Mapping radiative cooling potential predictions for Africa

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Abstract

Radiative cooling (RC) is a passive cooling technology which enables to cool down surfaces by rejecting radiation to outer space. The potential of this phenomenon depends on environmental factors. Africa is a continent with most of its land within the tropics, so cooling needs are in general high along the year and radiative cooling can play an important role for covering them in a renewable way. A powerful spatial interpolation method, known as Kriging, has been used to estimate values at unknown points of Africa and thus create continuous maps of radiative cooling potential (q_c). Additional maps have been created, showing the dry bulb temperature and the relative humidity over Africa. Results showed mean annual values of cooling potential of 77.64 W/m^2 and peak values of 135.80 W/m^2 in the desert. Observing the resulting maps, the higher the temperature and the lower the relative humidity, the higher the cooling potential.

Keywords: Radiative cooling, renewable cooling potential, mapping, spatial interpolation, Kriging, Africa

1. Introduction

Radiative cooling (RC) phenomenon takes advantage of the high transparency of the atmosphere in the infrared longwave spectral band, from 8 to 13 µm (known as atmospheric window), to reject radiation, allowing to obtain temperatures below ambient (Li et al., 2019) in a renewable way. According to Bijarniya et al. (2020), environmental factors like ambient temperature, cloud cover, moisture, wind velocity and pollution affect RC performances.

Africa is a continent with most of its land within the tropics, so cooling needs are in general high along the year and radiative cooling can play an important role for covering them in a renewable way. In fact, a recent report by the International Energy Agency (Birol et al., 2018) predicts that the refrigeration demand will triple worldwide by 2050 if no action is taken. On the other hand, the physicist Aaswath Raman predicted that the cooling demand will have a sixfold increase by 2050 because of the increase in use of the Asiatic and African countries (Raman, 2018). Aili et al. (2021) mapped the annual all-day mean RC power of all the world and found a high cooling power in Africa, especially in the northern countries.

The Radiative Collector and Emitter (RCE) is a device which combines radiative cooling with solar heating (SH) in a single device using an adaptive cover. The concept was theoretically presented by Vall et al. (2018). The RCE provides hot water during the day (SH) and cold water during the night (RC). As for the cooling mode of the RCE it is required to know the nighttime RC power potential, this work focuses on developing the map of Africa with this information.

During the night, when solar radiation is null, considering an emittance of ideal surfaces (ε_s) equal to one and assuming the surface temperature equal to the ambient, RC is maximized and can be determined using eq. 1 and eq. 2 (Vilà et al., 2020). The first term in eq. 1 refers to radiative heat exchanges, the second term is the infrared energy rejected by the surface and by the sky (q_{sky}), while last terms refer to convective and conductive heat transfer, respectively.

$$q_c(T_a) = \sigma T_a^4 - q_{sky} - q_{conv} - q_{cond} \qquad [Wm^{-2}] \qquad \text{(eq. 1)}$$

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$$q_c(T_a) = \sigma T_a^4\left(1 - \varepsilon_{sky}\right) - q_{conv} - q_{cond} \quad [Wm^{-2}] \qquad \text{(eq. 2)}$$

where σ is the Stefan-Boltzmann constant $[W/m^2K]$, T_a is the ambient temperature $[K]$ and ε_{sky} is the sky emissivity $[-]$.

According to Chang and Zhang (2019), if the radiative surface is designed to work at a surface temperature equal to the ambient (T_a), convective and conductive heat exchanges can be neglected, as shown in eq. 3.

$$q_c(T_a) = \sigma T_a^4\left(1 - \varepsilon_{sky}\right) \qquad [Wm^{-2}] \qquad \text{(eq. 3)}$$

Higher T_a implies high cooling potential at low relative humidity (RH) and low cooling potential at high RH (Dong et al., 2019). This study not only presents maps for radiative cooling (RC) potential, but also for temperature (T_a) and relative humidity (RH) of Africa, and determines the influence of these weather parameters in cooling potential.

2. Data acquisition and methodology

Meteonorm database (Remund et al., 2019) was used to download the information from weather stations in Africa, corresponding to the radiation period from 1991 to 2010 and the temperature period from 2000 to 2009.

A total amount of 615 weather files were downloaded from Meteonorm, but some of them implied a worse performance of the interpolation. After analyzing the effect of some weather stations on the metrics of the prediction model, the observations of Tamanrasset (south of Algeria), Saint Helena Island (south of the Atlantic Ocean) and Pozo Izquierdo (south of Las Palmas de Gran Canaria) were neglected, as shown in Fig. 1.

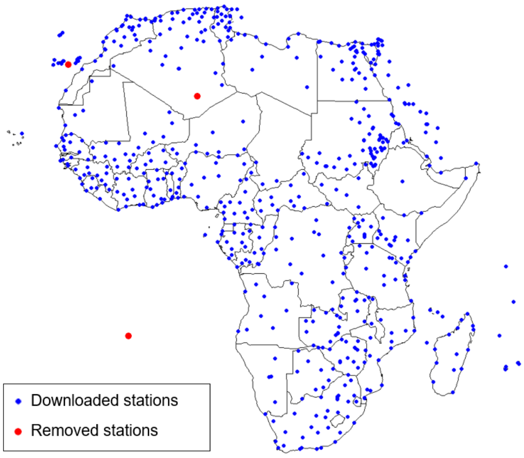

Fig. 1: Weather stations downloaded (blue) and removed (red)

RStudio was then used to clean and format the downloaded data, from which mean annual values at each location were calculated. Radiative cooling was determined using eq. 4. A mesh of 500,000 points was created to apply the spatial interpolation technique all over the continent. Although Northern Africa is the region where less stations are available, the selected interpolation method enables to have and accurate idea of RC potential on these countries.

$$q_c(T_a) = \sigma T_a^4 - q_{sky} \qquad [Wm^{-2}] \qquad \text{(eq. 4)}$$

The infrared energy radiation emitted by the sky (q_{sky}) was obtained directly from the Meteonorm database, which calculates this parameter using the Aubinet model (Aubinet, 1994).

Kriging interpolation enabled to determine radiative cooling, dry bulb temperature and relative humidity at each point of the previously created grid of Africa. It is a geostatistical interpolation technique to estimate values and determine the uncertainty of each interpolated result (standard deviation). Weights are not only based on the distance (the points near to the point of study have a higher influence on the prediction), but also ensure an unbiased model and a minimum variance (Vilà et al., 2020). A variogram is used to determine the weights of each point of the estimation and a mathematical model which best fits the variogram is found in order to minimize the error.

Data from the 612 files were divided into two subsets: 80% of the locations were used in the Kriging method, and the remaining 20% were used to evaluate the interpolation performance. 123 predicted values (x_{pred_i}) were compared with the observed ones (x_{obs_i}). The metrics of the prediction models examined were: the coefficient of determination (R^2, eq. 5) and the root mean squared error ($RMSE$, eq. 6).

$$R^2 = \frac{\sum_{i=1}^{N}\left(x_{pred_i} - x_{obs_i}\right)^2}{\sum_{i=1}^{N}\left(x_{obs_i} - \mu_i\right)^2} \qquad \text{(eq. 5)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(x_{pred_i} - x_{obs_i}\right)^2}{N}} \qquad \text{(eq. 6)}$$

where μ_i is the arithmetic mean of the observed values (x_{obs_i}). R^2 is dimensionless, while $RMSE$ has the same units as the variable interpolated (cooling power, temperature and relative humidity).

3. Results and discussion

Annual values of average cooling power potential after interpolating are shown in Fig. 2. The highest RC potential is found in the Sahara Desert, especially in Algeria, Niger, north of Mali and Sudan; although with a lower capacity, South Africa also stands out.

A mean nighttime RC power potential of 77.64 Wm^{-2} is observed, which is higher than the average studied in United States (48.30 Wm^{-2}) (Li et al., 2019), Europe (47.30 Wm^{-2}) (Vilà et al., 2021) and Northwest China (Chinese region with the highest potential on average, 60.10 Wm^{-2}) (Chen et al., 2021).

Tropical region is remarkable for a low RC power potential with high temperature (above the average, Tab. 1) and very high relative humidity (around maximum values).

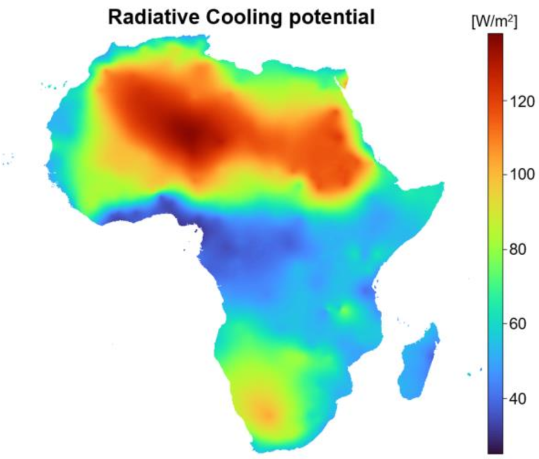

Fig. 2: Annual nighttime RC potential map of Africa

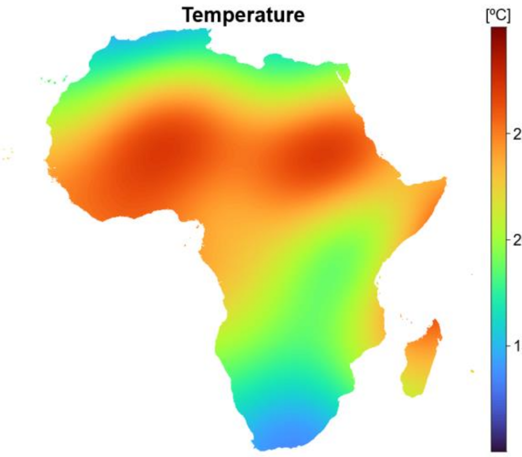

Fig. 3: Annual nighttime temperature map of Africa

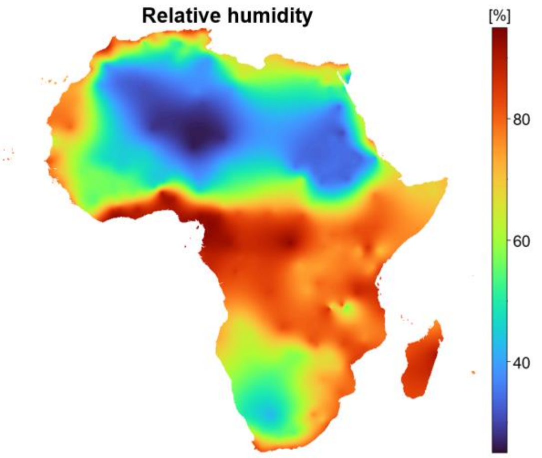

Fig. 4: Annual nighttime relative humidity map of Africa

The lowest RC potential is observed along the coastal zone from Nigeria to Gabon, with relative high T_a (Fig. 3) and extremely high RH (Fig. 4), confirming what demonstrated Dong et al. (2019).

It should be noted that the north of Africa is in the northern hemisphere, while the south of Africa is in the southern hemisphere. Both hemispheres have opposite seasons. The southern hemisphere is warmer in winter than the northern and cooler in summer (van Loon, 1991). On the other hand, countries like Gabon, Congo or Uganda, cross the equator and their climate conditions are stable through all the year. As the maps presented include mean annual results, these seasonal differences are not noticeable and do not affect the aim of this work: to estimate the average annual cooling power.

The best climate conditions in Africa for radiative cooling are: high temperature and low relative humidity, that is to say, the weather of the Sahara. Although there are some countries with low RH, specifically on the north, the tropical ones are very humid, which leads to mean values of RH above 60% (Tab. 1).

Tab. 1: Range and mean annual values of q_c, T_a and RH in Africa

	Minimum	**Maximum**	**Mean**
Radiative Cooling (q_c) [Wm^{-2}]	31.35	135.80	77.64
Temperature (T_a) [ºC]	13.63	27.96	21.95
Relative humidity (RH) [-]	25.98	93.29	60.93

Fig. 5, Fig. 6 and Fig. 7 show a clear comparison between predicted and observed data. A perfect interpolation would include all the points over the red straight line with a slope equal to 1. Analyzing the results, the average radiative cooling potential, temperature and relative humidity differences are 3.31 Wm^{-2}, 1.49 ºC and 2.68 %, respectively. As an overall, there are no big differences between the downloaded and the interpolated data, so results present a high coincidence.

On the other hand, the standard deviation maps (Fig. 8, Fig. 9 and Fig. 10) show that the points near the weather stations have less error (blue points), as expected. Maximum deviation points are located in regions with less climatic data available, like the Sahara Desert, Somalia and Namibia.

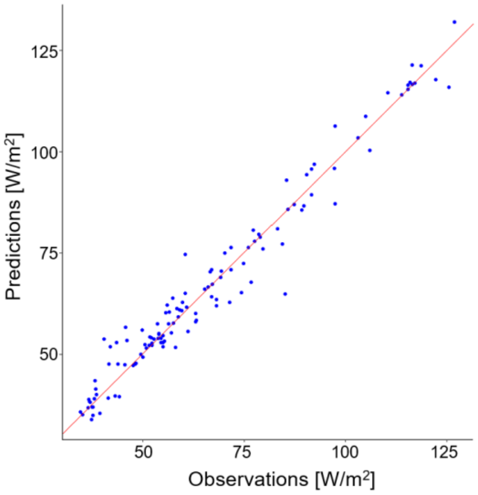

Fig. 5: Comparison between the predicted and the observed radiative cooling potential

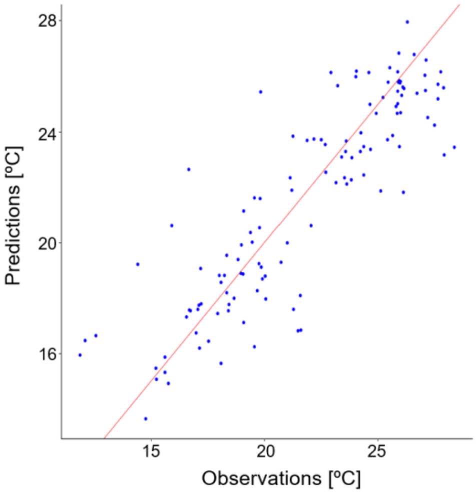

Fig. 6: Comparison between the predicted and the observed temperature

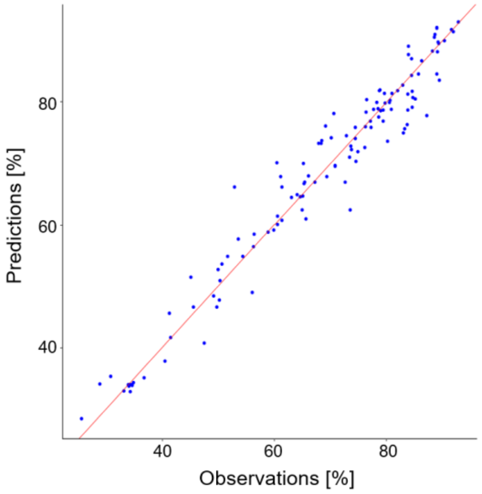

Fig. 7: Comparison between the predicted and the observed relative humidity

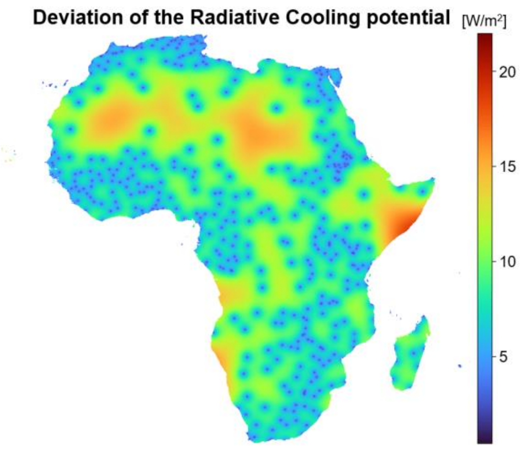

Fig. 8: Standard deviation of the nighttime radiative cooling potential of Africa

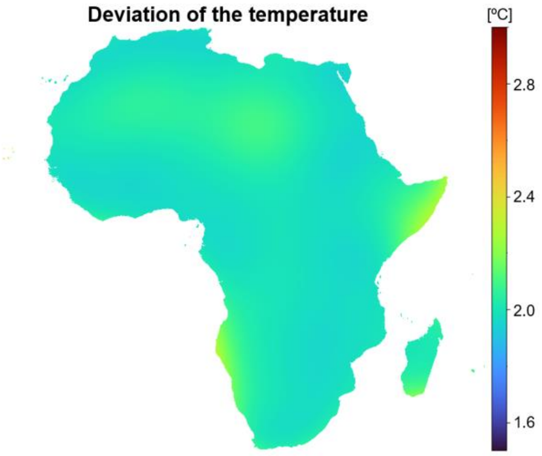

Fig. 9: Standard deviation of the nighttime temperature of Africa

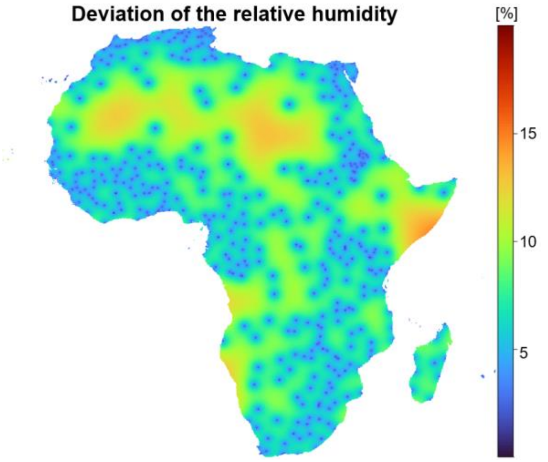

Fig. 10: Standard deviation of the nighttime relative humidity of Africa

q_c and RH show good accuracy (low RMSE values) and explain more than 95% of the variance (Tab. 2). Performance measures for the temperature show worse assessments metrics, but they are acceptable considering that the study by Li et al. (2016) (climatology field) endorse the results with a lower coefficient of determination.

Tab. 2: Measures of the prediction performance for each of the parameters calculated

	Radiative Cooling (q_c)	**Temperature (T_a)**	**Relative humidity (RH)**
R^2	0.96	0.75	0.95
RMSE	4.72 Wm^{-2}	2.01 ºC	3.75 %

4. Conclusions

In this work RC power potential has been mapped for Africa, showing an outstanding performance compared with United States, Europe and China, especially all over the Sahara Desert, where mean annual values above 100 Wm^{-2} are found, with peaks of 135.80 Wm^{-2}. Actually, the cooling potential of Africa is 64.14% higher than Europe, 60.75% higher than United States and 29.18% higher than Northwest China.

Vilà et al. (2021) found that the areas of Europe with the greatest RC power potential were the regions of southern Europe, so it makes sense that the north of Africa is characterized by the highest cooling power of this continent.

Temperature and relative humidity are climatic parameters which strongly affect RC and required conditions in Africa for 110 Wm^{-2} or more are: RH below 43% and T_a above 17ºC. Moreover, it has been corroborated what demonstrated Dong et al. (2019): high temperatures and low relative humidity are required to achieve high cooling power.

The spatial interpolation has correctly predicted nighttime RC power potential in Africa. Small differences between the predicted and the observed parameters are found and adequate metrics of R^2 and RMSE are obtained.

Future work could focus on the obtention of seasonal instead of annual values. This way, the effect of each hemisphere would be analyzed on the cooling power.

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