Global Aridity Index and Potential Evapo-Transpiration (ET0) Climate Database v2

Antonio Trabucco [1, 2], Robert J. Zomer [3, 4],

1. *Euro-Mediterranean Center on Climate Change, IAFES Division, Sassari, Italy.*
2. *Department of Science for Nature and Environmental Resources (DIPNET), University of Sassari, Via De Nicola 9, 07100 Sassari, Italy*
3. *Key Laboratory for Plant Diversity and Biogeography of East Asia (KLPB), Kunming Institute of Botany, Chinese Academy of Science, Kunming 650201, Yunnan, China*
4. *Centre for Mountain Ecosystem Studies, World Agroforestry Center (ICRAF), East and Central Asia Region, Kunming 650201, China*

The **Global Aridity Index (*Global*-Aridity_ET0) and Global Reference Evapo-Transpiration (*Global-ET0*)** datasets provide high-resolution (30 arc-seconds) global raster climate data for the 1970-2000 period, related to evapo-transpiration processes and rainfall deficit for potential vegetative growth, based upon implementation of a Penman Montieth Reference Evapo-transpiration (ET0) equation.

These geo-spatial datasets have been produced by **Antonio Trabucco and Robert Zomer**, with the support of the CGIAR-CSI (funding from IFPRI Project No. 203008.000.002 515-01-01). These datasets have been downloaded and are available from the CGIAR-CSI GeoPortal (https://cgiarcsi.community). The **Consortium for Spatial Information (CGIAR-CSI)** is an initiative of the Consultative Group for International Agriculture Research (CGIAR), linking the international science, research and development communities, with CGIAR scientists, national and international partners, and others working to apply and advance geospatial science for sustainable development, conservation, and poverty alleviation in developing countries.

Comments, feedback, suggestions or bug reports regarding downloading of the Global-ET0 and Global-Aridity datasets should be sent to: csi@cgiar.org. Technical questions regarding the Global-ET0 and Global-Aridity_ET0 datasets can be directed to Antonio Trabucco: antoniotrabucco@cmcc.it .

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Methodology and Dataset Description

Global Reference Evapo-Transpiration (*Global-ET0*)

Potential Evapo-Transpiration (*PET*) is a measure of the ability of the atmosphere to remove water through Evapo-Transpiration (*ET)* processes. Among several equations to estimate PET, a FAO application of the Penman-Monteith equation (Allen et al. 1998), here referred as FAO-PM, is currently widely considered as a standard method (Walter et al. 2000). The FAO introduced the definition of *PET* as the *ET* of a reference crop (ET0) under optimal conditions, having the characteristics of well-watered grass with an assumed height of 12 centimeters, a fixed surface resistance of 70 seconds per meter and an albedo of 0.23 (Allen et al. 1998). The FAO-PM is a predominately physically based approach, which can be used globally because it does not require estimations of additional site-specific parameters. However, a major drawback of the FAO-PM method is its relatively high need for specific data for a variety of parameters (i.e. windspeed, relative humidity, solar radiation, etc.).

Just recently, a new version of the Worldclim dataset (WorldClim 2.0) has been released (Fick and Hijmans, 2017). In addition to being updated with improved data and analysis, it includes now several climate variables, such as temperature (average, minimum and maximum), precipitation, solar radiation, wind speed and water vapor pressure, which are sufficient to effectively parameterize the FAO-PM equation to estimate evapo-transpiration. The WorldClim 2.0 is an updated high-resolution global geo-database (30 arc seconds or ~ 1km at equator) of monthly average data (1970-2000), based on spatial interpolation using thin-plate splines of a high number of climate station observations, with covariates including elevation, distance to the coast and other satellite data.

From the original Penman-Monteith equation, given the specific properties of the reference crop, the FAO Penman-Monteith method (FAO-PM) to estimate ET0 can be calculated as:

$$ET0 = \frac{0.408 * \Delta * (R_n - G) + \gamma \frac{900}{T_{avg} + 273} * u_2 * (e_s - e_a)}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)}$$

Where

ET0 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}

T_{avg} is the mean daily air temperature at 2 m height, as °C

u_2 is the wind speed at 2 m height, as m s^{-1}

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}

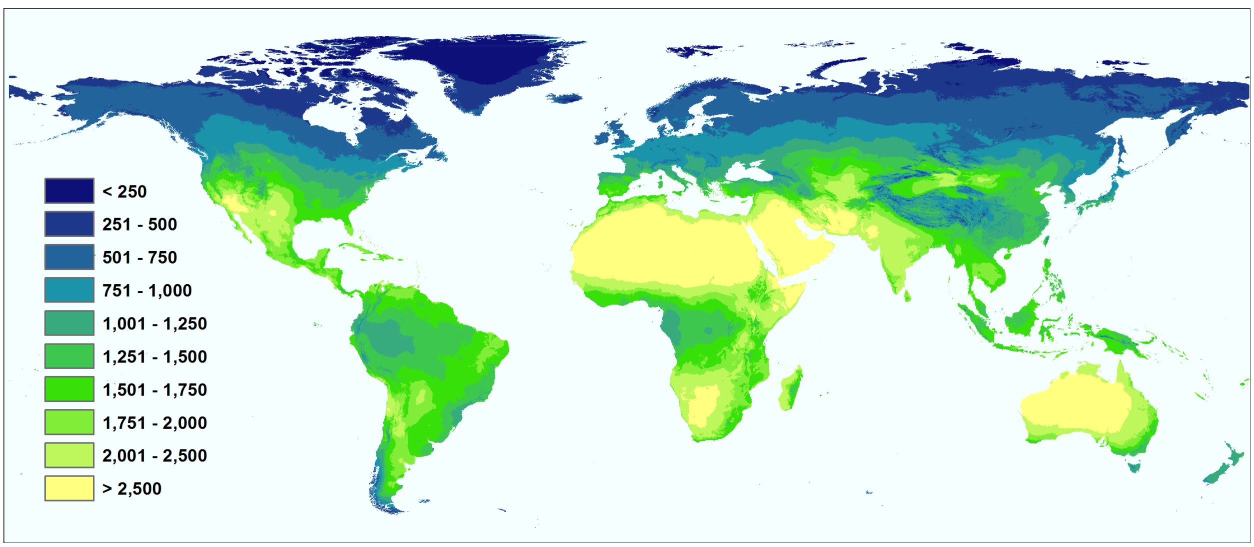
γ is the psychrometric constant, as kPa °C^{-1}

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

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

The variables available from the Worlclim2 dataset (Minimum, Maximum and Average Temperature; Solar Radiation; Wind Speed, Water Vapor Pressure) allow to calculate any specific parameter needed for the FAO-PM method. See Annex I for a detailed description of the methods used to derive these parameters using the WorldClim2 variables.

Figure 1. Global Evapo-Transpiration of reference crop (ET0) calculated for the entire globe.



Global Aridity Index_ET0 (*Global-AI_ET0*)

Aridity is usually expressed as a generalized function of precipitation, temperature and reference evapo-transpiration (*ET0)*. An Aridity Index (UNEP, 1997) can be used to quantify precipitation availability over atmospheric water demand.

Global mapping of mean Aridity-Wetness Index from the 1970-2000 period at 30' spatial resolution is calculated as:

$$\text{Global-Aridity\_ET0 } (AI\_ET0) = MA\text{-}Pr \,/\, MA\text{-}ET0 \qquad [1]$$

where:

MA-Pr = Mean Annual Precipitation

MA-ET0 = Mean Annual Reference Evapo-Transpiration

Mean annual precipitation (MA-Pr) values were obtained from the WorldClim2 Global Climate Data (Fick and Hijmans, 2017), for years 1970-2000, while ET0 layers estimated on a monthly average basis by the Global-ET0 (i.e. modeled using the PM-FAO method, as described above) were aggregated to mean annual values (MA-ET0).

The ***Global-Aridity_ET0*** surface (Figure 2) shows moisture availability for potential growth of reference vegetation excluding the impact of soil mediating water runoff events. UNEP (UNEP 1997) breaks up Aridity Index, in the traditional classification scheme presented in Table 2.

Note: In the ***Global-Aridity_ET0*** dataset, which uses this formulation, Aridity Index values increase for more humid conditions, and decrease with more arid conditions.

Figure 2. Global Aridity Index_ET0 (*Global-AI_ET0)* calculated for the entire globe. Note that higher AI_ET0 (green/blue colors) represents more humid conditions, with low AI_ET0 (brown/yellow colors) representing higher aridity.

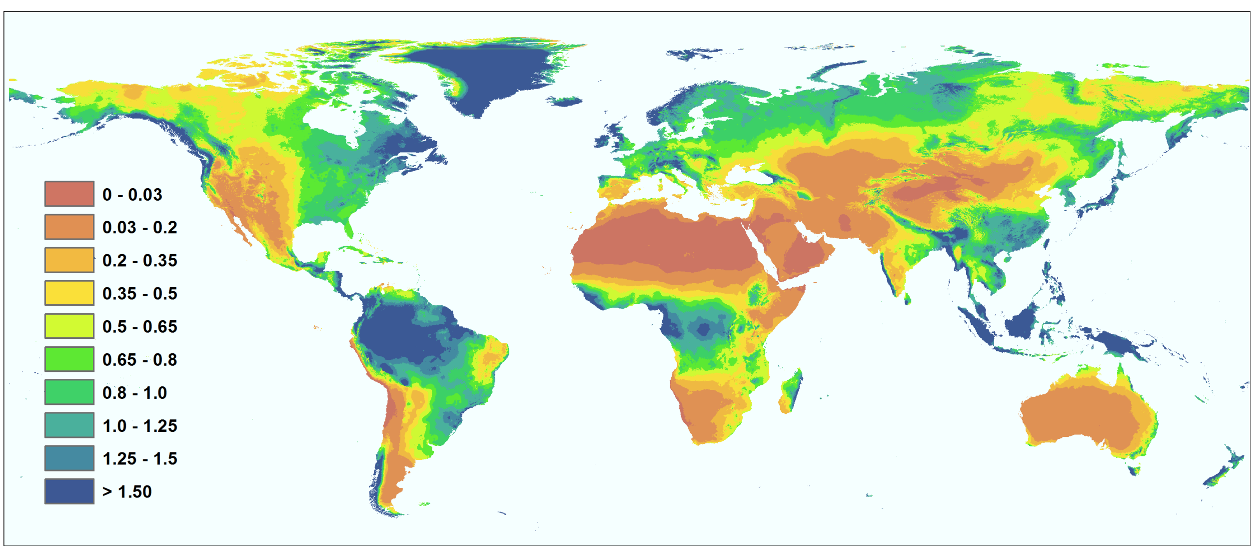


Table 2. Generalized climate classification scheme for Aridity Index values (UNEP 1997).

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

DATA FORMAT

Global-ET0 grid layers are available as monthly averages (12 data layers, i.e. one layer for each month) or as an annual average (1 data layer) for the 1970-2000 period.

Global-AI_ET0 is available as one grid layer representing the annual average over the 1970-2000 period. The following nomenclature is used to describe the dataset:

Prefix is either:

et0_		for ET0 layers
ai_et0_	f	or Aridity Index_ET0

Suffix is either:

1, 2, ... 12	Month of the year
yr	Yearly average

Examples:

et0_2	is the ET0 average for the month of February
et0_yr	is the ET0 annual average
ai_eto_yr	is the AI annual average

The ***Global-ET0*** geodataset values are defined as the total mm of ET0 per month or per year.

The Aridity Index values reported within the **Global Aridity Index_ET0** geodataset have been multiplied by a factor of 10,000 to derive and distribute the data as integers (with 4 decimal accuracy). This multiplier has been used to increase the precision of the variable values without using decimals (real or floating values are less efficient in terms of computing time and space compared to integer values).

Global Aridity Index_ET0 values need to be multiplied by 0.0001 to retrieve the values in the correct units.

The geospatial dataset is in geographic coordinates; datum and spheroid are WGS84; spatial units are decimal degrees. The spatial resolution is 30 arc-seconds or 0.008333 degrees. Arc degrees and seconds are angular distances, and conversion to linear units (like km) varies with latitude, as below:

Latitude	Linear distance equivalent to 30 arc sec
0°	0.9266 km
20°	0.8707 km
40°	0.7098 km
60°	0.4633 km

The ***Global-ET0*** and ***Global-Aridity*** data layers are processed and finalized as GeoTIFF data format. These layers have been zipped (.zip) into monthly series or individual annual layers available for online access.

Data Use and Distribution

This data has been generated by not-for-profit institutions with the objective of supplying accessible and useful information to developing country organizations. We actively encourage use of these products for scientific purposes. This is not however the case for commercial purposes. The entire dataset is available for commercial use at a modest cost, but permission must be sought. Commercial sectors interested in using this data should contact Antonio Trabucco: antoniotrabucco@cmcc.it and Robert Zomer: r.zomer@mac.com .

References:

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Walter, I.A., R.G. Allen, R. Elliott, M.E. Jensen, D. Itenfisu, B. Mecham, T.A. Howell, R. Snyder, P. Brown, S. Eching, T. Spofford, M. Hattendorf, R.H. Cuenca, J.L. Wright, and D. Martin (2000) ASCE’s standardized reference evapotranspiration equation. Proc. 4th Nat’l. Irrig. Symp., ASAE, Phoenix, AZ.

ANNEX I. FAO Penman-Monteith calculation using WorldClim2

In 1948, Penman combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed. This so-called combination method was further developed by many researchers and extended to cropped surfaces by introducing resistance factors. From the original Penman-Monteith equation, given the specific properties of the reference crop, the FAO Penman-Monteith method (FAO-PM) to estimate ET0 can be calculated as:

$$ET0 = \frac{0.408 * \Delta * (R_n - G) + \gamma \frac{900}{T_{avg} + 273} * u_2 * (e_s - e_a)}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)}$$

Where

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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 $°C^{-1}$

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

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

γ, Psychrometric constant

The Atmospheric Pressure (Pr, [KPa]) is the pressure exerted by the weight of the atmosphere and is thus dependent on elevation (elev, [m]). To a certain (and limited) extent the evaporation is promoted at higher elevations:

$$\mathrm{Pr} = 101.3 * \left(\frac{293 - 0.0065 * elev}{293}\right)^{5.26}$$

Elevation from the STRM dataset is used. Thus, the Psychrometric constant, [γ, kPa C-1] is expressed as:

$$\gamma = \frac{c_p * Pr}{\varepsilon * \lambda} = \frac{0.001013 * Pr}{0.622 * 2.45}$$

Where c_p is the specific heat at constant pressure [MJ kg-1 °C-1] and is equal to 1.013 10^{-3}, λ is the latent heat of vaporization [MJ kg-1] and is equal to 2.45, while ε is the molecular weight ratio between water vapour and dry air and is equal to 0.622.

e_s, saturation vapour pressure

Saturation vapor Pressure [KPa] is strictly related to temperature values (T)

$$e_{s\_T} = 0.6108 * exp^{\left[\frac{17.27*T}{T+237.3}\right]}$$

Values of saturation vapour pressures, as function of temperature, are calculated for both Minimum Temperature [Tmin, C] and Maximum temperature [Tmax, C]. Due to non linearity of the equation, the mean saturation vapour pressure [e_s, KPa] is calculated as the average of saturation vapour pressure at min [e_{s_min}] and maximum temperature [e_{s_max}]

$$e_s = \frac{e_{s\_Tmax} + e_{s\_Tmin}}{2}$$

The water vapour pressure [ea, KPa] is the vapour pressure exerted by the water in the air and is usually calculated as function of Relative Humidity. Water vapour pressure is already available as one of the Worldclim2 variables.

Δ, slope vapour pressure curve

The Slope of Saturation Vapor Pressure [Δ, kPa C-1] at a given temperature is given as function of average temperature:

$$\Delta = \frac{4098 * 0.6108\ exp^{\left(\frac{17.27 * T_{avg}}{T_{avg} + 237.3}\right)}}{\left(T_{avg} + 237.3\right)^2}$$

R_n, net radiation at the crop surface

Net radiation [Rn, MJ m^{-2} day^{-1}] is the difference between the net shortwave radiation [Rns, MJ m^{-2} day^{-1}] and the net longwave radiation [Rnl, MJ m^{-2} day^{-1}], and is calculated using solar radiation from WorldClim2 (Rs). In worldclim 2 solar radiation (Rs) is given as KJ m-2 day-1. Thus for computation of ET0, its unit should be converted to MJ m-2 day-1 and thus its value should be divided by 1000. The net accounting of either longwave and shortwave radiation sums up the incoming and outgoing components.

$$R_n = R_{ns} - R_{nl}$$

The net shortwave radiation [Rns, MJ m^{-2} day^{-1}] is the fraction of the solar radiation Rs that is not reflected from the surface. The fraction of the solar radiation reflected by the surface is known as the albedo [α]. For the green grass reference crop, α is assumed to have a value of 0.23. The value of Rns is:

$$R_{ns} = R_s * (1 - \alpha)$$

The difference between outgoing and incoming longwave radiation is called the net longwave radiation [Rnl]. As the outgoing longwave radiation is almost always greater than the incoming longwave radiation, Rnl represents an energy loss. Longwave energy emission is related to surface temperature following Stefan-Boltzmann law. The net energy flux leaving the earth's surface is influenced as well by humidity and cloudiness

$$R_{nl} = \sigma * \left(\frac{T_{max,K}^4 + T_{min,K}^4}{2}\right) * \left(0.34 - 0.14 * \sqrt{e_a}\right) * \left(1.35 * \frac{R_s}{R_{so}} - 0.35\right)$$

Where σ represent the Stefan-Boltzmann constant (4.903 10-9 MJ K-4 m-2 day-1), $T_{max,k}$ and $T_{min,k}$ the maximum and minimum absolute temperature (in Kelvin; K = C° + 273.16), e_a is the actual vapour pressure; R_s the measured solar radiation [MJ m^{-2} day^{-1}] and R_{so} is the calculated clear-sky radiation [MJ m^{-2} day^{-1}]. R_{so} is calculated as function of extraterrestrial solar radiation [R_a, MJ m^{-2} day^{-1}**]** and elevation (elev, m):

$$R_{so} = R_a * (0.75 + 0.00002 * elev)$$

The extraterrestrial radiation, [R_a, MJ m^{-2} day^{-1}**]**, is estimated from the solar constant, solar declination and day of the year. It requires specific information about latitude and Julian day to accomplish a trigonometric computation of the amount of solar radiation reaching the topo of the atmosphere following trigonometric computations as shown in Allen et al. (1998).

Instead, for simplicity, changes in soil heat fluxes are ignored (G=0).

r_s, bulk surface resistance, and r_a, aerodynamic resistance

The resistance nomenclature distinguishes between aerodynamic resistance and surface resistance factors. The surface resistance parameters are often combined into one parameter, the ‘bulk’ surface resistance parameter which operates in series with the aerodynamic resistance. The surface resistance, rs, describes the resistance of vapour flow through stomata openings, total leaf area and soil surface. The aerodynamic resistance, ra, describes the resistance from the vegetation upward and involves friction from air flowing over vegetative surfaces. Although the exchange process in a vegetation layer is too complex to be fully described by the two resistance factors, good correlations can be obtained between measured and calculated evapotranspiration rates, especially for a uniform grass reference surface.

The reference surface is a hypothetical grass reference crop, well-watered grass of uniform height, actively growing and completely shading the ground, with an assumed crop height of 0.12 m, and an albedo of 0.23. For such reference crop the surface resistance is fixed to 70 s m^{-1} and implies a moderately dry soil surface resulting from about a weekly irrigation frequency.

When crop height is equal to 0.12 and wind/humidity measurements are taken at 2 meters height, then the aerodynamic resistance can be simplified as:

$$r_a = \frac{208}{u_2}$$