



Analysis of Maximum Winds in Madagascar: Estimation of Wind Return Periods Using Percentiles and the Generalized Extreme Value (GEV) Distribution from 1991 to 2020

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Abstract

The study of extreme winds in Madagascar is essential not only for understanding severe climatic phenomena and their impacts on infrastructure, but also for assessing human thermal comfort. This work proposes an innovative approach to estimating the return periods of maximum winds, based on the analysis of the 90th, 95th, and 99th percentiles and modeling using the Generalized Extreme Value (GEV) distribution. Hourly data from the ERA5-Land database, with a spatial resolution of 9 km and covering three decades (1991 - 2020), were used to provide a more accurate assessment of the frequency and intensity of extreme events. The northwestern region exhibits the longest return periods for 99th percentile winds, indicating greater exposure to severe phenomena, whereas the northeastern region shows significantly shorter recurrence cycles for the 90th and 95th percentile winds, reflecting less extreme but persistent conditions. This study provides more suitable tools for risk and disaster management, while also addressing infrastructure safety and comfort optimization in the context of climate change.

Subject Areas

Environmental Sciences

Keywords

Generalized Extreme Value (GEV), Maximum Winds, Wind Return Period, Madagascar

1. Introduction

Extreme winds are a key parameter in the study of violent climatic phenomena, particularly cyclones and tropical storms. Located in an area of intense cyclonic activity, Madagascar is particularly vulnerable to these events. Our research proposes a model for the return periods of maximum winds; two complementary statistical approaches have been combined: analysis by the 90th, 95th, and 99th percentiles to identify critical wind thresholds for different event intensities, and application of the GEV (Generalized Extreme Value) law. This is a recognized method for accurately modeling the distribution of extreme values over the long term, based on the seminal work of Coles (2001) in “An Introduction to Statistical Modeling of Extreme Values,” which establishes the theoretical framework for GEV modeling, and Katz *et al.* (2002) in “Statistics of Extremes in Climate Change,” which specifically applies these methods to extreme winds [1] [2].

The major interest of this study lies in its practical application to the design of sustainable buildings. Data on return periods can be used to optimize the orientation of buildings to limit the impact of prevailing winds. Knowledge of extreme wind speeds guides the technical and energy-related design of structures, reducing energy consumption by helping to design efficient natural ventilation systems.

These extreme climate data are essential from the design phase onward, particularly for developing bioclimatic housing that is safe, comfortable, and energy-efficient, especially within the Malagasy context.

2. Methodology

2.1. Collection of Hourly Wind Data

The hourly average wind data at 10 m, from 1991 to 2020, are sourced from ERA5-Land. They consist of the zonal component u and the meridional component v , which are used to calculate the horizontal wind speed and direction at 10 m. This data is a high spatial resolution (9 km) meteorological reanalysis produced by the European Center for Medium-Range Weather Forecasts (ECMWF). However, it is important to note that ERA5-Land is specifically designed to provide data on land areas [3] [4]. The temporal and spatial resolutions of ERA5-Land make this dataset very useful for all types of land surface applications [3] [4]. These are listed in **Table 1**.

Table 1. Temporal and spatial resolutions of ERA5-Land.

Data type	Gridded
Projection	Regular latitude-longitude grid
Horizontal coverage	Global
Horizontal resolution	$0.1^\circ \times 0.1^\circ$; Native resolution is 9 km
Vertical coverage	From 2 m above the surface to a soil depth of 289 cm

Continued

Vertical resolution	4 ECMWF surface model levels: Layer 1: 0 - 7 cm, Layer 2: 7 - 28 cm, Layer 3: 28 - 100 cm, Layer 4: 100 - 289 cm. Some parameters are defined at 2 m above the surface.
Temporal coverage	January 1950 to present
Temporal resolution	Hourly
File format	GRIB

Source: [5].

2.2. Calculation of Hourly Wind Speeds

Since the hourly wind data from ERA-land have u (zonal) and v (meridional) components, we analyze the horizontal wind speed and direction at 10 m:

$$V(t, x, y) = \sqrt{u(t, x, y)^2 + v(t, x, y)^2} \quad (1)$$

where:

- $V(t, x, y)$: wind speed (m/s) at time t , at grid point (x, y) ;
- $u(t, x, y)$: zonal component (m/s);
- $v(t, x, y)$: meridional component (m/s);
- t : time (hourly);
- x, y : spatial coordinates (longitude, latitude).

The hourly values are converted to monthly maximums using Equation (2). For a given month m and year y , the monthly maximum is:

$$M_{m,y}(x, y) = \max_{t \in T_{m,y}} V(t, x, y) \quad (2)$$

where:

- $M_{m,y}(x, y)$: monthly maximum wind speed;
- $T_{m,y}$: set of time points in month m of year y ;
- $\max$: maximum operator.

2.3. Percentile Definition and Calculation

A percentile divides an ordered dataset into 100 equal parts and is used to analyze distribution and determine the relative position of a value.

The percentiles are calculated at each grid cell, and for a given month m , the following series is constructed: $\{M_{m,1991}(x, y), M_{m,1992}(x, y), \dots, M_{m,2020}(x, y)\}$ with a sample size $N = 30$ from 1991 to 2020. The percentile p is defined for each grid cell (x, y) :

$$Q_p(x, y) = \inf \{z \mid F_m(z; x, y) \geq p\} \quad (3)$$

where:

$$F_m(z; x, y) = \frac{1}{N} \sum_{i=1}^N \mathbf{1}_{\{M_{m,i}(x, y) \leq z\}} \quad (4)$$

- $Q_p(x, y)$: the p th percentile at grid point (x, y) ;
- $F_m(z; x, y)$: empirical distribution function of monthly maxima;

- $p \in \{0.90, 0.95, 0.99\}$
- $\mathbf{1}$: indicator function;
- $N = 30$
- $M_{m,i}$: monthly maximum for year i .

Percentiles are used as threshold values.

$$z_p(x, y) = Q_p(x, y) \quad (5)$$

The $z_p(x, y)$ values are then fed into the GEV model.

2.4. Using the GEV Model

The use of a Generalized Extreme Value (GEV) model with the block-maximum method is based on the extreme value theorem, which states that the distribution of the maximum values of a sample of independent and identically distributed variables converges to a GEV distribution when the block size is sufficiently large [6].

The empirical percentiles (Q_{90}, Q_{95}, Q_{99}) of the monthly maxima are used as intensity thresholds. For each of these thresholds, a generalized extreme value (GEV) distribution is fitted to the monthly maxima, allowing the non-exceedance probability $F_{\text{GEV}}(z)$ to be estimated.

The cumulative distribution function (CDF) of the GEV is given by:

$$(z; \mu, \sigma, \zeta) = \begin{cases} \exp\left(-\left[1 + \zeta\left(\frac{z-\mu}{\sigma}\right)\right]^{\frac{-1}{\zeta}}\right) & \text{si } \zeta \neq 0, 1 + \zeta\left(\frac{z-\mu}{\sigma}\right) > 0, \\ \exp\left(-\exp\left(-\frac{z-\mu}{\sigma}\right)\right) & \text{si } \zeta = 0 \quad (\text{cas Gumbel}). \end{cases} \quad (6)$$

where:

- μ : location parameter;
- σ : scale parameter;
- ζ : shape parameter;
- z : wind speed.

Parameter estimates for the GEV distribution using Maximum Likelihood Estimation (MLE) [7]

μ (Location parameter):

- Definition: Locates the center of the distribution.
- Interpretation: Corresponds approximately to the mode or median when $|\zeta|$ is small (< 0.3 , i.e., distribution close to Gumbel), otherwise the asymmetry becomes significant.

- Domain: $\mu \in \mathbf{R}$.

σ (Scale Parameter):

- Definition: Measures the dispersion of the data.
- Interpretation: The larger σ is, the more spread out the distribution is.
- Constraint: $\sigma > 0$.

ζ (Shape Parameter):

- Definition: Determines the behavior of the distribution tail.

- Interpretation:
 - $\zeta > 0$: Heavy tail (Fréchet).
 - $\zeta = 0$: Exponential tail (Gumbel).
 - $\zeta < 0$: Bounded tail (Weibull).
- Critical domain: $1 + \zeta(z_i + \mu)/\sigma > 0$.

Log-Likelihood (l)

For a sample $z_1, \dots, z_m$ the log-likelihood is:

$$l(\mu, \sigma, \zeta) = -n \log \sigma - \left(1 + \frac{1}{\zeta}\right) \sum_{i=1}^n \log \left[1 + \zeta \left(\frac{z_i + \mu}{\sigma}\right)\right] - \sum_{i=1}^n \left[1 + \zeta \left(\frac{z_i + \mu}{\sigma}\right)\right]^{-\frac{1}{\zeta}} \quad (7)$$

Under the constraint:

$$1 + \zeta \left(\frac{z_i + \mu}{\sigma}\right) > 0 \quad \forall i \quad (8)$$

Maximization of Log-Likelihood

Numerical steps [8]:

- Initialization: Use coarse estimators (mean, standard deviation, empirical skewness).
- Optimization:
 - Newton-Raphson or BFGS method (quasi-Newton algorithms).
 - Use constraints to avoid $\sigma \leq 0$ or invalid supports.
- Calculate standard errors using the inverse Hessian matrix $H = -\nabla^2 l$ to obtain confidence intervals.

2.5. Definition of the Return Period

The return period is a statistical tool used for extreme events (e.g., strong winds, heavy rainfall) to estimate the frequency of a given event.

The associated return periods are then calculated by:

$$T(z) = \frac{1}{1 - F(z; \mu, \sigma, \zeta)} \quad (9)$$

Where z corresponds to the empirical percentiles.

2.6. Analysis of Monthly Maximum Winds

Comparisons of hourly mean wind data from ERA5-Land with in situ measurements should be interpreted with caution. This is because observations exhibit high variability on small spatial and temporal scales and are strongly influenced by local topography, vegetation, and man-made obstacles factors that are only accounted for in a smoothed manner within the CEPMMT's integrated forecasting system. In addition, an explicit estimation of empirical return periods was performed using the Kolmogorov-Smirnov test (indirect comparison via the KS_p parameter between the wind data and the GEV distribution (P-value of the KS test). The fit is accepted if $KS_p > 0.05$ [9].

The AIC is included in the statistical calculations and in the mapping, using the

formula [10]:

$$AIC = 2k - 2\log(L) \quad (10)$$

where:

- k : number of parameters (here 3)
- L : likelihood

Hourly wind data in m/s over a 30-year period (1991 - 2020), sourced from ERA5-Land, were used to estimate the annual monthly maximum wind speeds at each grid point in Madagascar, with a resolution of 9 km. The return period was calculated for the 90th, 95th, and 99th percentiles for each month using the GEV distribution. We analyzed the distribution of monthly maximum wind speeds for each percentile to determine the range of maximum wind speeds. This distribution was chosen for its ability to describe extreme events in the context of climatic phenomena. The Beaufort scale is used to interpret the results (see **Table 2**).

Table 2. Beaufort wind scale and observed effects on land.

Force	Wind speed		Designation	Observed effects on land
	km/h	Knots		
0	Less than 1	Less than 1	Calm	Smoke rises vertically
1	1 to 5	1 to 3	Light air	Smoke drift indicates wind direction; vanes do not move
2	6 to 11	4 to 6	Light breeze	Wind felt on face; leaves rustle; vanes begin to move
3	12 to 19	7 to 10	Gentle breeze	Leaves and small twigs in constant motion; light flags extend
4	20 to 28	11 to 16	Moderate breeze	Dust and loose paper raised; small branches move
5	29 to 38	17 to 21	Fresh breeze	Small deciduous trees begin to sway; crested wavelets form on inland waters
6	39 to 49	22 to 27	Strong breeze	Large branches in motion; whistling heard in telephone wires; umbrellas used with difficulty
7	50 to 61	28 to 33	Near gale	Whole trees in motion; walking against wind requires effort
8	62 to 74	34 to 40	Gale	Twigs broken from trees; walking against wind is almost impossible
9	75 to 88	41 to 47	Strong gale	Slight structural damage occurs (e.g., roofing shingles dislodged)
10	89 to 102	48 to 55	Storm	Trees uprooted; considerable structural damage occurs
11	103 to 117	56 to 63	Violent storm	Widespread damage
12	118 to 133	64 to 71	Hurricane	Rare. Potential for extensive vegetation damage and significant structural damage

Source: [11].

3. Results

3.1. Maximum Wind Distribution

We will represent the extreme wind distribution of the 90th, 95th, and 99th percentiles for the months of January (summer) and July (winter) for the period from 1991 to 2020.

Month of January:

Distribution of monthly maximum wind speeds at the 90th percentile for January 1991 - 2020:

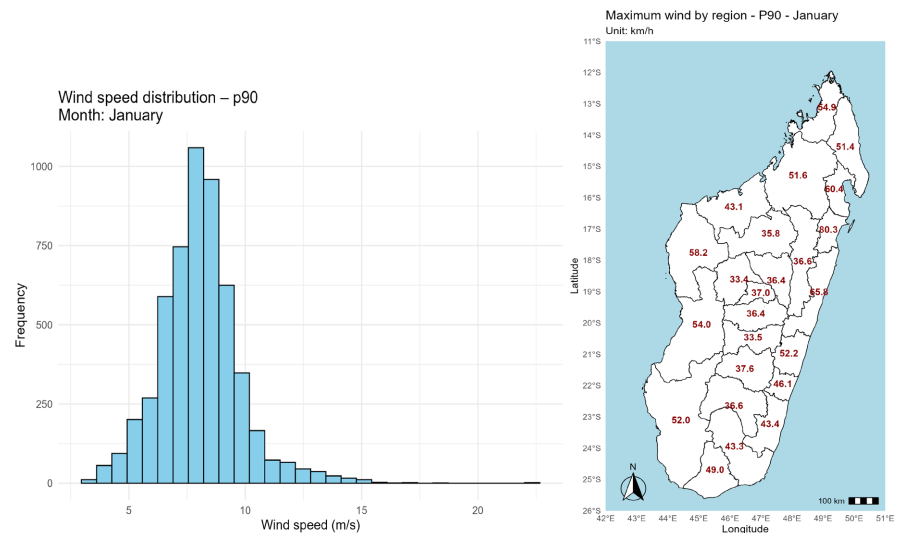


Figure 1. Distribution of maximum wind speeds (left) and maximum wind speeds by region (right), (90th percentile—January 1991 - 2020).

Maximum wind speeds range from 3.3 to 22.3 m/s (see **Figure 1**). The most common speed is 7.6 m/s (27.4 km/h): a gentle breeze on the Beaufort scale, lifting dust and paper, while light branches sway. A gust reaching 22.3 m/s (80.3 km/h) in the Analanjirofo region is equivalent to a strong gust of wind, capable of causing moderate damage to buildings (including roof shingles).

Distribution of monthly maximum wind speeds for the 95th percentile from January 1991 - 2020:

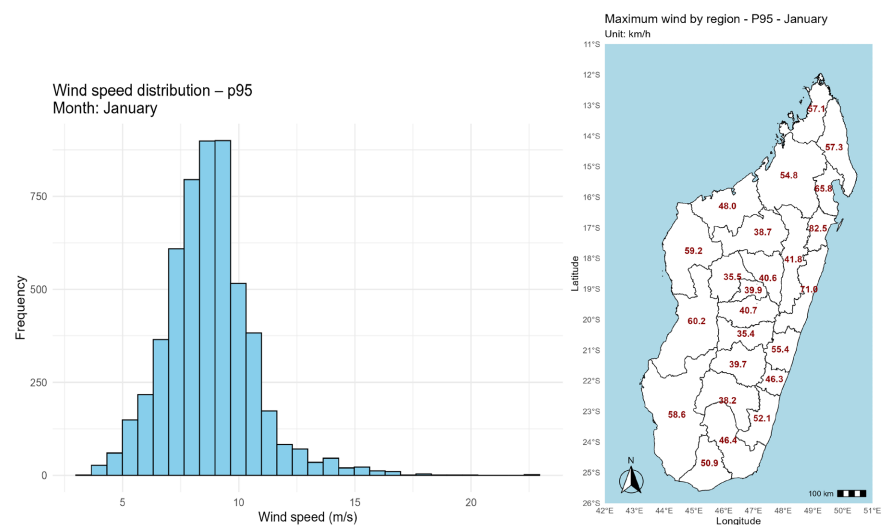


Figure 2. Distribution of maximum wind speeds (left) and maximum wind speeds by region (right), (95th percentile—January 1991 - 2020).

Maximum wind speeds range from 3.6 to 22.9 m/s (see **Figure 2**). The most common speed is 8.5 m/s (30.6 km/h): a moderate breeze on the Beaufort scale, causing young trees to sway and ripples to form on calm waters. At 22.9 m/s (82.5 km/h) in the Analanjirofo region, the wind, classified as a strong gale, can cause

minor damage to infrastructure.

Distribution of monthly maximum wind speeds for the 99th percentile from January 1991 - 2020:

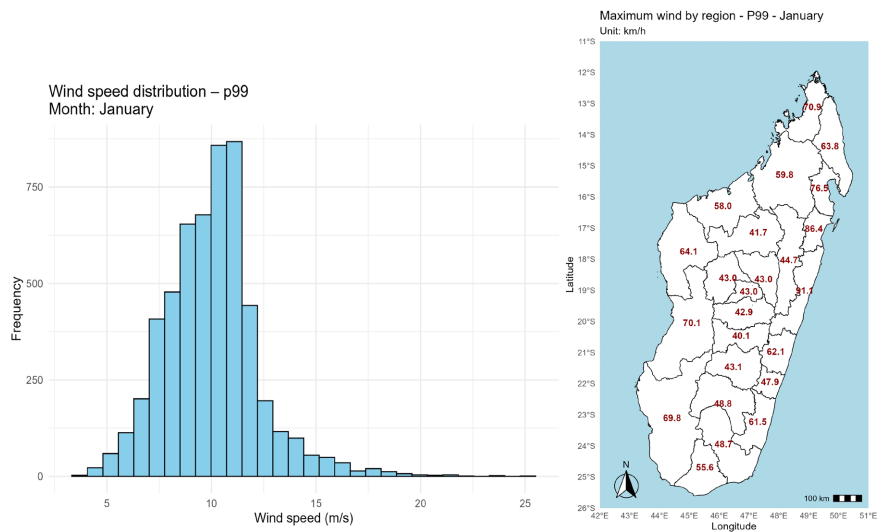


Figure 3. Distribution of maximum wind speeds (left) and maximum wind speeds by region (right), (99th percentile—January 1991 - 2020).

Maximum wind speeds range from 3.9 to 25.3 m/s (see **Figure 3**). The most frequent wind speed peaks at 11.5 m/s (41.4 km/h)—a brisk wind that bends large tree branches and makes umbrellas difficult to control. During a storm (25.3 m/s, or 91.1 km/h) in the Antsinanana region, the wind becomes destructive: trees are uprooted, and buildings are severely damaged.

Month of July:

Distribution of monthly maximum wind speeds for the 90th percentile from July 1991 - 2020:

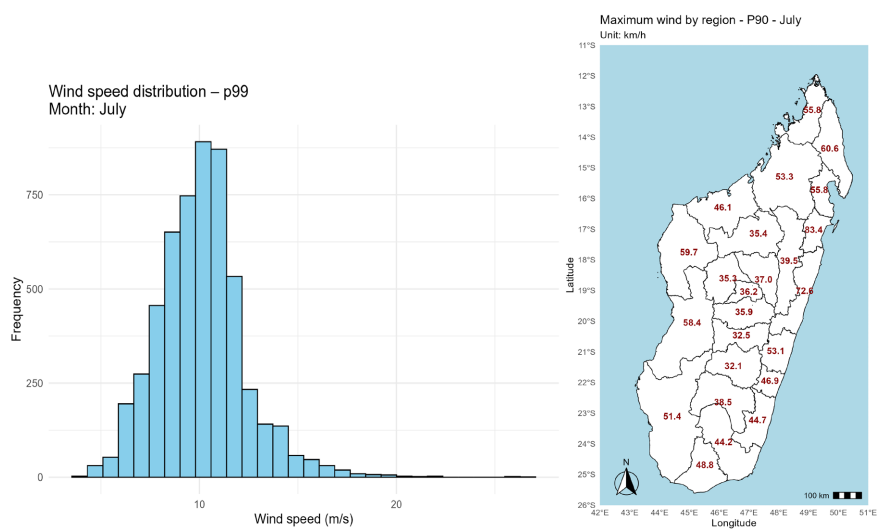


Figure 4. Distribution of maximum wind speeds (left) and maximum wind speeds by region (right), (90th percentile—July 1991 - 2020).

Maximum wind speeds range from 3.2 to 23.2 m/s (see **Figure 4**). The most common speed is 7.6 m/s (27.4 km/h): a moderate breeze characterized by flying debris. Gusts of 23.2 m/s (83.4 km/h) in the Analanjirofo region, classified as strong winds, pose a slight threat to buildings.

Distribution of monthly maximum wind speeds for the 95th percentile from July 1991 - 2020:

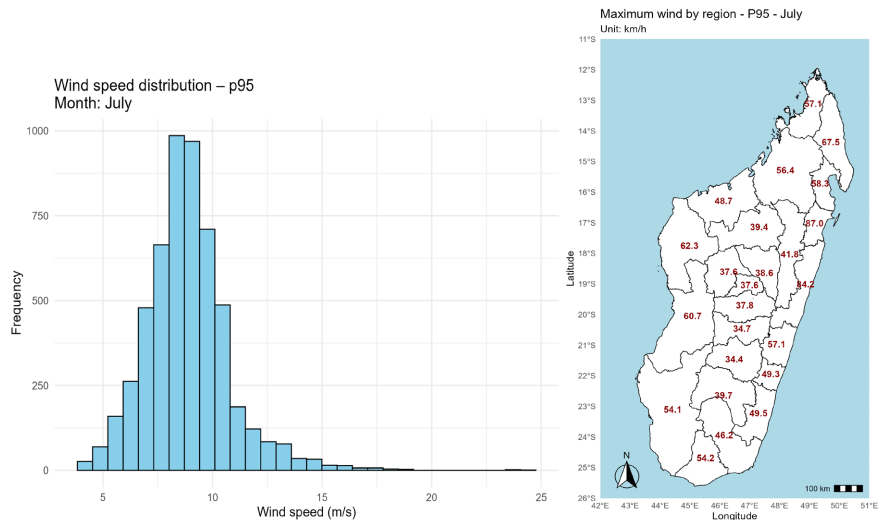


Figure 5. Distribution of maximum wind speeds (left) and maximum wind per region (right), (95th percentile—July 1991 - 2020).

Maximum wind speeds range from 4 to 24.2 m/s (see **Figure 5**). The most common speed is 7.6 m/s (27.4 km/h: a pleasant breeze). A wind of 24.2 m/s (87 km/h) in the Analanjirofo region, classified as a strong gale, poses a moderate risk to roofs.

Distribution of monthly maximum wind speeds at the 99th percentile from July 1991 - 2020:

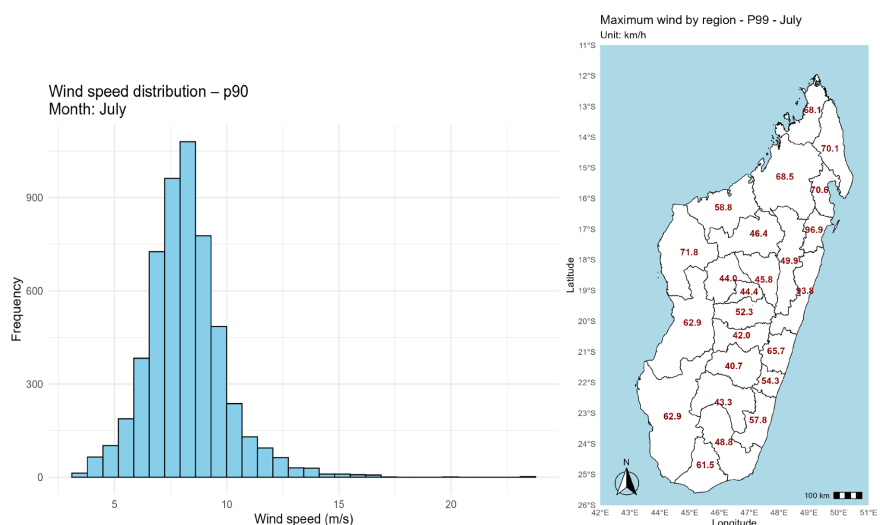


Figure 6. Distribution of maximum wind speeds (left) and maximum wind speeds by region (right), (99th percentile—July 1991 - 2020).

Maximum wind speeds range from 4.2 to 26.9 m/s (see **Figure 6**). The most common speed is 10.1 m/s (36.4 km/h: a pleasant breeze). In contrast, 26.9 m/s (96.9 km/h) in the Analanjirofo region triggers a violent storm, devastating to vegetation and homes.

3.2. Return Periods for Extreme Winds

These were determined for different percentile values and interpreted for various regions of Madagascar. By way of illustration, we will show the case of maximum winds for the 90th, 95th, and 99th percentiles for the months of July (winter) and November (summer) for the data period from 1991 to 2020.

The national average of the K_s values from the Kolmogorov-Smirnov test for January and July is 0.8, which is greater than 0.05, and the AIC values from the Akaike criterion are -65.1; therefore, the results are significant.

Month of January:

Figure 7 shows a return period range of 14 to 31 years for extreme winds (90th percentile). Part of the southern Diana region and part of the northern Sofia region have a return period of 31 years. The Analanjirofo region has a return period for extreme winds (90th percentile) of 14 years.

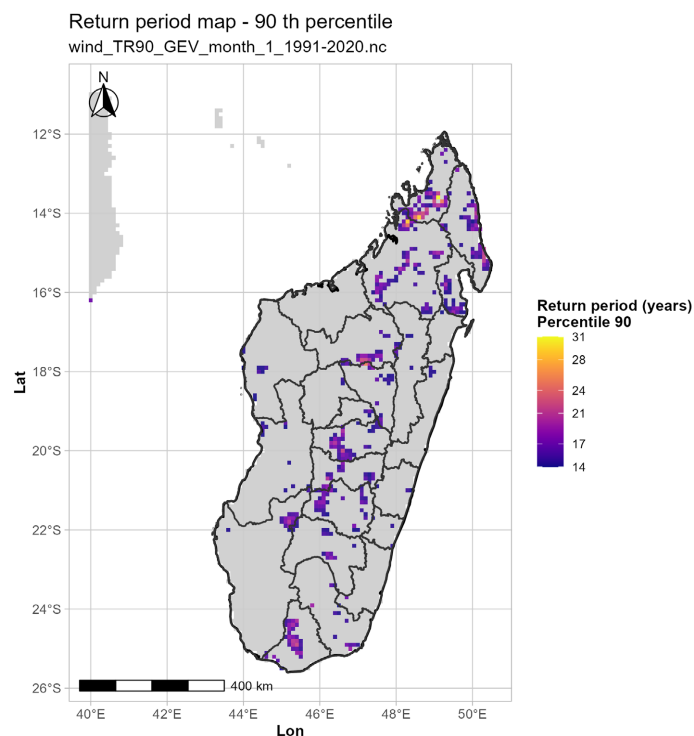


Figure 7. Map of maximum wind return periods for the 90th percentile (November 1991 to 2020).

According to **Figure 8**, extreme winds (95th percentile) occur once every 28 to 56 years; the central part of the Diana region has a return period of 56 years. The eastern part of the Androy region has a return period for extreme winds of 51 years.

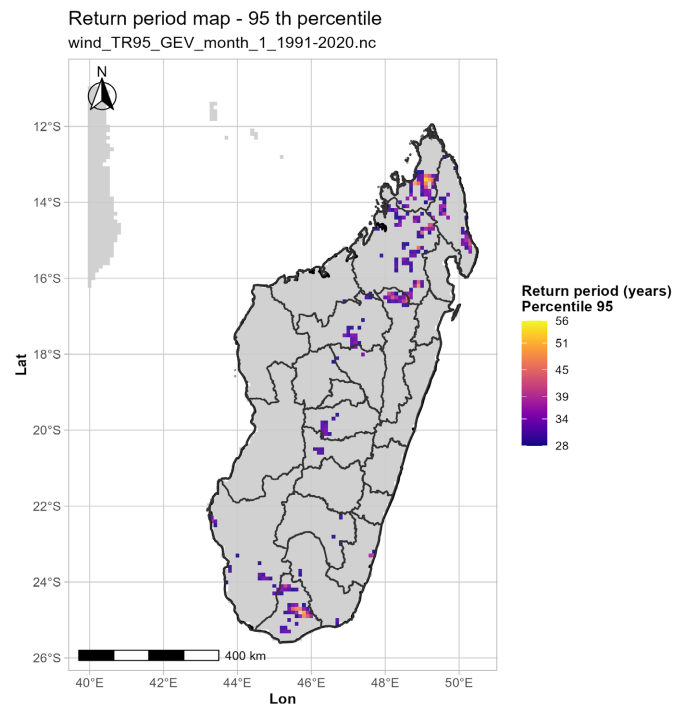


Figure 8. Map of maximum wind return periods for the 95th percentile (November 1991 to 2020).

Figure 9 shows a return period for extreme winds (99th percentile) ranging from 187 to 466 years, concentrated in the Boeny region and a small part of the northwestern Analamanga region of Madagascar.

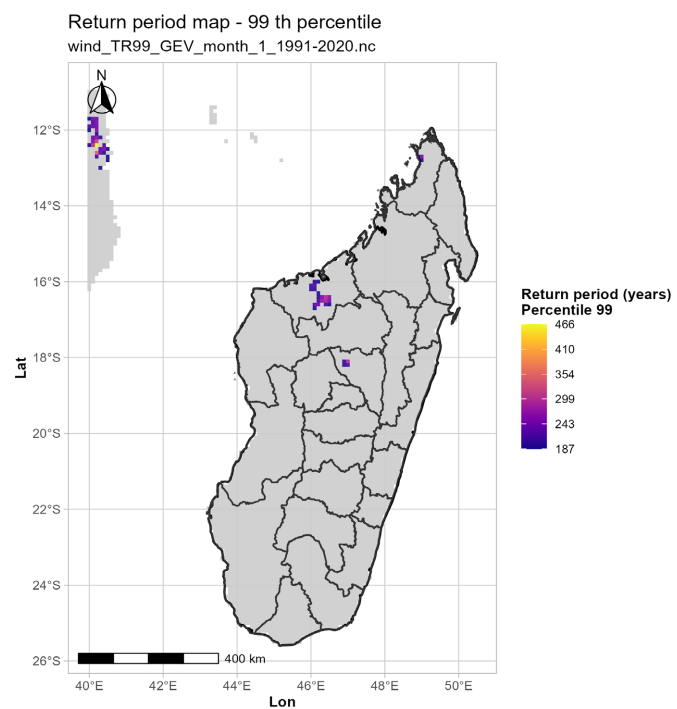


Figure 9. Map of maximum wind return periods for the 99th percentile (November 1991 to 2020).

Month of July:

Figure 10 shows that extreme winds (90th percentile) recur every 14 to 31 years, primarily affecting the southern part of the Sava region. The far north of the Sofia region and the far south of the Diana region have a return period of 28 years. The southwestern part of the Melaky region has a return period of 21 to 24 years.

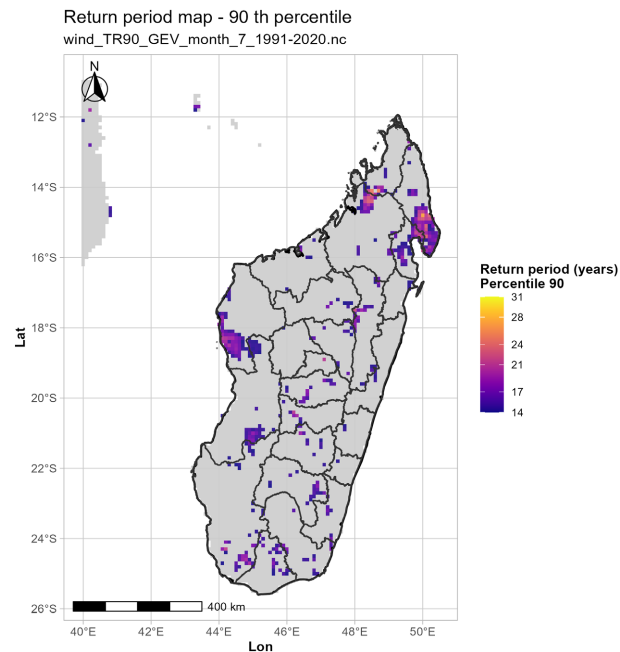


Figure 10. Map of maximum wind return periods for the 90th percentile (July 1991 to 2020).

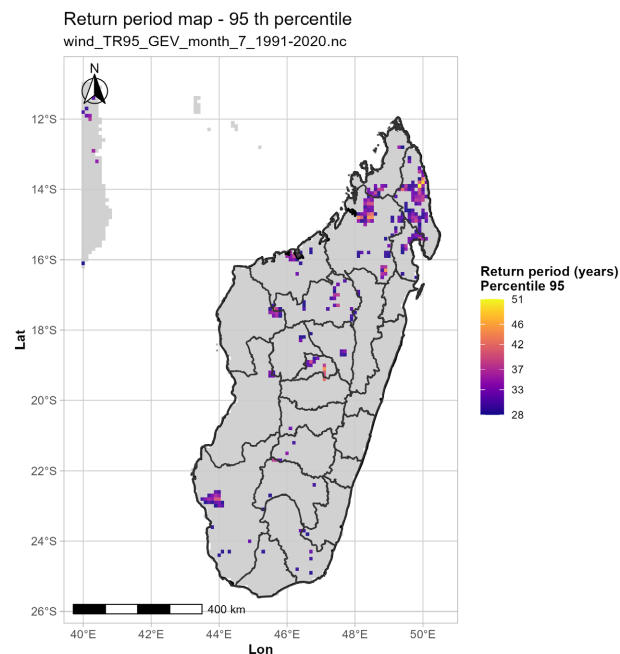


Figure 11. Map of maximum wind return periods for the 95th percentile (July 1991 to 2020).

Figure 11 shows that extreme winds (95th percentile) recur every 28 to 51 years. The northwestern part of the Sofia region and the south-central part of the Itasy region have a return period of 51 years. The central-eastern part of the Sava region also has a return period of 51 years.

Finally, the return period for extreme winds (99th percentile) ranges from 238 to 399 years in the western part of the Boeny region and a small part of the Sofia region (**Figure 12**).

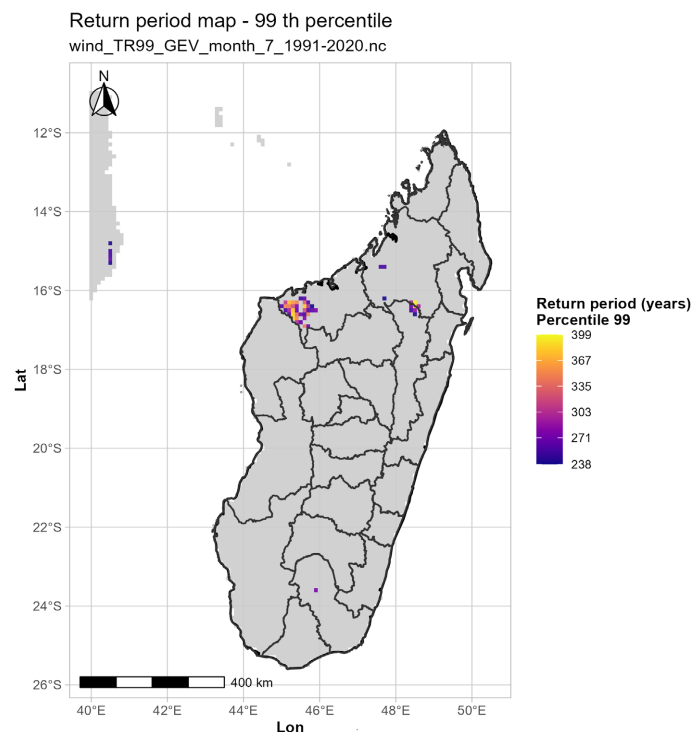


Figure 12. Map of maximum wind return periods for the 99th percentile (July 1991 to 2020).

4. Discussion

Analysis of the results suggests that nearly all parts of Madagascar are vulnerable to extreme winds, but particularly parts of the Diana, Sofia, Sava, Melaky, and Androy regions. Among these, the Analanjirofo region has the highest wind speeds at the 90th, 95th, and 99th percentiles. Note that the higher the percentiles of extreme winds, the longer the return periods, and vice versa. The northern, northeastern, northwestern, southern, and central parts of Madagascar are most affected by the return period of extreme winds. If we look at the average occurrence of extreme winds for the 90th, 95th, and 99th percentiles, we see that they cause discomfort for humans and affect most of Madagascar. The return period for extreme winds is 13 to 31 years for the 90th percentile, 28 to 56 years for the 95th percentile, and 187 to 466 years for the 99th percentile. It should be noted that this study is based on ERA5-Land hourly wind data, which is land-based and not merged. In the research by Jourdain, N. *et al.* (2020). “Cyclone Risk in the

Southwest Indian Ocean: From Seasonal Forecasting to Climate Change.” Springer, they found a return period of 20 to 50 years for extreme winds for ERA wind data that is over the sea [12]. The study by Terry *et al.* (2018). “Tropical Cyclones in the Southwest Indian Ocean: Impacts and Risks,” found a return period of 15 years for extreme winds [13]. These two results are not far from our result because the cyclone loses speed when it hits land, so in our case we can take the extreme winds of the 90th and 95th percentiles. However, to obtain more robust results, it would be advisable to take into account sampling variability as well as the uncertainty associated with the model parameters. These results are essential for infrastructure planning, comfort levels, and climate risk management, particularly in the context of cyclone forecasting.

5. Conclusions

To conclude, the study of extreme winds in Madagascar, based on ERA5-Land wind reanalysis data and GEV law modeling, provides a more accurate estimate of extreme wind speeds, with notable variations depending on the percentiles. The results are comparable to previous studies by Terry *et al.* and Jourdain, N. *et al.* on extreme winds in tropical areas. Although ERA-Land data offer valuable spatio-temporal coverage, their limitations in complex areas (coastal and mountainous) highlight the need to supplement them with in situ observations.

This information is essential for risk reduction (adapting infrastructure to high winds), urban planning (optimizing natural ventilation for thermal comfort), and climate policies (identification of vulnerable areas).

With a view to improving bioclimatic housing and territorial resilience, the data can be cross-referenced with thermal comfort indices.

This integrated approach makes it possible to reconcile safety and well-being in a context of increasing climate variability.

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest.

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