variables (RH, Wind Speed, solar radiation) additionally used in the PM equation, to maintain relative divergence between Hargreaves and Penman-Monteith values steady (and in turn correction coefficients) from historical to future conditions. In fact, none of the mentioned citations (Tabari and Talaee 2011, Haslinger and Bartsc 2016, Tegos et al. 2017, Tegos et al 2015) uses corrected parameters factors to climate projections. Valuable effort to improve use of correction coefficient for future climate conditions, could possibly define correction factors that would be climate explicit (possibly in relation to Temperature regimes), rather than just spatially explicit. Any shift in the climate regime, due to climate change, would be associated with the shift of corrected parameters. To Acknowledge the

value of corrected parameters to improve reliability of Hargreaves equation, we have added the following in technical validation section *Among other factors, the significant and specific influence of relative humidity and wind speed lead to particular deviations of results across broad climate regions between Hargreaves and Penman-Monteith model results (Allen et al., 1998). This uncertainty has led to several successful attempts (Tegos et al. 2017, Aschonitis et al. 2017) to provide calibration and correction factors map for Hargreaves estimates, based on parametric regression between Hargreaves PET and PM ET0 monthly values for historical condition, that can close the gap between results from Hargreaves and PM methods. While recognizing the value of such efforts, expansion on the use of these parametric corrections have still been quite limited on future projections, This would require at any site not basic changes in correlation between temperature (used in Hargreaves equations) with the others variables (RH, Wind Speed, solar radiation) additionally used in the PM equation, to maintain relative divergence between Hargreaves and Penman-Monteith values steady (and in turn correction coefficients) from historical to future conditions.*

Reviewer Comments:
Among the various equations employed for estimating PET. Suggest to add as citation the paper which presents a detailed review of PET model (McMahon et al 2016).

Author Response:
Citation was added

Reviewer Comments:
The Hargreaves (Hargreaves, 1994b) equation demonstrated the nearest results to the classic PM (Droogers & Allen, 2002; Itenfisu et al., 2003). The Hargreaves method with substantially less data requirements, i.e., requiring only measured values of maximum and minimum temperatures and precipitation, was recommended for more general use and therefore is considered more appropriately applicable to data scarce regions and situations (Droogers & Allen, 2002). For the purposes of this paper, to maintain clarity, we refer to reference evapotranspiration calculated using the Penman-Monteith as "ET_0" and calculations using the Hargreaves equation as "PET".
Please refer to my above comment on the historical criticism of the uncalibrated Hargreaves model. The txt must provide more details in the point.

Author Response:
See point above

Reviewer Comments:
There is a need for additional discussion of Aridity index (Vicente-Serrano et al. 2010 (Ref 6)). The original index was based on the use of the PET Thornthwaite model however recent a research has been criticized the use Thornthwaite model for assessing aridity severity (Tegos et al. 2023 (Ref 7)) and other PET models are recommended.

Author Response:
Indeed, some of the analyses results in the paper highlighted precisely the higher level of accuracy of Hargreaves respect to Thornthwaite method, among temperature-based methods. Herein, the choice of using Hargreaves rather ThornTwhaite for the calculation was substantially justified. Following this reviewer insight, we find some relevant merit to

add in the usage note the following: *Aridity Index provides estimate meteorological droughts on annual temporal scale, while other methods (e.g. SPEI, PSDI) can be further implemented using these and Worldclim datasets to derive other more specific agrometeorological drought indicators at monthly and seasonal scale (Vicente-Serrano et al. 2010; Tegos et al. 2023).*

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3. Tegos A, Malamos N, Efstratiadis A, et al.: Parametric Modelling of Potential Evapotranspiration: A Global Survey. *Water.* 2017; **9** (10): | Publisher Full Text

4. Tegos A, Malamos N, Koutsoyiannis D: A parsimonious regional parametric evapotranspiration model based on a simplification of the Penman–Monteith formula. *Journal of Hydrology.* 2015; **524** 708-717 | Publisher Full Text

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Competing Interests: No competing interests were disclosed.

Reviewer Report 27 September 2024

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Summary

Zomer et al. propose an open dataset of projected evapotranspiration (ET) and aridity index (AI) for the globe and at high resolution. The projected datasets are based on CMIP6 earth system models, across 4 emission scenarios and for the time period 2021-2040 and 2041-2060. This dataset builds upon the datasets and methodologies used in previously existing datasets of ET and AI for the historical period also produced by the authors.
We have evaluated this work from a user perspective, and our comments mainly highlight clarifications needed to facilitate the use/understanding of the dataset and ensure that the provided information allows for its proper use. The work seems robust but addressing some of these points would strengthen this assessment.

General comments

- 22 CMIP6 models are mentioned, but only 14 can be found openly on the WorldClim projection datasets at the resolution of 30 arcsec. (https://worldclim.org/data/cmip6/cmip6_clim30s.html). ACCESS-ESM1-5; CanESM5; CanESM5-CanOE; CNRM-CM6-1, CNRM-CM6-1-HR; CNRM-ESM2-A; GISS-E2-1-G; INM-CM4-8; MIRO-ES2L,MPI-ESM1-2-LR do not seem to appear. Conversely, the model EC-Earth3-Veg is available in Worldclim, and not used in this study. It would be useful for readers who want to replicate or use the dataset, for comparison for instance, to know (a) where the missing downscaled models were obtained from, and (b) why not all available models were used.
- The authors seem to use the terminologies of “potential evapotranspiration” and “reference evapotranspiration” interchangeably. Other datasets or articles have made a clear distinction between the two terms (Bellino et al. 2020; Xiang et al. 2020) and Allen et al. (1998) discourage the use of the term “potential evapotranspiration”. It seems paramount to clarify the definitions as early as possible in the note, to ease understanding and limit potential misuses of the dataset. Specific instances where the use of the terms can be

confusing are listed in the detailed comments below.
- Given the amount of datasets, the note is at times hard to follow, and in particular the justification of the methods used and the validation (Methods and Technical Validation section). One outline that may be recommended would be to cover successively :
  - The comparison of the historical climate databases - currently : in Technical validation, there is first a comparison of WorldClim with CLIMWAT and, then only, the comparison with CRU. All these could be addressed at once and in a systematic manner. An early diagram or Table to summarize all historical datasets and their characteristics would be helpful in that regard.
  - The choice of the evapotranspiration equation - currently : in Methods, please see minor suggestions in the comments below
  - The validation of the ESMs of CMIP6 for the future indices proposed in this work - currently : this aspect is missing and would be valuable.
- The future AI is calculated for the periods 2021-2041 and 2041-2061 that are available in the CMIP6 downscaled database of Worldclim. Could the authors comment on why they do not calculate the indices and produce the maps for the horizons 2061-2081 and 2081-2100 as well?

Detailed comments

Section « Abstract »
- The database is named three times with three different names/formatting (“Future Global Aridity Index and PET Database”, “Future_Global_AI_PET Database”, Future_Global_AI_PET Database). A more consistent naming is needed.

Section « Introduction »

§1
- « *Estimates of reference evapotranspiration (ET0) have been widely used across diverse scientific fields and practical domains* » : The reference evapotranspiration should be defined in this paragraph.
- « *with PET measurements and related indices playing a crucial role in agricultural and natural resource management* » : This sentence might apply for simulated PET as well. Please consider expanding on the word « measurements », either including simulated PET, or detailing the types of PET measurements, and why measurements specifically. Additionally, it would be helpful to give examples of or define the « related indices » the authors refer to.
- « *these metrics, along with their derived indices, assume a pivotal role* » We would suggest replacing the word « metrics » with a more specific word as it is unclear whether it is reference ET, PET measurements, or PET in general.
- « *such measurements* » : here as well we would suggest being more specific to avoid confusion, and considering whether « measurements » is what the authors mean.

§2
- Introducing a sense of the time windows and time horizons in this paragraph might be helpful to avoid misconceptions of the use of the aridity index. « current conditions » can be seen as the current day, week, month, decade or decades. Similarly, « anticipated changes » are here likely over the coming decades. When mentioning the « operational decision-making processes” as well, irrigation management, crop cultivation practices and the anticipation of drought and flood likely require different time horizons as these decisions will be taken at different frequencies and anticipation times.

§3

- "*Due to a continuing lack of high resolution downscaled CMIP6 future projection data for several climate variables needed to parameterize a full implementation of the Penman-Monteith equation, and a desire to maintain continuity to use the WorldClim datasets (reportedly the most widely used climatic datasets for environmental, biogeographical or ecological analysis (Bobrowski et al., 2021)), a similar approach and methodology as used to develop the first version of the Global-AI_PET, i.e., which relied on the Hargreaves equation for calculating PET, was applied to the CMIP6 ESM data.*" Three datasets are introduced in this sentence. If CMIP6 projection data are well introduced, WorldClim and Global-AI_PET might need references, links (provided in the following sentence for WorldClim) and indications of whether they cover the historical and/or future periods. Given the amount of information added, consider splitting the sentence in two.
- "*Using bias-corrected downscaled data (30 arc seconds resolution) provided by WorldClim.org,*" Here as well, we would suggest elaborating on the word "data", e.g. which variables, which periods.
- Here is the first occurrence in the main text of the database name "Future_Global_AI_PET". It would be suitable to remind the full database name and make it clear that this dataset is the one presented here as the name of the Data Note does not make it clear.

Section « Methods »

Sub-section « Earlier efforts and previous datasets »

- This section clearly sets the context for this new dataset, showing that all previous efforts were on historical datasets. As such, it would be preferable to place it before §3 of the introduction (related to the first comment on §3).

Sub-section « Estimating potential evapotranspiration »

- *"FAO-56 defined PET as the ET of a reference crop (ET0) under optimal conditions."* This statement seems inaccurate as Allen et al. (1998) in FAO-56 discourage the use of the term "potential evapotranspiration".
- *"independently of specific crop characteristics, crop development stages, and management practices*" : Should water availability appear in this list?
- "*As such, additional crop-specific coefficients (Kc) can be employed to derive ET estimates for specific crops (ETc), which can, in turn, be deduced from ET0*." : We would suggest rephrasing this sentence into something along the lines of "As such, additional crop-specific coefficients (Kc) and ET0 can, in turn, be employed to derive ET estimates for specific crops (ETc)."
- "*Centre Commun de Recherche of the European Economic Community*" : Consider using the English name : "European Commission's Joint Research Centre"
- "*A study of ET0 equations using lysimeter ET and synoptic climatic data by Centre Commun de Recherche of the European Economic Community (Choisnel et al., 1992) in 1992 of ET0 equations compared twelve equations using the classical Penman as the reference method (Hargreaves, 1994b).*" : Consider reformulating, for instance by removing "in 1992 of ET0 equations".
- "*For the purposes of this paper, to maintain clarity, we refer to reference evapotranspiration calculated using the Penman-Monteith as "ET0" and calculations using the Hargreaves equation as "PET*". : This notation is contradictory with the following paragraph where "five different temperature-based methods of calculating PET were tested" including Hargreaves, Penman-Monteith, and others. See also main comment on the two notations.
- "ET0 values were calculated using the more complex Penman–Monteith model" : Please specify "more complex" or ideally give the Penman-Monteith equation you use. Additionally,

check the spelling of “Penman-Monteith” as several spellings are found in the text (Penmen, Montieth). Lastly, the abbreviation “PM” is used in some instances but not systematically.

Sub-section « Hargreaves equation »

- “calculate ET0, as shown below: PET =” : This is another occurrence where the abbrevations used are confusing, especially with ET0 defined earlier as the Penman-Monteith reference evapotranspiration, and PET as the Hargreaves one.
- “The data to parametrize the equation were obtained from the WorldClim.org online data repository (Fick & Hijmans, 2017), which provides bias-corrected downscaled monthly values of minimum temperature, maximum temperature, and precipitation for 24 CMIP6 Earth System Models (ESMs), for each of four SSP: 126, 245, 370 and 585.” In the introduction, the authors mention 22 models. Which number is correct? (see also previous comment on the models not found in Worldclim).
- The reference to Wang et al. (2018) for extraterrestrial radiation is likely erroneous. Please check.
- “PET and AI were estimated for two historical periods, WorldClim 1.4 (1960–1990) and WorldClim 2.1 (1970–2000), representing on average a decades’ change, by applying the Hargreaves methodology described above.” From what we understand in the “technical validation” section, the data from Worldclim 1.4 is used to calculate PET and AI with the Hargreaves equation for the period 1960-1990, and the data from Worldclim 2.1 is used to calculate ET0 and AI with Penman-Monteith equation for the period 1970-2000. Is that correct and is the Hargreaves equation also applied on the data from Worldclim 2.1?

Sub-section « Multi-model ensembles »

- The idea of creating 3 different means is interesting. The choice of the 5 “outliers” seems clear based on Figure 3, that plots mean annual temperature against mean annual precipitation for the period 2021-2040 in the 4 SSP. However, it is not as visible for the period 2041-2060, where other models could be identified as “outliers” (Figure 4). Was the choice made primarily based on the comparison for the 2021-2040 period? Would there be another way to justify the choice of these 5 models as “high risk”?
- Level of agreement and coefficient of variation : This metric is used to compare the agreement of the models within each of the 3 multimodel means. Table 4 is only briefly commented in “Agreement was fairly high for the basic parameters of annual average temperature and annual average precipitation, somewhat less for annual averaged PET and AI, slightly increasing in the 2041–2060 time period.” It would be interesting to explain what “fairly high” means. All the CoV are under 5% (except for the aridity index). It could be worth noting that the “all” multimodel ensemble does have higher CoV than the other 2, but rather low as well. Also, it makes sense that the “consensus” and “high risk” ensembles have lower CoV because they include fewer models, at least for the period 2021-2040 for which they were chosen. In addition, there is no difference between CoV aridity index for “all” and “high risk” for the period 2041-2060, probably because the choice of these 5 “high risk” models is less relevant for this period?
- Concerning the regional differences: maybe some examples?
- Consider identifying the models constituting the High Risk and the Majority consensus ensembles on Figures 3 and 4.
- “for the each of the two time period” : replace with “for each of the two time periods”

Section « Technical validation »

- The discussion over the previously published dataset is already available in Zomer 2022**.**

This analysis is presented again, here. For the sake of clarity, consider whether it is necessary to present these results again or if simply referring to this work could be enough.

- In addition, using the CLIMWAT and CRU data to compute PM-ET0, and then comparing with the PM-ET0 from Worldclim, obviously leads to better results than using Hargreaves. We know from the start that the Hargreaves equation will be chosen, because there is not enough variables in the downscaled CMIP6 models to use the Penman-Monteith equation. The point of using the Hargreaves equation instead of Penman-Monteith has been treated in the Methods section. It is hard to understand why so many steps of technical validation are necessary to prove that it is possible to use this equation.
- The criticism on the caveats of the evapotranspiration calculation are interesting, but they apply to both Penman-Monteith and Hargreaves, and could appear immediately after the comparison of the two equations with observation data.
- The presentation of the CRU_TS dataset arrives late in the note. As mentioned previously, it would be helpful to have all datasets introduced in a section earlier in the text.
- Worldclim is validated against CLIMWAT. What is the period covered by CLIMWAT? (in Zomer 2022: “roughly” 1970-2000, but more precisely)? The CRU data is said to be averaged for the period 1970-2000. It would make sense that all databases use the same time period. In that regard, it would also make sense to compare the Aridity index calculated with Hargreaves on the Worldclim 2.1 database, instead of using the Global-AI_PET_v1, that is calculated for the period 1960-1990.
- The number of CLIMWAT weather stations changes throughout this section (from 5000 to 4242 to 3842). Please explain when presenting CLIMWAT the different subsets used and for which purpose.
- “very fairly high” : needs reformulating.
- “However, the AI estimates based on the Global-AI_PET_v1 analysis, when compared to AI estimates based on parameters provided by the CLIMWAT weather station data (Table 5; Figure 9e), showed a high level of correspondence (r2 = 0.91), statistically the same but nominally slightly higher than that from the Global-AI_PET_v3 estimates (r2 = 0.90).” Does that mean that the bias on precipitation compensates for the bias in evapotranspiration?
- “statistically the same but nominally slightly higher than” : in all fairness, if they cannot be statistically distinguished, the fact that one is higher than the other is not significant and cannot be exploited.
- “the relatively (or moderately) high accuracy (r2 = 0.72) attained by the Hargreaves implementation of the algorithm is considered sufficient for use within many modeling and other efforts”. What is the exact meaning of “is considered sufficient”? To which extent is there a choice given the available variables?
- “Results showed a moderate level of agreement (r2 = 0.67) between the ET0_CRU_TS and Hargreaves (Global_PET_v1) data, with a significantly higher level of agreement, as expected, for the Penman-Monteith (Global_ET0_v1) results.” What is the r2 for the second comparison? Also, Global_ET0_v1 has not been presented in “earlier efforts and previous datasets” and appears directly in Table 5.
- “mission critical purposes” : could you clarify what you mean by this, by reformulating or maybe giving examples?
- “the both” : remove “the”

Tables

- Table 2 : We suggest mentioning the reference in the caption. The caption currently states “between observed and predicted estimates”, but if our understanding is correct it is the

Penman-Monteith model applied to observations.
- Table 5: Check for typos (“regression”, “elevation”). This table is helpful as it recaps (almost all) datasets used here. As such, it would be helpful to show the list of datasets used in the study earlier on in the text. See also the comment on the comparison diagram.

Figures
- Better resolution in Figures may be recommended, particularly for Figures 3 and 4 which can be hard to read.
- Figure 2 : The label of the Thornthwaite method overlaps with the southern part of Africa. A reference to the previous report (https://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/pub101/RR101.pdf) may be needed.
- Figure 7 : This figure could be further commented on. For instance: Most of the “high risk’ averages are wetter than the other averages in the period 2021-2041. The “consensus” and “all” means have the same mean global aridity index, except for the SSP 585 which is much drier in the “consensus” than in “all”. It seems that there should be 6 points for each SSP, but, for instance, only 3 points correspond to SSP 585. Similarly, the white triangles for the 2041-2060 High Risk ensemble appear in the legend but do not appear in the figure.
- Figure 10 : The caption states “Hargreaves PET” but the figure labels are “ET0”.

References

1. Xiang K, Li Y, Horton R, Feng H: Similarity and difference of potential evapotranspiration and reference crop evapotranspiration – a review. *Agricultural Water Management*. 2020; **232**. Publisher Full Text
2. Bellino, J.C. Shoemaker, W.B.: Daily reference and potential evapotranspiration, and supporting meteorological data from the North American Regional Reanalysis, solar insolation data from the GOES satellite, and blue-sky albedo data from the MODIS satellite, Florida, 2019. *U.S. Geological Survey data release,*. 2020. Publisher Full Text

Is the rationale for creating the dataset(s) clearly described?

Yes

Are the protocols appropriate and is the work technically sound?

Partly

Are sufficient details of methods and materials provided to allow replication by others?

Partly

Are the datasets clearly presented in a useable and accessible format?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: For the two reviewers involved : ET modelling ; Assessment of Future Climate ; Global Hydrological Modelling

We confirm that we have read this submission and believe that we have an appropriate level

of expertise to confirm that it is of an acceptable scientific standard, however we have significant reservations, as outlined above.

Author Response 29 Jan 2025

Robert Zomer

Response to Reviewer #2 **Camille Crapart**, Institute of Environmental Geosciences - CNRS, INRAE, IRD, Grenoble-INP, Universite Grenoble Alpes, Grenoble, France
Louise Crochemore, Institute of Environmental Geosciences - CNRS, INRAE, IRD, Grenoble-INP, Université Grenoble Alpes, Grenoble, France The authors thank the reviewers for their effort in reviewing this manuscript, and their thorough and detailed comments. The authors have strived to address all the points as best we can, as we understand them, and believe it has improved the manuscript and its readability. Again we a heartened by the evalution of the reviewers that the work "seems robust".

General comments

- 22 CMIP6 models are mentioned, but only 14 can be found openly on the WorldClim projection datasets at the resolution of 30 arcsec. (https://worldclim.org/data/cmip6/cmip6_clim30s.html). ACCESS-ESM1-5; CanESM5; CanESM5-CanOE; CNRM-CM6-1, CNRM-CM6-1-HR; CNRM-ESM2-A; GISS-E2-1-G; INM-CM4-8; MIRO-ES2L,MPI-ESM1-2-LR do not seem to appear. Conversely, the model EC-Earth3-Veg is available in Worldclim, and not used in this study. It would be useful for readers who want to replicate or use the dataset, for comparison for instance, to know (a) where the missing downscaled models were obtained from, and (b) why not all available models were used.

Response: You are completely correct in that at the time of your review there were only 14 ESM on the WorldClim website. However, when we first downloaded these datasets (in 2022) there were in fact 25 ESM available online. We contacted Dr. Robert Hijmans at UC Davis, who is responsible for the WorldClim datasets, to enquire what happened to the other datasets and if there were any issues associated with them not being available that we should know about. He assured us that all the datasets were still available online and provided us with an updated link where all of the 25 datasets are archived. He also assured us that there were no issues, however he had made a selection of the higher resolution (in original processing) ESM to reduce bandwidth and load on his site. We have updated the link to the datasets in the text. As it turns out, there is a link to the page with all the datasets on the very bottom of the page we referenced. Where it says: "For some GCMs there are variations available here." Here is the updated link. We have revised this in the text. https://worldclim.org/data/cmip6_all/cmip6_clim30s.html We found spatial artifacts (visible cross-hatching across large areas of land) in the two EC-Earth3-Veg ESMs, which we deemed made them unusable, so we dropped them from the database and also from inclusion in any ensembles. This issue was already there in the original files. We have informed WorldClim regarding this issue.

- The authors seem to use the terminologies of "potential evapotranspiration" and "reference evapotranspiration" interchangeably. Other datasets or articles have made a clear distinction between the two terms (Bellino et al. 2020; Xiang et al. 2020) and Allen et al. (1998) discourage the use of the term "potential evapotranspiration". It seems paramount to clarify the definitions as early as possible in the note, to ease

understanding and limit potential misuses of the dataset. Specific instances where the use of the terms can be confusing are listed in the detailed comments below.

Response: We have gone through the paper and now all references to Penman-Monteith Reference ET is referred to as "ET_0", and all references to other methods, primarily Hargreaves as implemented in this paper, are referred to as "PET

- Given the amount of datasets, the note is at times hard to follow, and in particular the justification of the methods used and the validation (Methods and Technical Validation section). One outline that may be recommended would be to cover successively :
  - The comparison of the historical climate databases - currently : in Technical validation, there is first a comparison of WorldClim with CLIMWAT and, then only, the comparison with CRU. All these could be addressed at once and in a systematic manner. An early diagram or Table to summarize all historical datasets and their characteristics would be helpful in that regard.

Response: We have slightly revised the order, and left most of the comparison in the Technical Validation section, since this is the purpose of presenting this particular data. Table 1 summarizes all historical and other datasets together at once, as suggested.

- - The choice of the evapotranspiration equation - currently : in Methods, please see minor suggestions in the comments below

Response: We have responded to these below:

- - The validation of the ESMs of CMIP6 for the future indices proposed in this work - currently : this aspect is missing and would be valuable.

Response: We agree that a more rigorous evaluation of the ESM's themselves would be valuable. beyond the historical comparisons and measures of uncertainty (ensemble coefficients of variability) we provide. However, as we provide a full complement of ESMs (n = 22), and there is significant regional differentiation and a range of scale and thematic applicability amongst the ESM, we provide this as a global public good and leave the choice of which model and how to use it up to the user. There is a large body of literature available on this topic to provide guidance.

- The future AI is calculated for the periods 2021-2041 and 2041-2061 that are available in the CMIP6 downscaled database of Worldclim. Could the authors comment on why they do not calculate the indices and produce the maps for the horizons 2061-2081 and 2081-2100 as well?

Response: Two considerations went into our decision to limit our analyzes to the two time periods 2021-2041 and 2041-2061: First, computing constraints and data storage capacity. The current work represents nearly a year, or more of processing time already. And second, ESM uncertainty increases as the time period is extended into the future, making the results less operationally useful or practical for policy purposes.

Detailed comments

Section « Abstract »

- The database is named three times with three different names/formatting ("Future Global Aridity Index and PET Database", "Future_Global_AI_PET Database", Future_Global_AI_PET Database). A more consistent naming is needed.

Response: All instances in the manuscript are now revised to: Future_Global_AI_PET Database

Section « Introduction »
§1

- « *Estimates of reference evapotranspiration (ET0) have been widely used across diverse scientific fields and practical domains* » : The reference evapotranspiration should be defined in this paragraph.

Response: We have added the following sentence to the paragraph. Reference ET is more specifically defined in the Methods section: "While potential evapotranspiration (PET) reflects maximum possible water loss across varied vegetation types, useful in broader ecosystem and hydrological studies, reference evapotranspiration (ET_0) estimates the maximum possible water loss from a well-watered reference crop, and as such, is particularly useful for agriculture and irrigation management.."

- « *with PET measurements and related indices playing a crucial role in agricultural and natural resource management* » : This sentence might apply for simulated PET as well. Please consider expanding on the word « measurements », either including simulated PET, or detailing the types of PET measurements, and why measurements specifically. Additionally, it would be helpful to give examples of or define the « related indices » the authors refer to.

Response: We have changed the following sentences: "Estimates of reference evapotranspiration (ET_0) have been widely used across diverse scientific fields and practical domains (Hargreaves, 1994a; Zomer *et al.*, 2022), with PET and various indices, playing a crucial role in agricultural and natural resource management" "As an example, indices relying on PET estimates include the Standardized Precipitation Evapotranspiration Index (SPEI), Palmer Drought Severity Index (PDSI), Crop Water Stress Index (CWSI), Water Deficit Index (WDI), Evaporative Stress Index (ESI), and the Aridity Index (AI), Indices like the SPEI, AI, PDSI, CWSI, WDI, and ESI incorporate PET to understand water availability, climate impacts, and drought."

- « *these metrics, along with their derived indices, assume a pivotal role* » We would suggest replacing the word « metrics » with a more specific word as it is unclear whether it is reference ET, PET measurements, or PET in general.

Response: Actually, the intention is to not be specific, but refer to PET estimates as a class in general (that is, as we see it ET_0 is a subset of PET, so when we refer to PET, it can be inclusive of ET_0). We have changed the sentence to: "In an era of rapid environmental and climatic transformations, PET estimates, along with their related indices, assume a pivotal role as direct and critical reference measures.

- « *such measurements* » : here as well we would suggest being more specific to avoid confusion, and considering whether « measurements » is what the authors mean.

Response: Changed to "estimates" .

§2

- Introducing a sense of the time windows and time horizons in this paragraph might be helpful to avoid misconceptions of the use of the aridity index. « current conditions » can be seen as the current day, week, month, decade or decades. Similarly, « anticipated changes » are here likely over the coming decades. When mentioning the « operational decision-making processes" as well, irrigation management, crop cultivation practices and the anticipation of drought and flood likely require different time horizons as these decisions will be taken at different

frequencies and anticipation times.

Response: To facilitate understanding of time horizons we have changed the sentence to: "The AI serves as proxy for a comprehensive evaluation of a set of hydro-climatological and hydro-ecological variables to determine historical, recent conditions and projected changes in hydrological cycles at specified future times and time scales." §3

- "*Due to a continuing lack of high resolution downscaled CMIP6 future projection data for several climate variables needed to parameterize a full implementation of the Penman-Monteith equation, and a desire to maintain continuity to use the WorldClim datasets (reportedly the most widely used climatic datasets for environmental, biogeographical or ecological analysis (Bobrowski et al., 2021)), a similar approach and methodology as used to develop the first version of the Global-AI_PET, i.e., which relied on the Hargreaves equation for calculating PET, was applied to the CMIP6 ESM data.*" Three datasets are introduced in this sentence. If CMIP6 projection data are well introduced, WorldClim and Global-AI_PET might need references, links (provided in the following sentence for WorldClim) and indications of whether they cover the historical and/or future periods. Given the amount of information added, consider splitting the sentence in two.

Response: We have revised the sentence as per below: "A set of future projections of global PET and AI (Figure 1) were produced to construct the Global-Future_AI_PET Database (Zomer and Trabucco, 2024), based on 22 Coupled Inter-Comparison Modeling Project – Phase 6 (CMIP6: (Eyring et al., 2016)) Earth System Models (ESM). Due to a continuing lack of high resolution downscaled CMIP6 future projection data for several climate variables needed to parameterize a full implementation of the Penman-Monteith equation, and a desire to maintain continuity with the previously used WorldClim (Fick and Hijmans, 2017) datasets (reportedly among the most widely used climatic datasets for environmental, biogeographical or ecological analysis (Bobrowski *et al.*, 2021)), Hargreaves equation for calculating PET, was applied to the CMIP6 ESM data. This maintains a similar approach and methodology as used to develop the Global-AI_PET Database v1 (Trabucco and Zomer, 2008).

- "*Using bias-corrected downscaled data (30 arc seconds resolution) provided by WorldClim.org,*" Here as well, we would suggest elaborating on the word "data", e.g. which variables, which periods.

Response: We have revised the sentence as per below: This maintains a similar approach and methodology as used to develop the Global-AI_PET Database v1 (Trabucco and Zomer, 2008). Using bias-corrected downscaled climatic parameters (i.e., minimum / maximum temperature, and precipitation), derived from interpolation of weather station data (30 arc seconds resolution), and provided by WorldClim.org, each ESM model projection was evaluated across four emission scenarios, or *Shared Socio-Economic Pathways* (SSP 126; 245; 370; 585).

- Here is the first occurrence in the main text of the database name "Future_Global_AI_PET". It would be suitable to remind the full database name and make it clear that this dataset is the one presented here as the name of the Data Note does not make it clear.

Response: Revised to: "The Future_Global_AI_PET Database (Zomer & Trabucco, 2024) described in this paper is archived and available online from the Science Data Bank (ScienceDB) at: https://doi.org/10.57760/sciencedb.nbsdc.00086."

Section « Methods »

Sub-section « Earlier efforts and previous datasets »

- This section clearly sets the context for this new dataset, showing that all previous efforts were on historical datasets. As such, it would be preferable to place it before §3 of the introduction (related to the first comment on §3).

Response: As suggested, we have moved this paragraph and placed it before §3.

Sub-section « Estimating potential evapotranspiration »

- *"FAO-56 defined PET as the ET of a reference crop (ET0) under optimal conditions."* This statement seems inaccurate as Allen et al. (1998) in FAO-56 discourage the use of the term "potential evapotranspiration".

Response: We have replaced this sentence with the following: "FAO-56 defines and provide guidance on calculating reference evapotranspiration (ET_0), that is, the evapotranspiration (ET) of a reference crop, rather than defining potential evapotranspiration (PET) directly. FAO-56 presents a standard method to estimate ET_0, which is widely accepted as a reference standard, and often closely related to PET in practice. In FAO-56, the ET_0 is calculated using the Penman-Monteith equation, which takes into account factors like temperature, relative humidity, wind speed, and solar radiation. While ET_0 is a measure of the evapotranspiration rate from a reference crop under optimal conditions, PET generally represents the water demand of vegetation if water is freely available. Though not synonymous, ET_0 from FAO-56 is widely used as an estimate for PET, particularly in agricultural and environmental applications."

- *"independently of specific crop characteristics, crop development stages, and management practices*" : Should water availability appear in this list?

Response: Changed to: "independent of specific crop characteristics, crop development stages, management practices, or water availability"

- "*As such, additional crop-specific coefficients (Kc) can be employed to derive ET estimates for specific crops (ETc), which can, in turn, be deduced from ET0*." : We would suggest rephrasing this sentence into something along the lines of "As such, additional crop-specific coefficients (Kc) and ET0 can, in turn, be employed to derive ET estimates for specific crops (ETc)."

Response: Changed to: "As such, additional crop-specific coefficients (Kc) and ET_0 can, in turn, be employed to derive ET estimates for specific crops (ETc)."

- "*Centre Commun de Recherche of the European Economic Community*" : Consider using the English name : "European Commission's Joint Research Centre"

Response: Changed to: "European Commission's Joint Research Centre"

- "*A study of ET0 equations using lysimeter ET and synoptic climatic data by Centre Commun de Recherche of the European Economic Community (Choisnel et al., 1992) in 1992 of ET0 equations compared twelve equations using the classical Penman as the reference method (Hargreaves, 1994b)*." : Consider reformulating, for instance by removing "in 1992 of ET0 equations".

Response: Changed to: "A study of ET_0 equations using lysimeter ET and synoptic climatic data by European Commission's Joint Research Centre (Choisnel *et al.*, 1992) compared twelve equations using Penman-Monteith (Allen et al., 1998)as the reference standard."

- "*For the purposes of this paper, to maintain clarity, we refer to reference evapotranspiration calculated using the Penman-Monteith as "ET0" and calculations using*

the Hargreaves equation as "PET". : This notation is contradictory with the following paragraph where "five different temperature-based methods of calculating PET were tested" including Hargreaves, Penman-Monteith, and others. See also main comment on the two notations.

Response: Now change to: "four different temperature-based methods of calculating PET were compared with the Penman-Montieth method for calculating ET_0, and tested to determine which equation"

- "ET0 values were calculated using the more complex Penman–Monteith model" : Please specify "more complex" or ideally give the Penman-Monteith equation you use. Additionally, check the spelling of "Penman-Monteith" as several spellings are found in the text (Penmen, Montieth). Lastly, the abbreviation "PM" is used in some instances but not systematically.

Response: Penman-Monteith equation is now given in the paper.

Sub-section « Hargreaves equation »

- "calculate ET0, as shown below: PET =" : This is another occurrence where the abbrevations used are confusing, especially with ET0 defined earlier as the Penman-Monteith reference evapotranspiration, and PET as the Hargreaves one.

Response: This was a mistake.. Changed to: "to calculate PET, as shown below:"

- "The data to parametrize the equation were obtained from the WorldClim.org online data repository (Fick & Hijmans, 2017), which provides bias-corrected downscaled monthly values of minimum temperature, maximum temperature, and precipitation for 24 CMIP6 Earth System Models (ESMs), for each of four SSP: 126, 245, 370 and 585." In the introduction, the authors mention 22 models. Which number is correct? (see also previous comment on the models not found in Worldclim).

Response: Corrected to: 22

- The reference to Wang et al. (2018) for extraterrestrial radiation is likely erroneous. Please check.

Response: No… not erroneous. This paper has an extensive discussion of extraterrestrial radiation.

- "PET and AI were estimated for two historical periods, WorldClim 1.4 (1960–1990) and WorldClim 2.1 (1970–2000), representing on average a decades' change, by applying the Hargreaves methodology described above." From what we understand in the "technical validation" section, the data from Worldclim 1.4 is used to calculate PET and AI with the Hargreaves equation for the period 1960-1990, and the data from Worldclim 2.1 is used to calculate ET0 and AI with Penman-Monteith equation for the period 1970-2000. Is that correct and is the Hargreaves equation also applied on the data from Worldclim 2.1?

Response: We calculate PET and AI using the Hargreaves equation for both WorldClim 1.4 (1960-1990) and WorldClim 2.1 (1970-2000). Both these datasets are included in the database under Historical Datasets. In addition, WorldClim 2.1 was used to calculate ET0 and AI with Penman-Monteith, as described in an earlier paper, but this is not included in the Future_Global_AI_PET Database. We refer to it only for comparative purposes.

Sub-section « Multi-model ensembles »

- The idea of creating 3 different means is interesting. The choice of the 5 "outliers" seems clear based on Figure 3, that plots mean annual temperature against mean

annual precipitation for the period 2021-2040 in the 4 SSP. However, it is not as visible for the period 2041-2060, where other models could be identified as “outliers” (Figure 4). Was the choice made primarily based on the comparison for the 2021-2040 period? Would there be another way to justify the choice of these 5 models as “high risk”?

Response: The reviewers point out an important observation regarding the selection of the 5 high risk models. These were selected primarily based on the comparison for the 2021-2040 period, with some consideration of the 2041-2060 period. However, choosing different set of models for different periods could also highlight some inconsistencies across the trends over the future time periods. We recognized the shortcomings of making optimal choice. However, we provide these only as examples, but the database contains all 22 models, allowing users to construct their own ensemble combinations.

- Level of agreement and coefficient of variation : This metric is used to compare the agreement of the models within each of the 3 multimodel means. Table 4 is only briefly commented in “Agreement was fairly high for the basic parameters of annual average temperature and annual average precipitation, somewhat less for annual averaged PET and AI, slightly increasing in the 2041–2060 time period.” It would be interesting to explain what “fairly high” means. All the CoV are under 5% (except for the aridity index). It could be worth noting that the “all” multimodel ensemble does have higher CoV than the other 2, but rather low as well. Also, it makes sense that the “consensus” and “high risk” ensembles have lower CoV because they include fewer models, at least for the period 2021-2040 for which they were chosen. In addition, there is no difference between CoV aridity index for “all” and “high risk” for the period 2041-2060, probably because the choice of these 5 “high risk” models is less relevant for this period?

Response: Change sentence to: “Agreement was fairly high for the basic parameters of annual average temperature and annual average precipitation with all values below 5%, indicating very low variability relative to the mean, suggesting strong consistency or agreement. Somewhat less for annual averaged PET and AI, which is slightly increased in the 2041–2060 time period.” We are not entirely sure why there is no difference in the 2041-2060 period, but we don’t think it is because the selected 5 are less relevant.

- Concerning the regional differences: maybe some examples?

Response: Since this is a data note, and not a research article, we really prefer not to present too many results, other than as required for the user of the dataset. Even though we have indeed done all this analysis, we leave this to the user to explore. There really is just too much of it to present, and CoV is not arguably that prominent an issue.

- Consider identifying the models constituting the High Risk and the Majority consensus ensembles on Figures 3 and 4.

Response: Yes, we have considered this, but difficult to differentiate as is with the number of overlapping models.

- “for the each of the two time period” : replace with “for each of the two time periods”

Response: Done.

Section « Technical validation »

- The discussion over the previously published dataset is already available in Zomer 2022.This analysis is presented again, here. For the sake of clarity, consider whether it

is necessary to present these results again or if simply referring to this work could be enough.

Response: It is the authors opinion that for the sake of clarity it is still valuable to have this discussion here, as we are referring to a dataset that is used as a comparison in the technical validation.

- In addition, using the CLIMWAT and CRU data to compute PM-ET0, and then comparing with the PM-ET0 from Worldclim, obviously leads to better results than using Hargreaves. We know from the start that the Hargreaves equation will be chosen, because there is not enough variables in the downscaled CMIP6 models to use the Penman-Monteith equation. The point of using the Hargreaves equation instead of Penman-Monteith has been treated in the Methods section. It is hard to understand why so many steps of technical validation are necessary to prove that it is possible to use this equation.

Response: Yes, thank you for your advice and support on this. We agree with your assessment. However, due to skepticism by a previous reviewer of the Hargreaves methodology, we added discussion on this topic for those that are skeptical or unaware of its wide use and utility. However, we agree that this is redundant and muddled the text with too many datasets and regressions. We have streamlined this now, taken out much of the ancillary data on the datasets (elev, temp, etc..) and revised Table 5 and both Figure 9 and 10.

- The criticism on the caveats of the evapotranspiration calculation are interesting, but they apply to both Penman-Monteith and Hargreaves, and could appear immediately after the comparison of the two equations with observation data.

Response: The authors agree that this discussion is more relevant to the Technical Validation section.

- The presentation of the CRU_TS dataset arrives late in the note. As mentioned previously, it would be helpful to have all datasets introduced in a section earlier in the text.

Response: The CRU_TS dataset is only used in the technical validation section, as such we introduce it here. Basically, we introduce the datasets used for comparison in sequence, corresponding to their relative figures.

- Worldclim is validated against CLIMWAT. What is the period covered by CLIMWAT? (in Zomer 2022: “roughly” 1970-2000, but more precisely)? The CRU data is said to be averaged for the period 1970-2000. It would make sense that all databases use the same time period. In that regard, it would also make sense to compare the Aridity index calculated with Hargreaves on the Worldclim 2.1 database, instead of using the Global-AI_PET_v1, that is calculated for the period 1960-1990.

Response: We have now emphasized the 1970-2000 dataset for comparison and cover roughly the same period as the CLIMWAT and the CRU_TS, i.e. 1970-2000. We continue to include the WC_1.4 data (1960-1990), since this is both included in the Future Global-AI_PET Database and because it has previously been downloaded and used many thousands of times, as a reference to those users. In regards the “roughly” 1970-2000 time period, from the CLIMWAT website: In compiling the data, an effort was made to cover the period 1971 - 2000, but when data for this period were not available, any recent series that ends after 1975 and that has at least 15 years of data have been included. Some of the series are "broken", but they nevertheless have at least 15 years of data (e.g. 1961-70 and 1992-2000).” So… “roughly” 1970-2000.

- The number of CLIMWAT weather stations changes throughout this section (from 5000 to 4242 to 3842). Please explain when presenting CLIMWAT the different subsets used and for which purpose.

Response: There are 5000 stations reported in the full CLIMWAT dataset. We were able to locate and use 4242 stations for the spreadsheet analysis (some stations didn't seem to correspond to the ancillary data, e.g. the DEM). When we extracted the values from the geospatial datasets, there were various no_data values or other anomalies that we excluded. We then created a subset of available data points common among all datasets, which came out to 3842 stations.

- "very fairly high" : needs reformulating.

Response: Changed to "fairly high"

- "However, the AI estimates based on the Global-AI_PET_v1 analysis, when compared to AI estimates based on parameters provided by the CLIMWAT weather station data (Table 5; Figure 9e), showed a high level of correspondence (r2 = 0.91), statistically the same but nominally slightly higher than that from the Global-AI_PET_v3 estimates (r2 = 0.90)." Does that mean that the bias on precipitation compensates for the bias in evapotranspiration?

Response: This could perhaps be the case, however, we don't really speculate on this, as again, this is a data note primarily intended to describe the data, and not really interpret results. But short answer, we are not really sure if this is the case, or not.

- "statistically the same but nominally slightly higher than" : in all fairness, if they cannot be statistically distinguished, the fact that one is higher than the other is not significant and cannot be exploited.

Response: Changed to: "statistically the same as that from"

- "the relatively (or moderately) high accuracy (r2 = 0.72) attained by the Hargreaves implementation of the algorithm is considered sufficient for use within many modeling and other efforts". What is the exact meaning of "is considered sufficient"? To which extent is there a choice given the available variables?

Response: We have change this sentence to: "... maybe considered sufficient for use within many modeling and other efforts, however, with caveats in light of the variability associated with both the input data and accuracy of the estimation algorithm when applied globally.

- "Results showed a moderate level of agreement (r2 = 0.67) between the ET0_CRU_TS and Hargreaves (Global_PET_v1) data, with a significantly higher level of agreement, as expected, for the Penman-Monteith (Global_ET0_v1) results." What is the r2 for the second comparison? Also, Global_ET0_v1 has not been presented in "earlier efforts and previous datasets" and appears directly in Table 5.

Response: This sentence has been revised to report 1970-2000 results: "Results showed a moderate level of agreement (r^2 = 0.68) between the ET_0_CRU_TS and Hargreaves (PET_WC_2.1) data, with a significantly higher level of agreement, as expected, for the Penman-Monteith(Global_ET_0_v3: r^2 = 0.89) results."

- "mission critical purposes" : could you clarify what you mean by this, by reformulating or maybe giving examples?

Response: Removed "mission critical purposes".

- "the both" : remove "the"

Tables

- Table 2 : We suggest mentioning the reference in the caption. The caption currently

states “between observed and predicted estimates”, but if our understanding is correct it is the Penman-Monteith model applied to observations.

Response: We have changed this to: “Results of the comparison are given as the mean difference (Mean Diff) between Penman_Monteith estimates based on observed weather station data and predicted estimates using the various different methods, and their standard deviations (Std Dev). Source: (Trabucco *et al.*, 2008).”

- Table 5: Check for typos (“regression”, “elevation”). This table is helpful as it recaps (almost all) datasets used here. As such, it would be helpful to show the list of datasets used in the study earlier on in the text. See also the comment on the comparison diagram.

Response: Thanks… corrections made. **Figures**

- Better resolution in Figures may be recommended, particularly for Figures 3 and 4 which can be hard to read.

Response: We have attempted to improve the figures 3 and 4, there are still some issues with overlap that can’t be helped. We believe that the overall pattern of the distribution is well presented however.

- Figure 2 : The label of the Thornthwaite method overlaps with the southern part of Africa. A reference to the previous report (https://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/pub101/RR101.pdf) may be needed.

Response: Sorry about the label… unfortunately, we just can’t seem to go back to find the original graphic files to fix that. Reference was given in the text, now added to caption.

- Figure 7 : This figure could be further commented on. For instance: Most of the “high risk’ averages are wetter than the other averages in the period 2021-2041. The “consensus” and “all” means have the same mean global aridity index, except for the SSP 585 which is much drier in the “consensus” than in “all”. It seems that there should be 6 points for each SSP, but, for instance, only 3 points correspond to SSP 585. Similarly, the white triangles for the 2041-2060 High Risk ensemble appear in the legend but do not appear in the figure.

Response: There’s a paper that could be written on this figure, as it represents the main findings if one were to be analyzing the dataset. However, this is a “Data Note”, and not a research paper, as such, we present this as an overview of the distribution of the results for the user of the database, and do not attempt to interpret these results here.

- Figure 10 : The caption states “Hargreaves PET” but the figure labels are “ET0”.

Response: Labeled revised to: “Validation and comparison of various results with the CRU_TS dataset.”

Competing Interests: No competing interests were disclosed.

Reviewer Report 05 August 2024

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The authors provided new high-resolution (30 arc-seconds) global raster datasets of average monthly and annual potential evapotransipation (PET) and aridity index (AI) for two historical (1960-1990; 1970-2000) and two future (2021-2040; 2041-2060) time periods for each of 22 CMIP6 Earth System Models across four emission scenarios (SSP: 126, 245, 370, 585). The database also includes three averaged multi-model ensembles produced for each of the four emission scenarios.

The work is robust. Some minor comments are the following:
1. The regressions in Fig.9 and 10 are based on y=ax instead of y=ax+b. The R2 of the two regression lines are different with the first one providing artificially higher R2. The calculation of R2 for a linear regression with intercept forced to 0 is theoretically problematic and should be avoided (Eisenhauer, 2003). Another reason for not using linear regression with 0 intercept in 1:1 plots is that the regression line neglects information associated to the performance of a model in the low values.
2. For the PET methods description, you give only the equations of Hargreaves but not the equations of the other four methods used in this study.
3. Just for your consideration, there are newer modifications of Hargreaves and Thornthwaite methods based on ASCE Penman-Monteith method. For the original Hargreaves method, the study of Aschonitis et al. (2017) provided global maps of correction coefficients (substituting the 0.023) and for the original thornthwaite method respective correction coefficients are given in Aschonitis et al. (2022). Both datasets are stored in Pangae database in various resolutions including the ~1 km.

Eisenhauer J, 2003 (Ref 1)
Aschonitis V, et al. 2017 (Ref 2)
Aschonitis V, et al. 2022 (Ref 3)

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2. Aschonitis V, Papamichail D, Demertzi K, Colombani N, et al.: High-resolution global grids of revised Priestley–Taylor and Hargreaves–Samani coefficients for assessing ASCE-standardized reference crop evapotranspiration and solar radiation. *Earth System Science Data*. 2017; **9** (2): 615-638 Publisher Full Text
3. Aschonitis V, Touloumidis D, ten Veldhuis M, Coenders-Gerrits M: Correcting Thornthwaite potential evapotranspiration using a global grid of local coefficients to support temperature-based estimations of reference evapotranspiration and aridity indices. *Earth System Science Data*. 2022; **14**

(1): 163-177 Publisher Full Text

Is the rationale for creating the dataset(s) clearly described?
Yes

Are the protocols appropriate and is the work technically sound?
Yes

Are sufficient details of methods and materials provided to allow replication by others?
Yes

Are the datasets clearly presented in a useable and accessible format?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Hydrology, Hydroclimatology, Soil Science, Environmental Modelling

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 29 Jan 2025

Robert Zomer

Response to Reviewer #1 Vassilis Aschonitis, Hellenic Agricultural Organization, Soil and Water Resources Institute, Thessaloniki, Greece The authors express their gratitude to the reviewer for his thoughtful and positive comments, and particularly his evaluation that the work is robust. See below for specific responses to the comments:

1. "The regressions in Fig.9 and 10 are based on y=ax instead of y=ax+b. The R2 of the two regression lines are different with the first one providing artificially higher R2. The calculation of R2 for a linear regression with intercept forced to 0 is theoretically problematic and should be avoided (Eisenhauer, 2003). Another reason for not using linear regression with 0 intercept in 1:1 plots is that the regression line neglects information associated to the performance of a model in the low values."

We do understand the point raised by the reviewer. We had also different feedbacks asking regression line with the intercept forced to 0, because of earlier reviews we received on our previous paper using the Penman-Montieth method submitted to Scientific Data. While setting regression with 0 intercept may provide limited model evaluation at low value, as the reviewer rightly suggest, on the other side it integrates the systematic modelling biases under/overestimate from low to high values range also in the performance evaluation. To balance out, we have set regression lines forced to 0 to provide the more stringent and conservative option comparing observed vs simulated values. Keeping this in consideration, we did not report the r^2 for trend lines in Fig. 9 and 10 (actually, there is one, but this is an oversight) as it seems inappropriate and misleading However, the r^2 values reported in the text and tables are from the regression analysis, and not from the forced regression lines.

As per your guidance, we have now redone Figures 9 and 10. The trend line no longer is forced through zero, and we have added the r^2 to all the graphs in Figures 9 and 10.

1. For the PET methods description, you give only the equations of Hargreaves but not the equations of the other four methods used in this study.

We have now added these to the paper.

1. Just for your consideration, there are newer modifications of Hargreaves and Thornthwaite methods based on ASCE Penman-Monteith method. For the original Hargreaves method, the study of Aschonitis et al. (2017) provided global maps of correction coefficients (substituting the 0.023) and for the original thornthwaite method respective correction coefficients are given in Aschonitis et al. (2022). Both datasets are stored in Pangae database in various resolutions including the ~1 km.

The global database of local correction coefficients (substituting the 0.023) is indeed an extremely valuable database to close the gap between PM reference methods and simpler temperature-based methods. The correction coefficients mentioned by the reviewer were produced based on partial weighted average of monthly ratios of alternative ET0 methods compared to the reference PM method. It provides a spatial distribution of correction coefficients based on global gridded data of the period 1950-2000. Aschonitis et al. (2017) have shown that there are not serious deviation of such correction coefficients between 1950-2000 and 2000-2020 period, but as we assume this study under climate change, we can not assume that the same climate dependent ET ratios (and thereafter the correction coefficient) held steady at same location in the far future (up to 2060). This would imply at any site not basic changes in the correlation between temperature (used in Hargreaves equations) with others variables (RH, Wind Speed, solar radiation) additionally used in the PM equation, to maintain relative divergence between Hargreaves and Penman-Monteith values steady (and in turn correction coefficients) from historical to future conditions. Valuable effort to improve use of correction coefficient for future climate conditions, could possibly define correction factors that would be climate explicit (possibly in relation to temperature regimes), rather than just spatially explicit. To acknowledge the value of corrected parameters to improve reliability of Hargreaves equation, we have added the following in technical validation section: *"Among other factors, the significant and specific influence of relative humidity and wind speed lead to particular deviations of results across broad climate regions between Hargreaves and Penman-Monteith model results (Allen et al., 1998). This uncertainty has led to several successful attempts (Tegos et al. 2017, Aschonitis et al. 2017) to provide calibration and correction factors map for Hargreaves estimates, based on parametric regression between Hargreaves PET and PM ET0 monthly values for historical condition, that can close the gap between results from Hargreaves and PM methods. While recognizing the value of such efforts, expansion on the use of these parametric corrections have still been quite limited on future projections, This would require at any site not basic changes in correlation between temperature (used in Hargreaves equations) with the others variables (RH, Wind Speed, solar radiation) additionally used in the PM equation, to maintain relative divergence between Hargreaves and Penman-Monteith values steady (and in turn correction coefficients) from historical to future conditions."* **References**

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Competing Interests: No competing interests were disclosed.