Elevational variation of temperature and relative humidity in the Parc National de Marojejy

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Abstract

The Parc National de Marojejy, home to the fourth highest peak of Madagascar (2130 m), has little been studied from a meteorological perspective. Climate data are important tools to better understand the impact of climate change on biodiversity and provide projections for future shifts. Five weather stations were set up on the eastern slope of the protected area, all at different elevations, ranging from 450 to 1900 m. Based on the data gathered between 2014 and 2020, albeit not continuously recorded throughout this period, the diurnal, seasonal, and annual variation of relative humidity and temperature are analyzed. The results show that temperature decreased with increasing elevation. Whereas relative humidity is highest at mid-elevation. Across the five elevational zones, the average annual mean temperature varies between 14.9°C and 21.8°C, the average annual relative humidity varies between 94.8% and 98.9%, the monthly average temperature varies between 11.1°C and 23.5°C, and the monthly average relative humidity varies between 88.6% and 99.3%. The cold season is between June and September and the warm season ranges between November and March.

Keywords: temperature, relative humidity, tropical mountain, Madagascar

Résumé détaillé

Le Parc National de Marojejy abrite le 4ème plus haut sommet de Madagascar (2130 m). Il a été peu étudié d'un point de vue météorologique. Pourtant, les données climatiques sont des outils importants pour mieux comprendre l'impact du changement climatique sur la biodiversité. Cinq stations météorologiques mesurant la température et l'humidité relative (type : MadgeTech RhTemp1000IS; un senseur de température et d'humidité relative, fabriqué par MadgeTech, Warner, New Hampshire, USA) ont été installées sur le versant oriental du parc à cinq niveaux altitudinaux. Les stations météorologiques ont été installées sur un intervalle d'environ 400 m d'altitude, sur cinq niveaux altitudinaux (450 m, 850 m, 1250 m, 1650 m et 1900 m). Les mesures d'humidité relative et de température ont commencé en décembre 2013 et se sont terminées en mars 2020. L'intervalle de lecture a été fixé à 1 h, et à l'heure locale UTC + 3. Les variations diurnes, saisonnières et annuelles de la température et de l'humidité relative sont analysées, basées sur des données d'observation entre janvier 2014 et mars 2020.

Les résultats montrent que pendant la période d'observation, la température a diminué avec l'augmentation de l'altitude. Alors que l'humidité relative est la plus élevée en moyenne altitude. En moyenne, la température moyenne annuelle varie entre 14,9 °C and 21,8 °C et l'humidité relative annuelle varie entre 94,8 % et 98,9 %, tandis que la température moyenne mensuelle varie entre 11,1 °C et 23,5 °C, et l'humidité relative moyenne mensuelle varie entre 88,6 % et 99,3 %. La saison froide se situe entre juin et septembre avec des températures descendant jusqu'à 4,5 °C. La saison chaude se situe entre novembre et mars, la température la plus élevée supérieure à 30 °C et l'humidité relative la plus faible inférieure à 40 % ont été enregistrées pendant ces périodes.

Mots clés : température, humidité relative, montagne tropicale, Madagascar

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Introduction

Tropical mountain habitats and the endemic species they contain are not only threatened by drastic land use changes, hunting, and invasive species, but are also sensitive to climate change including rising temperature and shifts in precipitation patterns (Bitencourt *et al*., 2016; Peters *et al*., 2019). Relative to other ecosystems and to habitats in the northern hemisphere, very little is known about the impacts of climate change on mountain habitat in the southern hemisphere.

Air temperature and relative humidity are identified as among critical weather components in climate studies (Kousari *et al*., 2011; Gunawardhana *et al*., 2017). Relative humidity is a percentage that indicates how saturated the air is with water vapor. Temperature, which is the thermal condition measured by different scales, has been revealed to diverge according to the relative influence of humidity, wind, and solar radiation.

Elevation is the dominant control of temperature and precipitation in mountains and can amplify the rate of warming (Pepin *et al*., 2015). Patterns of temperature, humidity, and precipitation along an elevation gradient directly influence the vertical distribution of biological communities. Because elevational gradients are continuous and can experience important climatic shifts over short distances, they are like "natural experiments" of the impact of global shifts in certain meteorological patterns on terrestrial ecosystems. Accurate measurements of climatic variables, especially surface air temperature and its elevational variations in mountainous areas, are vital for better understanding the impacts of climate change on range of different organisms and inference on how their distributions might change (Whittaker *et al*., 2001; Pepin *et al*., 2015).

Madagascar holds numerous tropical mountains, with the highest peak on the island rising to 2876 m, and these massifs form unique and diverse habitats with high beta-diversity shifts as a function of elevation. Madagascar's high massifs are remarkable for having a high degree of regional and local endemism, but remain largely unknown with respect to patterns of meteorological changes as a function of elevation. This in part is due to the remoteness of these areas, difficult access, and logistic complications to regularly gather climate data.

Here, we analyze the climate aspects of the eastern slopes of the Parc National de Marojejy, which holds the fourth highest peak on the island at 2130 m (see Goodman *et al*., 2023, herein, for further details on the massif). It is characterized by a large elevational range from 75 to 2130 m (Garreau & Manantsara, 2003; Goodman *et al*., 2018). The Parc National de Marojejy fits in tropical humid to superhumid rainforest of the Holdridge life zone system, with its annual rainfall of 2243 mm (Goodman *et al*., 2018), the variation of mean temperature along elevational gradient can divide the park into three zones: pre-montane, lower montane, and montane zones (Sisneros *et al*., 2011).

The aims of this paper are (1) to investigate variation in temperature and relative humidity based on the data obtained from the five weather stations installed along the eastern slopes of the Marojejy Massif and (2) to fill an important gap on climatic research in the mountains of Madagascar.

Materials and methods

Weather station installation and specifications

In December 2013, a field team associated with a bryophyte expedition to the Parc National de Marojejy installed five weather stations (type: MadgeTech RhTemp1000is; temperature and relative humidity data loggers; manufactured by MadgeTech, Warner, New Hampshire, USA) to record temperature and relative humidity data along the elevational gradient. The weather stations were installed at an elevational interval of approximately 400 m along the eastern slope of the park and placed in the vicinity Camp Mantella at 450 m (14.4368°S, 49.7754°E), above Camp Marojejya at 850 m (14.438°S, 49.7568°E), below Camp Simpona at 1250 m (14.4365°S, 49.7456°E), at 1650 m (14.4443°S, 49.7381°E), and 1900 m (14.4478°S, 49.7333°E) (Figure 1). All stations were installed away from tourist trails and in not noticeable places. Details on the sensor accuracy of the weather station model are given in Table 1.

Table 1. Specification of the sensors measuring in the weather stations.

	Temperature	Relative humidity (RH)
Sensor	Resistance Temperature Detector	Capacitive Polymer
Range	-40°C to +80°C	0% RH to 100% RH non-condensing
Resolution	0.01°C	0.1% RH
Calibrated accuracy	± 0.5°C	± 3.0% RH

Data and measurements

Relative humidity and temperature measurements began in December 2013 and ended in March 2020.

Figure 1. The weather stations were placed in rectangular plastic boxes with an open bottom and sides to protect the devices from direct solar radiation and to allow adequate ventilation. **A**) Protection grilles were glued in the bottom and sides of the box to prevent insects from entering. **B**) We attached and tied the plastic box to a horizontal wooden pole at a height of 1 m above the ground. (Photo by Lovanomenjanahary Marline.)

The reading interval was set to 1 h and at the local time UTC + 3. However, due to large fluctuations in the data during certain periods and malfunction of some of the devices, there are missing data for some months and years (Table 2). Herein we use the 1 h averaged data to analyze the diurnal and seasonal variations of temperature and relative humidity and employ daily data to analyze annual variation.

Table 2. Data representation. Light blue: data used for this study; dark blue: discarded and/or missing data.

	450 m	850 m	1250 m	1650 m	1900 m
Dec 2013-Jun 2014					
Jun 2014-Nov 2014					
Nov 2014-Nov 2015					
Nov 2015-Mar 2016					
Mar 2016-May 2017					
May 2017-Jun 2018					
Jun 2018-Aug 2018					
Aug 2018-Dec 2018					
Dec 2018-Oct 2019					
Oct 2019-Apr 2020					

Results

Elevational variation in temperature and relative humidity

Temperature shows a decreasing trend with increasing elevation. The annual average temperature varies between 14.9°C and 21.8°C (Figure 2). Maximum relative humidity at each elevation reaches 100%. Lowest relative humidity is found at higher elevation.

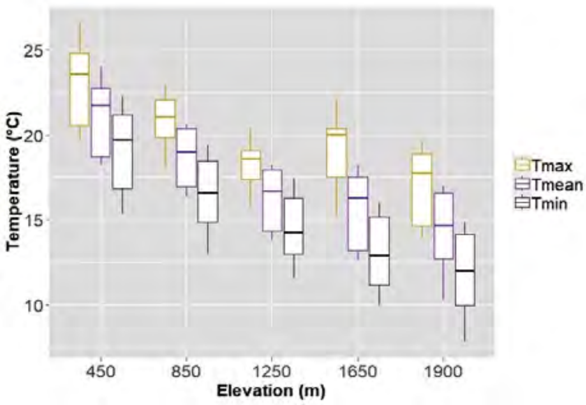

Figure 2. Elevational variations in the annual minimum temperature (Tmin), mean temperature (Tmean), and maximum temperature (Tmax) along the elevational gradient of the Parc National de Marojejy from December 2013 to April 2020.

Mean and minimum relative humidity are highest at mid-elevation and specifically the 1250 m site (Figure 3).

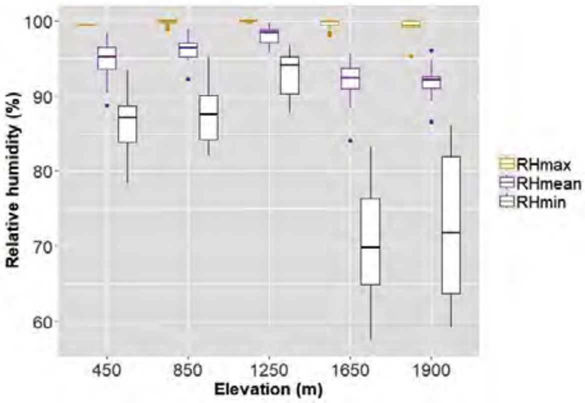

Figure 3. Elevational variations in the annual minimum relative humidity (RHmin), mean relative humidity (RHmean), and maximum relative humidity (RHmax) along the elevational gradient of the Parc National de Marojejy from December 2013 to April 2020.

Seasonal changes in temperature and relative humidity

Monthly mean temperature and relative humidity for each elevational zone are presented in Figure 4. The temperature plot shows a similar seasonal signature in the five elevational zones. The warmest months are from December to March, coinciding with the rainy season. There is a general cooling trend during the period from June to August (Figure 4A). The lowest recorded mean monthly temperature is 11.12°C at 1900 m in July. The highest mean monthly temperature is 23.49°C at 450 m in March.

The monthly relative humidity shows different patterns in each elevational zone (Figure 4B). At 1900 m, the monthly mean relative humidity fluctuates from 88.6% in September to 91.7% in October. Similarly, at 1650 m this parameter decreases for a few months starting in September (91.1% to 90.8% in October and November). At 450 m, on the other hand, the drop in relative humidity is slightly delayed and the decrease occurs from 91.7% in October to 88.8% in November. In contrast, at 1250 m, relative humidity throughout the year is distinctly more stable, as compared to higher and lower elevational zones and averaging between 98.1% and 99.7%.

Diurnal variation of temperature and relative humidity

In Figure 5, we display the mean diurnal temperature on a monthly basis at each elevational zone based on mean hourly records. Overall, temperature starts increasing around 6 h and starts to cool down after 16 h. At lower elevation (below 850 m), the hottest time of the day is between 12 h and 14 h. In contrast, at 1900 m, the hottest time of the day fluctuates from 8 h to 14 h and most likely associated with rapidly changing cloud cover. At mid-elevation (1250 m), temperature stays more constant throughout the day, as cloud development often prevents further warming. During the seven years of data collection, the highest recorded temperature was 33.9°C at the 450 m site, on 24 November 2016, and at 13 h and the lowest temperature was 4.5°C at 1900 m, 16 July 2019, and at 14 h.

In Figure 6, aspects of diurnal variation of relative humidity are given for each month and for each elevational zone and based on 1 h averaged data. Relative humidity plots show similar diurnal pattern for each zone. Overall, this variable starts to decline from 6 h to 16 h. During the month of June, relative humidity shows reduced variation for each zone, varying from 92.1% to nearly 100%. At 1250 m, relative humidity is consistent throughout the day

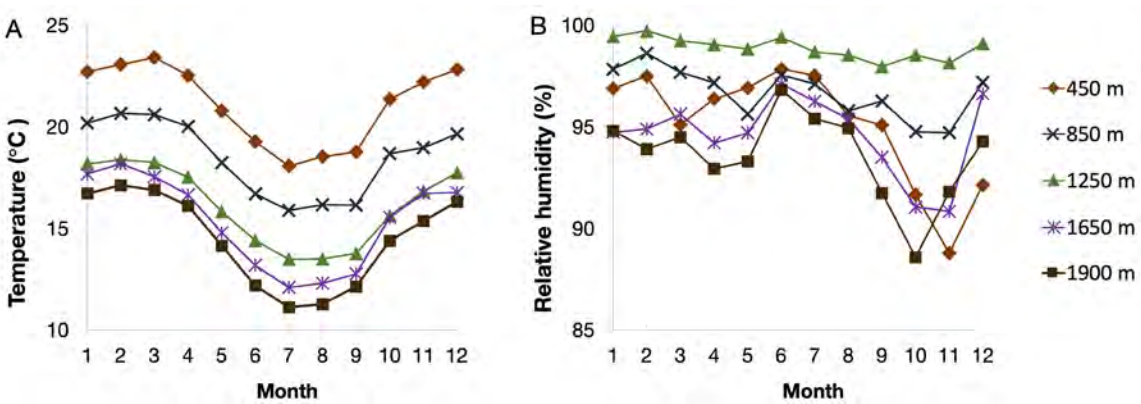

Figure 4. Monthly mean of temperature **A**) and relative humidity **B**) for each elevational site in the Parc National de Marojejy.

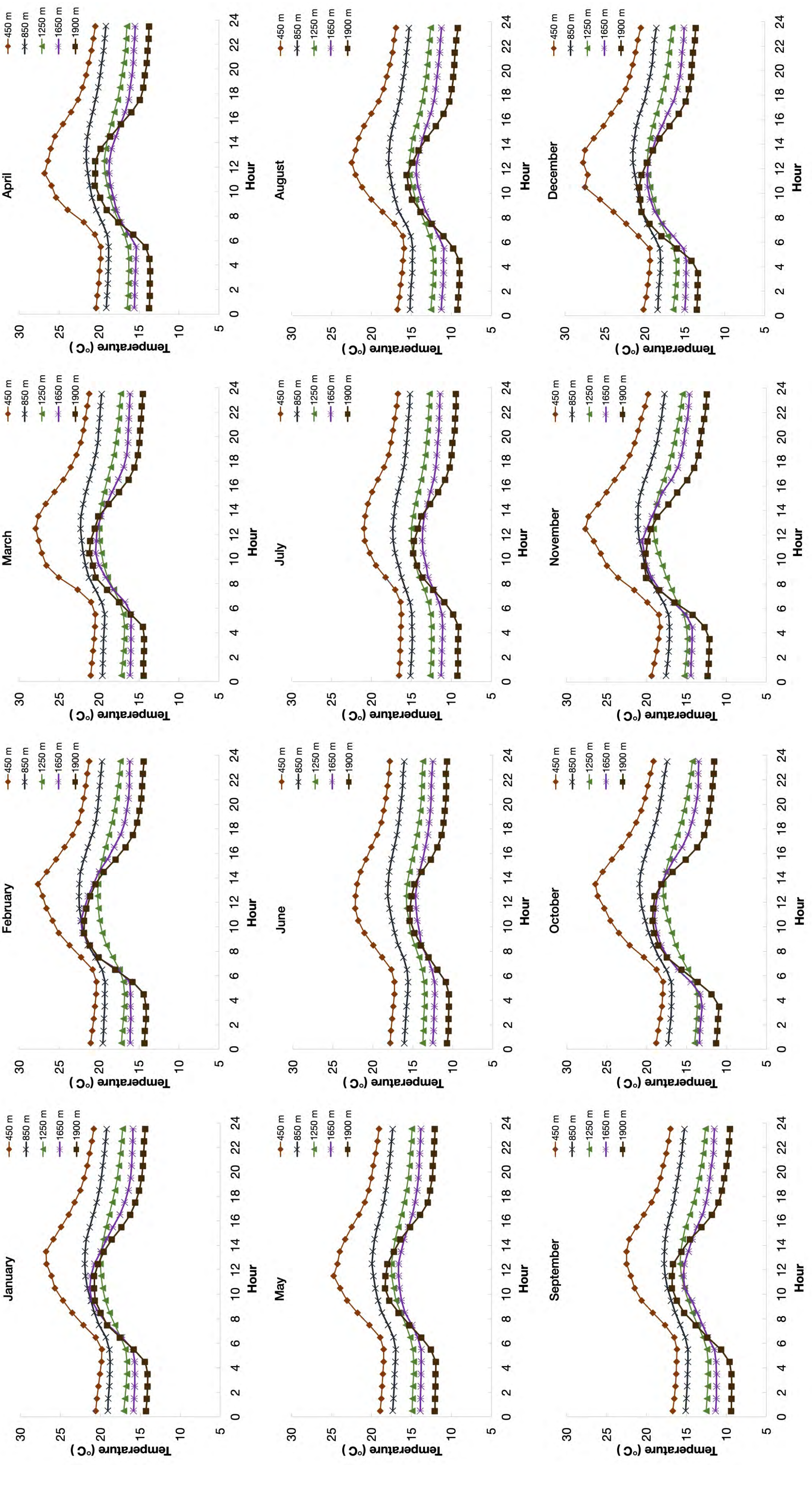

Figure 5. Diurnal variation in monthly mean temperature in five elevational zones along the eastern slope of the Parc National de Marojejy. The local time used in the analyses is UTC + 3.

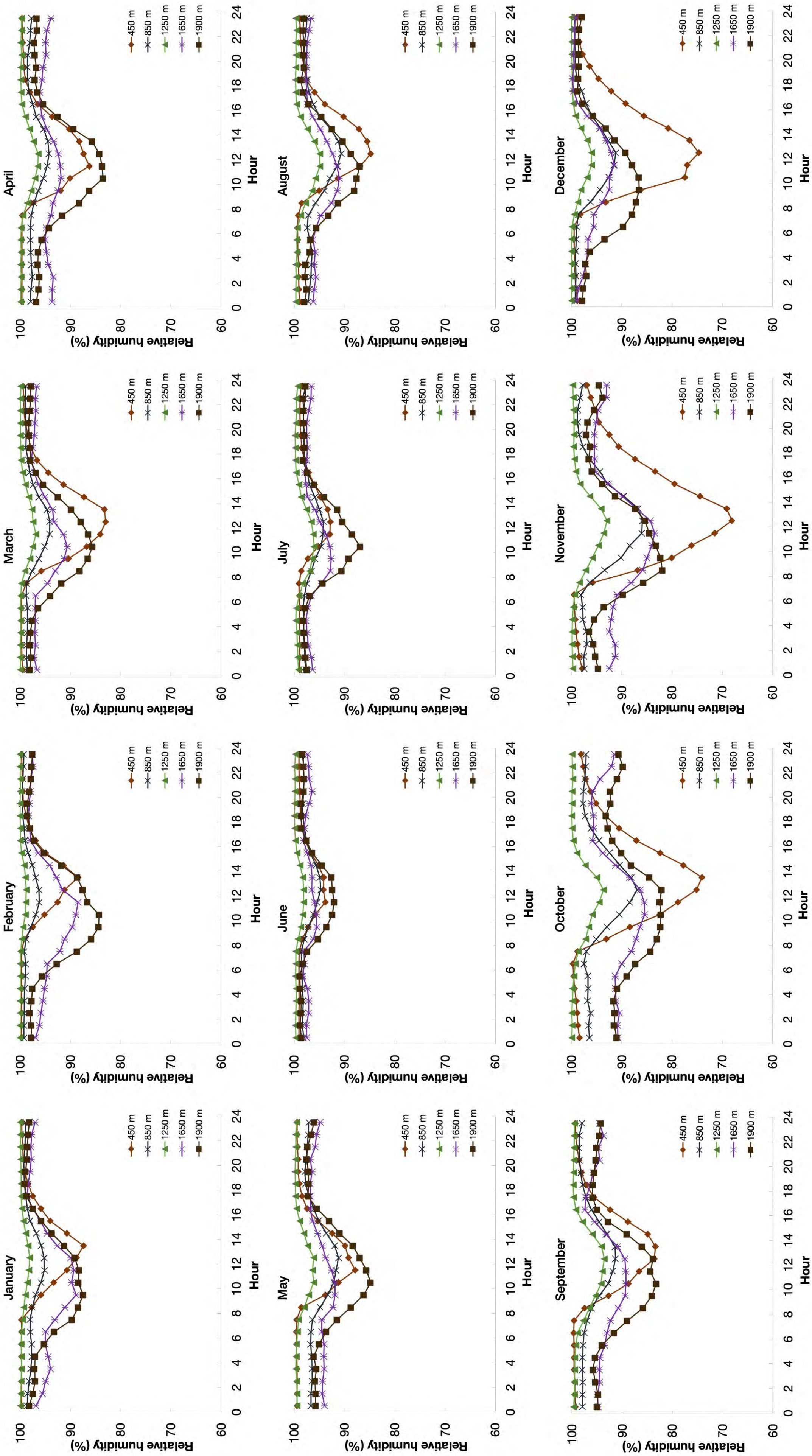

Figure 6. Diurnal variation in monthly mean relative humidity in five elevational zones along the eastern slope of the Parc National de Marojejy. The local time used in the analyses is UTC + 3.

for each elevation site (93%-100%). The lowest relative humidity recorded was 36.3% at 450 m on 25 November 2016 and at 13 h.

Discussion

Variation of temperature and relative humidity

On average and across all of the elevational zones, monthly mean temperature varies between 11.12°C and 23.5°C, whereas the monthly mean relative humidity varies between 88.6% and 99.3%. The cold season is between June and September with temperatures dropping to 4.5°C in the upper elevational zone. The warm season is between November and March, with temperatures over 30°C, and relative humidity dropping below 40%.

These patterns can be explained in part by regional trade wind patterns, and precipitation transported by these winds. The periodic cyclones and heavy rain during the months of November to April are associated with the Indian Ocean monsoons arriving from the northwest. The eastern trade winds generally carry light and variable rains with rare large scale storms between May and October. Moreover, relative humidity is a measure of the actual amount of water vapor as a function of air temperature and warm air can hold more water vapor (moisture) than cold air.

Temperature and relative humidity, drivers of elevational biodiversity pattern

The main drivers of elevational diversity patterns remain a subject of discussion. Climatic variables have been shown to play important roles in certain ecosystems (Bhattarai *et al*., 2004; Sanders *et al*., 2007). Climate directly controls the elevational and geographic range distribution of individual species (Rowe, 2009).

Marojejy is characterized by a large elevational range from 75 to 2132 m (Garreau & Manantsara, 2003). The nearly 2050 m altitudinal gradient superimposed on the 55,885 ha protected area and rugged topography, gives rise to very different vegetational communities (Tahinarivony, 2023, herein) in part associated with climatological patterns, in particular significant changes in temperature and relative humidity. The variation in factors such as rainfall intensity, length of dry season, humidity levels, and temperature ranges, are causal factors for variation in biological communities along elevational gradients (Rahbek, 2005; McCain, 2010; Übersicht *et al*., 2011; Lee *et al*., 2013; Baumann *et al*., 2016). For example, a study of bryophyte diversity and distribution along the slopes of the Marojejy Massif showed that temperature and relative humidity are the main drivers for the hump-shaped pattern of species richness at middle elevations (Marline *et al*., 2020).

Data accuracy and research perspective

We present the first analyses of climate variation along an elevational gradient for any large massif on Madagascar, here focusing on Marojejy. Due to battery failures and the need for data logger recalibration, it was necessary to reduce the data set from what should have been slightly less than seven years of continuous input (Table 2).

In any case, even with the reduced data set, we were able to gather important data to characterize temperature and relative humidity patterns across an elevational gradient on Marojejy. It is important to continue monitoring relative humidity and temperature across elevation on the massif to obtain long-term data on shifts in climatological patterns. More robust weather stations need to be used and a consistent protocol for gathering data is needed. Further, the addition of rainfall data and cloud coverage would be useful to better characterize long-term meteorological aspects on the massif, including the possible role of broad patterns of climate change. Such a system should also be installed on other tall mountains of the nearly 1600 km long length of Madagascar, which covers nearly 13° of latitude.

Conclusion

In this study, we employ temperature and relative humidity data from weather stations on Marojejy placed about every 400 m of altitude across a gradient from 450 to 1900 m. This study provided (1) new and fundamental insights into weather patterns in montane environments of Madagascar, for which little previous information was available and (2) vital baseline dataset that can be used to better understand diversity and distribution patterns of organism along the Marojejy elevational gradient, representing one of the most biologically rich protected areas on Madagascar. This study is an important first step to fill in a huge knowledge gap on the vulnerability of tropical mountains to climate change and the impact of such vicissitudes on the constituent organisms living in the natural ecosystems of these massifs.

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