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Climate Map of Madagascar According to the Köppen-Geiger Classification (Beck *et al.*, 2018) Based on Climate Data from 1991 to 2020

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Abstract

Detailed climate characterization—now essential for adapting to environmental changes and managing natural resources—requires integrated approaches that combine international standardization, high spatial resolution, and regular updates to reference data. The central challenge is updating climate norms in accordance with the recommendations of the World Meteorological Organization (WMO). In Madagascar, the historical zoning system of the General Directorate of Meteorology (DGM), although pragmatic and operational for local stakeholders, is based on an empirical classification (zones A through J) that does not accurately represent a small, distinct area with characteristics of a Mediterranean to temperate summer climate (Csb) or the fine distinction between temperate oceanic (Cfb) and temperate humid (Cfa) climates. This article aims to produce an updated climate map of Madagascar for the reference period 1991-2020 by applying the Köppen-Geiger classification improved by Beck *et al.* (2018). The method is based on a hierarchical approach that incorporates extreme temperatures and precipitation seasonality, using high-resolution ENACTS data (4 km × 4 km grid). Our results reveal a mosaic of eight active climate types. In the eastern regions (Af tropical rainforest and Am monsoon), abundant rainfall throughout the year requires rigorous management of moisture and runoff. In the west, the savanna climate (Aw) is characterized by severe water stress during the southern winter. In the central highlands, temperate climates (Cfa hot summer and Cfb mild summer) feature regular precipitation, in contrast to the far south, where hot arid climates (BWh) prevail, and the high-altitude Mediterranean climate (Csb) is found locally in the Diana Highlands—an area not previously identified by the DGM.

Subject Areas

Atmospheric Sciences

Keywords

Climate Zones, Climate Classifications, Madagascar, Köppen, Beck

1. Introduction

The Köppen-Geiger climate classification is one of the most widely used systems for the global description of Earth's climates. Based on an empirical approach, it combines temperature, precipitation, and their seasonal variability to define homogeneous climate zones. Originally developed by Köppen (1936) [1], this classification has undergone major revisions, notably by Peel *et al.* (2007) [2] and later by Beck *et al.* (2018) [3], who proposed a high-resolution global version based on gridded climate data.

In accordance with the recommendations of the World Meteorological Organization (WMO), climate normals are defined over 30-year periods and are updated every decade (commonly used periods: 1961-1990, 1971-2000, 1981 to 2010, and 1991 to 2020). The period from 1991 to 2020 thus constitutes the current reference norm, and it is essential to update the analyses as soon as each new 10-year period is reached, in order to reflect recent changes in the climate system and provide up-to-date benchmarks for applied studies.

Madagascar, represented by the General Directorate of Meteorology (DGM), is a member country of the WMO. As such, the regular updating of climate information is of particular importance: it provides users (decision-makers, farmers, water resource managers, land-use planners, and researchers) with reference data tailored to their most recent work, and thus operational for planning and managing climate risks.

In this context, this study aims to update Madagascar's climate mapping by applying the Köppen-Geiger classification, as refined by Beck *et al.* (2018) over the reference period from 1991 to 2020. This update incorporates essential physical variables such as temperature and precipitation, enabling a detailed and spatially explicit characterization of the island's climates, in line with current international standards.

2. Methods and Materials

2.1. Climate Data

The data used come from the ENACTS Version 3 (Enhancing National Climate Services) project [4], accessible via Météo Madagascar's Maproom. They combine in situ observations (weather stations) and satellite estimates to produce a high-resolution 4 km × 4 km raster grid covering the entire territory of Madagascar. The reference period is 1991 to 2020. The available variables are precipitation and

temperatures (maximum and minimum).

These data consist of daily values spatially aggregated into raster grids, with each pixel representing a homogeneous geographic cell. This approach makes it possible to map local climates despite the low density of the weather station network in Madagascar.

According to the WMO Guidelines on the Calculation of Climate Normals (WMO-No. 1203, 2017) [5], climate normals are calculated from monthly values, which are themselves derived from daily or hourly observations (**Table 1**).

Table 1. Method for calculating climatological normals [5].

Parameter	Daily to monthly aggregation	Calculation of the monthly normal (1991 to 2020 reference period)
Maximum (minimum) temperature	The monthly maximum (minimum) temperature is obtained by averaging the daily maximum (minimum) temperatures for the month.	The monthly normal for maximum (minimum) temperature is the average of the monthly maximum (minimum) temperatures over the reference period.
Precipitation	The monthly total is obtained by summing the daily precipitation for the month.	The monthly normal precipitation corresponds to the average of the monthly totals observed over the 30 reference years.

2.2. Derived Climate Variables

Average temperature T_{mean}

The annual average temperature T_{mean} for a given period (month, year) is calculated as the arithmetic mean of $T_{\max}$ and $T_{\min}$:

$$T_{\text{mean}} = \frac{T_{\max} + T_{\min}}{2} \tag{1}$$

Next, the annual average temperature T_{ann} over a series of n years is:

$$T_{\text{ann}} = \frac{1}{n}\sum_{i=1}^{n} T_{\text{mean},i} \tag{2}$$

where $T_{\text{mean},i}$ is the average temperature for year *i*. This quantity is used to define major climate groups (tropical, temperate, etc.) [3].

Average Monthly Temperature $T_{\text{mean_month}}$

$$T_{\text{mean_min_month}} = \frac{1}{|D_m|}\sum_{d\in D_m} T_{\min,d} \tag{3}$$

$$T_{\text{mean_max_month}} = \frac{1}{|D_m|}\sum_{d\in D_m} T_{\max,d} \tag{4}$$

$$T_{\text{mean_month}} = \frac{T_{\text{max_mean}} + T_{\text{min_mean}}}{2} \tag{5}$$

where:

- $T_{\max,d}$ and $T_{\min,d}$: maximum and minimum daily temperatures on day d (°C).
- D_m: the set of days in month m over the entire period from 1991 to 2020 (30 years).

For each month m, we first calculate the average of all daily maximum temperatures and the average of all daily minimum temperatures over the 30 year period. The monthly average temperature is the arithmetic mean of these two values.

$T_{\text{mean_month}}$ is the arithmetic mean of the 12 monthly mean temperatures. Each monthly temperature is first calculated as the average of the daily mean temperatures [3], which are themselves obtained by ($T_{\max}$ + $T_{\min}$)/2.

Temperature of the warmest month $T_{\max,\text{warm}}$

$$T_{\max,\text{warm}} = \max_{m=1,\cdots,12} T_{\text{mean_month}(m)} \tag{6}$$

The maximum value among the 12 monthly mean temperatures. It correspond to the mean temperature of the warmest month [3]. Used for the thermal subtypes of temperate climates (a, b, c) and to define polar climates (ET if $T_{\max,\text{warm}} < 10^{\circ}\text{C}$, EF if $T_{\max,\text{warm}} < 0^{\circ}\text{C}$).

Temperature of the coldest month $T_{min,cold}$

$$T_{\min,\text{cold}} = \min_{m=1,\cdots,12} T_{\text{mean_month}(m)} \tag{7}$$

The minimum value among the 12 monthly average temperatures. It represents the average temperature of the coldest month and is used to distinguish between groups [3]:

- $T_{\min,\text{cold}} \geq 18^{\circ}\text{C}$ → Group A (tropical)
- $3^{\circ}\text{C} < T_{\min,\text{cold}} < 18^{\circ}\text{C}$ → Group C (temperate)
- $T_{\min,\text{cold}} \leq -3^{\circ}\text{C}$ → Group D (continental)

Average monthly precipitation $P_{\text{mean_month}}$

$$P_{\text{mean_month}} = \frac{1}{N_y} \sum_{d \in D_m} P_d \tag{8}$$

where:

- P_d: precipitation on day d (mm).
- D_m: set of all days in month m over the entire period from 1991 to 2020 (30 years).
- $N_y = 30$: number of years.

For each month m, we sum all the daily precipitation values for that month over the 30-year period, then divide by the number of years (30). This yields the average precipitation for that month per year (mm/month) [3].

Average Annual Precipitation P_{ann}

Annual precipitation P_{ann} is calculated as the average of the annual totals $P_{\text{mean_month}(i)}$ (mm/year)

$$P_{\text{ann}} = \frac{1}{n} \sum_{i=1}^{n} P_{\text{mean_month}(i)} \tag{9}$$

For each month m, we calculate the sum of all daily precipitation amounts for that month over the 30 year period (1991 to 2020), then divide by the number of years ($N_y = 30$). This yields the average precipitation for that month per year. Next, P_{ann} is the sum of the 12 average monthly precipitation values. This varia-

ble is essential for calculating the aridity threshold ($P_{\text{threshold}}$) and for classifying climates A and B [3].

Precipitation in the driest month (P_{dry})

$$P_{\text{dry}} = \min_{m=1,\cdots,12} P_{\text{mean_month}(m)} \tag{10}$$

P_{dry} is the minimum value among the 12 monthly average precipitation values. It correspond to the precipitation in the driest month of the year and is used to distinguish tropical subtypes (Af, Am, Aw) as well as to verify the conditions of temperate climates with dry summers (Cs) [3].

Seasonal precipitation and threshold ($P_{\text{threshold}}$)

First, we define the totals and averages for the periods April through September and October through March [3]:

$$T_{\text{AprSep}} = \frac{1}{6}\sum_{m=4}^{9} T_{\text{mean_month}(m)} \tag{11}$$

$$T_{\text{OctMar}} = \frac{1}{6}\sum_{m\in\{10,11,12,1,2,3\}} T_{\text{mean_month}(m)} \tag{12}$$

$$P_{\text{AprSep}} = \sum_{m=4}^{9} P_{\text{mean_month}(m)} \tag{13}$$

$$P_{\text{OctMar}} = \sum_{m\in\{10,11,12,1,2,3\}} P_{\text{mean_month}(m)} \tag{14}$$

The warm season (summer) and the cold season (winter) are determined by comparing temperatures [3]:

$$\begin{aligned} &T_{\text{AprSep}} > T_{\text{OctMar}} \text{ then } \begin{cases} \text{summer} = \text{April through September} \\ \text{winter} = \text{October through Mars} \end{cases} \\ &\text{Otherwise } \begin{cases} \text{summer} = \text{October through Mars} \\ \text{winter} = \text{April through September} \end{cases} \end{aligned} \tag{15}$$

On calcule alors [3]:

$$P_{\text{summer,tot}} = \sum_{m\in\text{summer}} P_{\text{mean_month}(m)} \tag{16}$$

$$P_{\text{winter,tot}} = \sum_{m\in\text{winter}} P_{\text{mean_month}(m)} \tag{17}$$

$$P_{\text{smin}} = \min_{m\in\text{summer}} P_{\text{mean_month}(m)} \tag{18}$$

$$P_{\text{wmin}} = \min_{m\in\text{winter}} P_{\text{mean_month}(m)} \tag{19}$$

$$P_{\text{smax}} = \max_{m\in\text{summer}} P_{\text{mean_month}(m)} \tag{20}$$

$$P_{\text{wmax}} = \max_{m\in\text{winter}} P_{\text{mean_month}(m)} \tag{21}$$

$$pct_{\text{winter}} = \frac{P_{\text{winter,tot}}}{P_{\text{ann}}} \times 100 \tag{22}$$

$$pct_{\text{summer}} = \frac{P_{\text{summer,tot}}}{P_{\text{ann}}} \times 100 \tag{23}$$

The precipitation threshold for arid climates is [3]:

$$P_{\text{threshold}} = \begin{cases} 2T_{\text{mean_ann}} & \text{if } pct_{\text{winter}} > 70 \\ 2T_{\text{mean_ann}} + 28 & \text{if } pct_{\text{summer}} > 70 \\ 2T_{\text{mean_ann}} + 14 & \text{otherwise} \end{cases} \quad (24)$$

This threshold depends on the annual mean temperature and the seasonality of precipitation.

Beck *et al.* (2018) use equation (24) to calculate this threshold:

- If more than 70% of annual precipitation falls in winter: $P_{\text{threshold}} = 2 \times T_{\text{mean_ann}}$
- If more than 70% of annual precipitation falls in summer: $P_{\text{threshold}} = 2 \times T_{\text{mean_ann}} + 28$
- In other cases (uniform distribution): $P_{\text{threshold}} = 2 \times T_{\text{mean_ann}} + 14$

where $T_{\text{mean_ann}}$ is the annual mean temperature (˚C). Summer (winter) is defined as the warmest (coldest) six-month period between April-September and october-march.

Once this threshold is calculated, the criteria for arid climates are [3]:

- Arid climate (B): $P_{\text{ann}} < 10 \times P_{\text{threshold}}$
- Desert (BW): $P_{\text{ann}} < 5 \times P_{\text{threshold}}$
- Steppe (BS): $P_{\text{ann}} \geq 5 \times P_{\text{threshold}}$ (and $P_{\text{ann}} < 10 \times P_{\text{threshold}}$)

Number of warm months (num_months_gt_10)

$$\text{num_months_gt_10} = N_{>10} = \sum_{m=1}^{12} \mathbb{1}\left(\overline{T}_m > 10^{\circ}\text{C}\right) \quad (25)$$

where $\mathbb{1}(\cdot)$ is the indicator function.

Counts the number of months in which the average monthly temperature exceeds 10˚C. Used to distinguish the thermal subtypes of temperate climates [3]:

- $N_{>10} \geq 4$: subtype b (temperate summer)
- $N_{>10} < 4$: subtype c (cool summer)

2.3. Climate Classification (Beck *et al.*, 2018)

The classification is hierarchical: it first identifies the major climate group (A, B, C, D, E) based on the temperature of the coldest month (T_{coldest}) and the temperature of the warmest month (T_{warmest}). Next, each group is subdivided into subtypes based on the seasonality of precipitation, summer temperature, and the number of months with an average temperature exceeding 10˚C. **Table 2** summarizes the hierarchical structure of all groups and subtypes.

Table 2. Hierarchical structure of groups and subtypes in the Köppen-Geiger classification (adapted from Beck *et al.*, 2018).

Group	Name	Main condition	Subtype	Code	Additional criteria
A	Tropical	$T_{\text{min_cold}} \geq 18^{\circ}\text{C}$	Tropical rainforest	Af	$P_{\text{dry}} \geq 60$ mm
			Tropical monsoon	Am	$P_{\text{dry}} < 60$ mm but P_{wet} very high (compensation)
			Tropical savanna with dry winter	Aw	$P_{\text{dry}} < 60$ mm and the driest month is winter
B	Aride	$P_{\text{ann}} \geq 10 \times P_{\text{threshold}}$	Hot desert	BWh	$P_{\text{ann}} < 5 \times P_{\text{threshold}}$ and $T_{\text{ann}} \geq 18^{\circ}\text{C}$
			Cold desert	BWk	$P_{\text{ann}} < 5 \times P_{\text{threshold}}$ and $T_{\text{ann}} < 18^{\circ}\text{C}$

Continued

			Hot steppe	BSh	$5\times P_{threshold} \le P_{ann} < 10\times P_{threshold}$ and $T_{ann} \ge 18^{\circ}C$
			Cold steppe	BSk	$5\times P_{threshold} \le P_{ann} < 10\times P_{threshold}$ and $T_{ann} < 18^{\circ}C$
C	Temperate	$-3^{\circ}C < T_{min_cold} < 18^{\circ}C$	Dry summer, hot summer	Csa	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\times P_{smin}$, $P_{smin} < 40$ mm and $T_{max_warm} \ge 22^{\circ}C$
			Dry summer, temperate summer	Csb	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\times P_{smin}$, $P_{smin} < 40$ mm and $T_{max_warm} < 22^{\circ}C$ and number of months $> 10^{\circ}C \ge 4$
			Dry summer, cold summer	Csc	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\times P_{smin}$, $P_{sm} < 40$ mm and (default rule)
			Dry winter, hot summer	Cwa	$P_{smin} < P_{wmin}$, $P_{wmax} > 10\times P_{wmin}$ and $T_{max_warm} \ge 22^{\circ}C$
			Dry winter, temperate summer	Cwb	$P_{wmin} < P_{smin}$, $P_{smax} > 10\times P_{wmin}$ and $T_{max_warm} < 22^{\circ}C$ and number of months $> 10^{\circ}C \ge 4$
			Dry winter, cold summer	Cwc	$P_{wmin} < P_{smin}$, $P_{smax} > 10\times P_{wmin}$ and (default rule)
			No dry season, hot summer	Cfa	!is_Cs and !is_Cw and $T_{max_warm} \ge 22^{\circ}C$
			No dry season, temperate summer	Cfb	!is_Cs and !is_Cw, $T_{max_warm} < 22^{\circ}C$ and number of months $> 10^{\circ}C \ge 4$
			No dry season, cold summer	Cfc	!is_Cs and !is_Cw (default rule)
D	Continental	$T_{min_cold} \le -3^{\circ}C$	Continental, hot summer	Dfa	$T_{min_cold} \le -3^{\circ}C$ and $T_{max_warm} \ge 22^{\circ}C$
			Continental, temperate summer	Dfb	$T_{min_cold} \le -3^{\circ}C$, $T_{max_warm} < 22^{\circ}C$ and num_months_gt_10 ≥ 4
			Continental, cold summer	Dfc	$T_{min_cold} \le -3^{\circ}C$ (default rule)
E	Polar	$T_{max_warm} < 10^{\circ}C$	Tundra	ET	$0^{\circ}C \le T_{max_warm} < 10^{\circ}C$
			Ice cap	EF	$T_{max_warm} < 0^{\circ}C$

Definitions of parameters and legends:

- T_{ann} : annual average temperature
- T_{max_warm} : maximum temperature of the warmest month
- T_{min_cold} : minimum temperature of the coldest month
- P_{ann} : total annual precipitation
- P_{dry} : precipitation of the driest month
- $P_{threshold}$: Köppen precipitation threshold (a function of T_{ann} and seasonality)
- P_{smin} / P_{wmin} : minimum summer/winter precipitation
- P_{smax} / P_{wmax} : maximum summer/winter precipitation
- num_months_gt_10: number of months with $T_{moy} > 10^{\circ}C$
- Cs (dry summer): $P_{smin} < P_{wmin}$, $P_{wmax} > 3\times P_{smin}$, $P_{smin} < 40$ mm
- Cw (dry winter): $P_{wmin} < P_{smin}$, $P_{smax} > 10\times P_{wmin}$
- !is_Cs: neither Cs
- !is_Cw: neither Cw
- Cf (no dry season): !is_Cs & !is_Cw

2.4. Spatial Classification Method

The classification is implemented as a raster: each pixel with coordinates (x, y) is

assigned a climate class based on a hierarchical function [Beck *et al.*, 2018]:

$$\text{Class}(x,y) = f\left(T_{\text{ann}}, T_{\text{max_warm}}, T_{\text{min_cold}}, P_{\text{ann}}, P_{\text{dry}}, P_{\text{threshold}}, P_{\text{smin}}, P_{\text{wmin}}, P_{\text{smax}}, P_{\text{wmax}}, \text{num_months_gt_10}\right)$$

The classification follows a multi-step decision-making process [Beck *et al.*, 2018]:

Step 1: Identification of polar climates (Group E)

If $T_{\text{max_warm}} < 0^{\circ}\text{C}$: EF climate (ice cap)

If $0 \leq T_{\text{max_warm}} < 10^{\circ}\text{C}$: ET climate (tundra)

Step 2: Identification of arid climates (group B)

The Pthreshold value is first calculated based on the seasonal distribution of precipitation (Equation 24):

- If winter precipitation accounts for more than 70% of the annual total: $P_{\text{threshold}} = 2 \times T_{\text{ann}}$
- If summer precipitation accounts for more than 70% of the annual total: $P_{\text{threshold}} = 2 \times T_{\text{ann}} + 28$
- Otherwise: $P_{\text{threshold}} = 2 \times T_{\text{ann}} + 14$

Then:

- If $P_{\text{ann}} < 5 \times P_{\text{threshold}}$: desert climate
  - BWh (hot desert) if $T_{\text{ann}} \geq 18^{\circ}\text{C}$
  - BWk (cold desert) if $T_{\text{ann}} < 18^{\circ}\text{C}$
- If $5 \times P_{\text{threshold}} \leq P_{\text{ann}} < 10 \times P_{\text{threshold}}$: steppe climate
  - BSh (hot steppe) if $T_{\text{ann}} \geq 18^{\circ}\text{C}$
  - BSk (cold steppe) if $T_{\text{ann}} < 18^{\circ}\text{C}$

Step 3: Determining the primary group (A, C, D)

For non-polar and non-arid regions:

- Groupe A (Tropical): if $T_{\text{min_cold}} \geq 18^{\circ}\text{C}$
- Groupe C (Temperate): if $-3^{\circ}\text{C} < T_{\text{min_cold}} < 18^{\circ}\text{C}$
- Groupe D (Continental): if $T_{\text{min_cold}} \leq -3^{\circ}\text{C}$

Step 4: Assigning sub-types

For Group A (Tropical):

- Af (tropical rainforest): if $P_{\text{dry}} \geq 60$ mm
- Am (tropical monsoon): if $P_{\text{dry}} < 60$ mm et $P_{\text{ann}} \geq 25 \times \left(100 - P_{\text{dry}}\right)$
- Aw (tropical savanna): if $P_{\text{dry}} < 60$ et $P_{\text{ann}} < 25 \times \left(100 - P_{\text{dry}}\right)$

For Group C (Temperate):

First, we define the seasonality indicators:

- is_Cs = $P_{\text{smin}} < P_{\text{wmin}}$, $P_{\text{wmax}} > 3 \times P_{\text{smin}}$, $P_{\text{smin}} < 40$ mm
- is_Cw = $P_{\text{wmin}} < P_{\text{smin}}$, $P_{\text{smax}} > 10 \times P_{\text{wmin}}$
- is_Cf = !is_Cs & !is_Cw

Then:

- Csa: is_Cs and $T_{\text{max_warm}} \geq 22^{\circ}\text{C}$
- Csb: is_Cs, $T_{\text{max_warm}} < 22^{\circ}\text{C}$ and num_months_gt_10 ≥ 4
- Csc: is_Cs (default rule)

- Cwa: is_Cw and $T_{max_warm} \geq 22^{\circ}C$
- Cwb: is_Cw, $T_{max_warm} < 22^{\circ}C$ and num_months_gt_10 ≥ 4
- Cwc: is_Cw (default rule)
- Cfa: is_Cf and $T_{max_warm} \geq 22^{\circ}C$
- Cfb: is_Cf, $T_{max_warm} < 22^{\circ}C$ and num_months_gt_10 ≥ 4
- Cfc: is_Cf (default rule)

For Group D (Continental):

- Dfa: $T_{max_warm} \geq 22^{\circ}C$
- Dfb: $T_{max_warm} < 22^{\circ}C$ and num_months_gt_10 ≥ 4
- Dfc: $T_{max_warm} < 22^{\circ}C$ and num_months_gt_10 < 4 (default rule)

Each pixel is thus classified independently, allowing for the production of a continuous and spatially explicit climate map.

3. Results

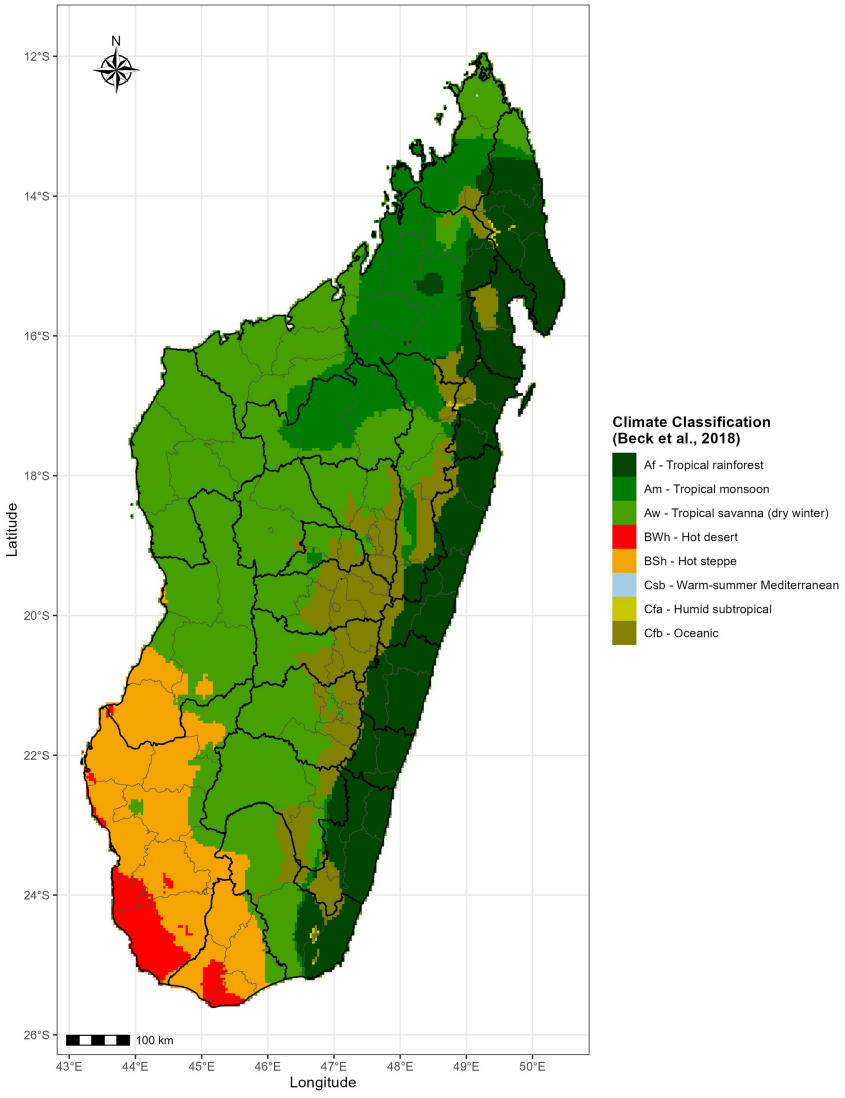


Figure 1. Climate classification of Madagascar (1991-2020).

Table 3. Climate classes in Madagascar (1991-2020).

Code	Full name	Regions	Main characteristics
Af	Tropical rainforest (114,530.18 km², *i.e.* 18.88%)	Alaotra-Mangoro (southeast), Ambatosoa (except the west-central part), Analanjirofo (except west-central), Anosy (southeastern part), Atsimo-Atsinanana (north, center and southeast), Atsinanana (except the northwestern fringe and southwestern fringe), Diana (small southeastern parts), Fitovinany (except the western fringe), Ihorombe (northeastern fringe), Sava (center and south), Sofia (eastern fringe and small central parts), Vatovavy (except the western fringe)	Abundant precipitation, regularly distributed throughout the year, with the driest month (P_{dry}) reaching at least 60 mm, which excludes any true dry season. The coldest-month temperature ($T_{\text{min_cold}}$) is consistently greater than or equal to 18˚C, ensuring permanent warmth and high atmospheric humidity—conditions ideal for the dense evergreen forest that covers the eastern plains and slopes of the island.
Am	Tropical monsoon (78,235.29 km², *i.e.* 12.9%)	Alaotra-Mangoro (northwest and small south-central-west parts), Atsimo-Atsinanana (small southwestern parts), Betsiboka (north and some central parts), Boeny (southeastern fringe), Diana (southwest and small south-central parts), Itasy (south-central), Ihorombe (small southeastern parts), Sava (north-central fringe), Sofia (almost central)	Very high annual precipitation due to monsoon compensation. The driest month (P_{dry}) is less than 60 mm, but the annual precipitation total remains very high (generally above 1500 - 2000 mm) thanks to an extremely intense rainy season (monsoon) that largely compensates for the short dry period. The coldest-month temperature exceeds 18˚C. This subtype occurs locally in transition zones or exposed sectors of the northwest and east coast, where precipitation, although concentrated over a few months, remains sufficient to maintain very dense vegetation.
Aw	Tropical savanna with dry winter (253,953.88 km², *i.e.* 41.87%)	Alaotra-Mangoro (west-central), Ambatosoa (small eastern coastal parts), Amoron'i Mania (west and north-central), Analamanga (northern part), Analanjirofo (small eastern coastal parts), Androy (eastern fringe), Anosy (north, center and southwest), Atsimo-Andrefana (northeastern fringe), Atsimo-Atsinanana (small eastern coastal parts, extreme southwest and extreme west-central), Atsinanana (small eastern coastal parts), Betsiboka (western, south-central and southeastern parts), Boeny (except the southeastern fringe), Bongolava (except small east-central parts), Diana (almost the northern part), Fitovinany (small eastern coastal parts), Ihorombe (west and center), Itasy (northern and western parts), Matsiatra Ambony (west), Melaky (except a small extreme southwest part), Menabe (north and center), Sava (extreme north), Sofia (west-central and small northern parts), Vakinankaratra (west), Vatovavy (small eastern coastal parts)	Marked dry season coinciding with the austral winter. The driest month (P_{dry}) is less than 60 mm, with a very marked dry season corresponding to the austral winter (May to October). The coldest-month temperature ($T_{\text{min_cold}}$) is always above 18˚C, but summer precipitation is concentrated over a short period (November to April), causing pronounced water stress in the cool season. This climate, typical of the central highlands at low altitude, favors savanna-type vegetation.
BWh	Hot desert (14,664 km², *i.e.* 2.42%)	Androy (south-center), Atsimo-Andrefana (southwest and small northwestern coastal parts), Menabe (small extreme southwest)	Structural drought where annual precipitation (P_{ann}) is very much below the aridity threshold: $P_{\text{ann}} < 5 \times P_{\text{threshold}}$. Mean annual temperature (T_{ann}) is greater than or equal to 18˚C, giving this class a hot desert character. In Madagascar, this subtype is confined to the extreme southwest, where rainfall is rare, highly irregular, and generally does not exceed 300 - 400 mm per year.

Continued

BSh	Hot steppe (76,223.7 km², *i.e.* 12.57%)	Androy (except the eastern fringe and south-center), Anosy (north-central-west), Atsimo-Andrefana (except the northeastern fringe and southwestern parts), Menabe (southern parts)	Semi-arid steppe climate where precipitation remains limited: $5\times P_{\text{threshold}} \le P_{\text{ann}} < 10\times P_{\text{threshold}}$, *i.e.* about 400 - 800 mm per year, but sufficient for the development of scattered herbaceous vegetation and thorny shrubs. Mean annual temperature (T_{ann}) is greater than or equal to 18˚C. This subtype occupies a broad band in the south and some southern parts of Madagascar, forming an ecological transition zone between the southern deserts and the wooded savannas of the west.
Csb	Mediterranean with temperate summer (16.91 km², *i.e.* ≈ 0%)	Diana (small north-central part)	Temperate climate characterized by a dry summer ($P_{\text{smin}} < P_{\text{wmin}}$, $P_{\text{wmax}} > 3\times P_{\text{smin}}$ et $P_{\text{smin}} < 40$ mm). The coldest-month temperature ($T_{\text{min_cold}}$) is between −3˚C and 18˚C, and the warmest-month temperature ($T_{\text{max_warm}}$) is below 22˚C, with at least 4 months whose mean temperature exceeds 10˚C (num_months_gt_10 ≥ 4). This high-altitude Mediterranean climate occurs locally in the sheltered highlands of Diana, where summer drought is attenuated by altitude.
Cfa	Humid temperate (no dry season, hot summer) (609.94 km², *i.e.* 0.1%)	Alaotra-Mangoro (small extreme northeast), Analanjirofo (small west-central parts), Anosy (small south-central-east), Sava (extreme west-central), Sofia (extreme southeast and extreme northeast)	Coldest-month temperature ($T_{\text{min_cold}}$) between −3 and 18˚C with a hot summer ($T_{\text{max_warm}} \ge 22$˚C approximately). Precipitation is distributed throughout the year without a clearly defined dry season, benefiting from maritime trade-wind inputs. This humid temperate climate occurs locally in sheltered valleys and eastern middle-altitude foothills, where altitude moderates winters while maintaining summer heat favorable to agriculture.
Cfb	Oceanic temperate (no dry season, mild summer) (68,268.65 km², *i.e.* 11.26%)	Alaotra-Mangoro (southwestern fringe, east-central and northeastern fringe), Ambatosoa (west-central), Amoron'i-Mania (eastern and south-central parts), Analamanga (southern parts, eastern fringe and west-central), Analanjirofo (west-central and extreme southwest), Anosy (eastern fringe and small south-central parts), Atsimo-Atsinanana (extreme northwest and almost southwestern parts), Atsinanana (extreme northwest and extreme southwest), Betsiboka (small extreme southeast), Bongolava (small east-central parts), Diana (extreme southeast), Fitovinany (western fringe), Ihorombe (southwestern parts, extreme southeast and northeast), Itasy (southeast, south-central and extreme west-central), Matsiatra Ambony (almost eastern parts), Sava (extreme west-central), Sofia (extreme northeast and extreme southeast), Vatovavy (western fringe).	Coldest-month temperature ($T_{\text{min_cold}}$) between −3 and 18˚C with a mild summer ($T_{\text{max_warm}} < 22$˚C) et au moins 4 mois dont la température moyenne dépasse 10˚C (num_months_gt_10 ≥ 4) and at least 4 months whose mean temperature exceeds 10˚C (num_months_gt_10 ≥ 4). Precipitation is regular or supplemented by high-altitude drizzle ("havana") during the austral winter, preventing total water stress. This high-altitude oceanic climate is typical of the central highlands of Madagascar (between 800 and 1500 m), where altitude lowers thermal averages while maintaining constant relative humidity favorable to highland grasslands.

Madagascar, located between 12˚S and 26˚S, has a wide variety of climates due to

its mountainous terrain (a north-south-oriented central mountain range, with Peak Boby reaching over 2800 m) and the influence of maritime trade winds. The map, generated using ENACTS data (4-km grid) and the classification by Beck *et al.* (2018), highlights a spatial distribution organized along an east-west gradient and a latitudinal gradient (see Figure 1).

Applying the classification method developed by Beck *et al.* (2018) to ENACTS data (1991-2020) across the entire territory of Madagascar reveals a range of eight distinct climate classes. This diversity reflects the well-known contrast between the east and west: a perpetually humid eastern slope influenced by maritime trade winds (classes Af and Am), a significantly drier western and southern coastline (classes BWh, BSh, and Aw), and the central highlands, which enjoy a temperate highland climate with distinct thermal seasons (classes Cfa and Cfb). Table 3 details, for each climate class present in Madagascar, the quantitative criteria (indices, temperature and precipitation thresholds) as well as a description of its local climatic characteristics.

Schematic spatial organization (map reading)

Based on the known general characteristics of Madagascar's climate, the following patterns are observed:

- East Coast (from approximately 13˚S to 24˚S): dominated by Af, Cfb, and Am climate zones (tropical rainforest, temperate oceanic, and monsoon). Moist oceanic trade winds discharge their moisture over the eastern slope, generating very high annual precipitation (2000 to 3500 mm). The dry season is short or nonexistent.
- BSh (hot steppe) in southwestern Madagascar; Cfa (humid temperate) in the northeastern, central, and southern parts; Cfb (oceanic temperate) in the central-eastern part of the island.
- Northern, northwestern, central, and south-central regions (along the entire length, from 15˚S to 20˚S): Aw climate (tropical savanna with a dry winter).
- Far south and southwest (Cape Androka, Tulear, from 21˚S to 25˚S): transition to BWh (hot desert) in the southwestern part of the Atsimo-Andrefana region and in the southern part of the Anosy region. Annual rainfall is less than 400 mm (sometimes less than 200 mm along the coast in the southwestern part).

4. Discussion

4.1. Geographical Correspondences between the DGM Climate Zones (1981-2010) and the Köppen-Geiger Classes Refined by Beck *et al.* (1991-2020)

Based on the DGM's description of climate zones [6] (see Figure 2 in the APPENDIX) and the implied locations of the regions of Madagascar, the following correspondences can be established (based on knowledge of Madagascar's climate) (See Table 4).

Table 4. Proposed correspondence between the DGM climate typology and the Köppen-Geiger classification, as updated by Beck *et al.* (2018), for Madagascar.

DGM zone	Designation	Probable correspondence with Köppen (Beck)
A	Very humid all year round (East, eastern slopes, Masoala)	Af (tropical rainforest)
B	Very humid (eastern Highlands, with attenuated exposure)	Am (tropical monsoon)
C	Humid with high rainfall (northwest, summer monsoon)	Aw (tropical savanna) but with high rainfall
D	Humid (central Highlands, softened relief)	Aw (savanna)/Cfb (humid temperate)/Cfa (humid subtropical)
E	Humid all year round (east-central, under trade winds)	Af/Aw/transitional Cfa
F	Humid with low precipitation, dry winter (West and Southwest)	Aw (savanna with dry winter)
G	Semi-humid and windy (southwest coast)	BSh (hot steppe)/BWh (hot desert)
H	Semi-humid (South, breezes)	Aw/transitional BSh
I	Semi-humid with low rainfall (interior South)	BSh or even BWh (hot desert)
J	Semi-arid (extreme South, Toliara)	BSh or even BWh (hot desert)

4.2. Divergences Notable Differences: Missing or Additional Classes

Table 5 compares the DGM system with the refined classification by Beck *et al.* (2018), highlighting the shortcomings of the former: the absence of the Mediterranean temperate Csb zone, which is found locally in the Diana highlands, and the grouping of the humid temperate Cfa and Cfb zones into a single zone, even though summer temperatures vary significantly with elevation.

Table 5. Comparative analysis of the limitations of the DGM climate zoning in relation to the refined Köppen-Geiger classification of Beck *et al.* (2018).

Beck class	Presence in DGM?	Comment
Csb (mediterranean with temperate summer)	No	The DGM has no high-altitude Mediterranean zone occurring locally in the sheltered highlands of Diana, where summer drought is attenuated by altitude.
Cfb (oceanic temperate) and Cfa (humid temperate)	Partially (zone D/E)	The DGM does not separate Cfb from Cfa, but notes cooler temperatures at altitude.

4.3. Factors Explaining Discrepancies

Spatial resolution and interpolation method:

- New climate classification (method by [3]): ENACTS data with a resolution of 4 km, which is effective at capturing subtle variations in topography (rain shadow effects, thermal inversion). This allows for the distinction between Cfa and Cfb and the identification of Csb in high-mountain areas.
- DGM: ENACTS data with a resolution of 10 km (for precipitation and temperatures), which is less precise. However, the DGM accounts for coastal breezes and local exposure (data on winds, humidity, and duration of sunshine), which gives it good robustness in climate class classification for areas

in southern Madagascar.

Different reference periods:

- New climate classification (method by [3]): 1991 to 2020 (recent period, including the years 2010 to 2020, which were marked by severe droughts in the South).
- DGM: 1981 to 2010 for temperatures and winds, 1983 to 2010 for precipitation, 1982 to 2010 for relative humidity, and 2000 to 2010 for sunshine duration. These different periods are older and wetter in the South (the 1980s and 1990s were less arid). Thus, the semi-arid zone J of the DGM is likely more limited in extent than Beck's BWh classification, which would explain why Beck classifies part of the Southwest as BWh.

5. Conclusions

Applying the Köppen-Geiger climate classification, as refined by Beck *et al.* (2018) [3], to ENACTS data for the period 1991-2020 reveals a complex and contrasting climatic mosaic in Madagascar, comprising eight active climate types, ranging from tropical rainforests (Af) to hot deserts (BWh). The resulting map highlights a clear east-west contrast: the eastern regions, influenced by maritime trade winds, are dominated by Af (tropical rainforest) and Am (monsoon) climates, while the western plains are largely characterized by the Aw savanna climate. The central highlands feature temperate climates (Cfa and Cfb) that are unique in the tropics, with their mild temperatures directly linked to elevation. Finally, the extreme southwest is home to hot desert (BWh) and hot steppe (BSh) climates. This mapping serves as a valuable tool for agronomy, biogeography, and water resource planning, providing a spatially explicit view of the climatic constraints and advantages of each region.

A comparison between the standardized classification by Beck *et al.* (2018) [3] and the historical zoning by the General Directorate of Meteorology (DGM) shows that these two approaches are more complementary than contradictory. On the one hand, Beck's map provides a detailed, international, and up-to-date view (covering the period from 1991 to 2020), highlighting a Mediterranean zone with a temperate summer (Csb) and a clear distinction between the humid temperate climates of the highlands (Cfa vs. Cfb). It is particularly recommended for basic research in ecology, biodiversity, and regional climate modeling. On the other hand, the DGM zoning, based on an empirical grid of ten zones (A through J), is more pragmatic and operational for local stakeholders (Ministry of Agriculture, water management, land-use planning). Its zones are directly correlated with ranges of precipitation and temperature.

This comparison illustrates—beyond specific cases—the crucial importance of two methodological parameters in any climate characterization: spatial resolution and the reference period. The same territory can, in fact, appear more or less arid or more or less temperate, depending on the tools used and the time frame considered. Ideally, we should aim for a hybrid classification that combines the rigor

and universality of the Köppen-Geiger thresholds with the clarity and operational simplicity of the DGM zones. Such an integrated approach would reconcile the demands of international research with the practical needs of development stakeholders in Madagascar, thereby contributing to greater resilience in the face of climate change.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Appendix

Climatic classification of Madagascar by the "Direction Générale de la Météorologie":

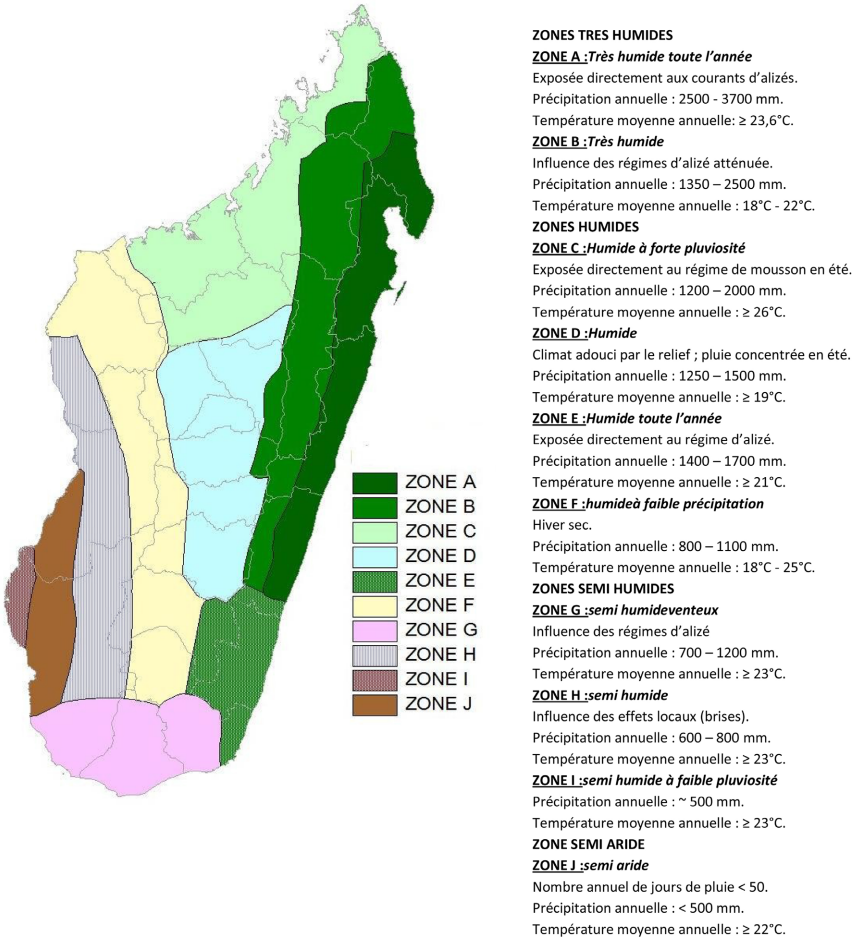


Figure 2. Climate zones of Madagascar (1981-2010) [6].