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Predicting the limits of the oasis effect as a cooling phenomenon in hot deserts

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Abstract

The water, a built environment, and a palm grove are an impressive trilogy making up the formidable oasis, rendering it strong enough to survive the harsh desert climate. Furthermore, the interaction between them creates several natural and physical phenomena. This research discusses the oasis effect, one of the most significant phenomena in the oasis ecosystem; this effect has been treated as a cooling phenomenon in theories and mathematical models. Therefore, we aimed to examine the impact and limits of this phenomenon in regard to the microclimate of oases through digital simulation, using the SPUCAL_oec software (Simulation Platform of Urban Climate in Arid Lands _ Oases Effect Calculator). Based on an innovative mathematical model, we developed SPUCAL_oec as an innovative vision for this green phenomenon, programmed to predict, calculate, and simulate the behavior and limits of the palm grove on the oasis microclimate. Finally, the results of SPUCAL_oec model showed that the oasis effect impacted the oasis microclimate owing to the existence of the palm grove. This effect could be as large as 6°C of temperature decrease and 12% increase in relative humidity. Furthermore, the SPUCAL software can aid designers and planners in making decisions regarding their design process.

Keywords: Oasis effect; Palm grove; Oasis; Model; Urban climate; Built environment; Arid lands; Desert; Vegetation

Nomenclature

T	Temperature from meteorological stations, °C	H1, H2	Humidity at points 1 and 2, %
Tmax	Maximum temperature, °C	Hp.h	Palm grove humidity per hour, %
Tmin	Minimum temperature, °C	Hetp.h	Potential evapotranspiration per hour, %
Th	Temperature per hour, °C	Hsat	Saturation humidity, %
Td	Desert temperature, °C	Hsat.h	Saturation humidity per hour, %
Tp	Palm grove temperature, °C	ETP	Potential evapotranspiration, g/m^3
Tp.h	Palm grove temperature per hour, °C	ETPh	Potential evapotranspiration per hour, g/m^3
T1, T2	Temperature at points 1 and 2, °C	h	Code for an hour
Hmax	Maximum humidity, %	ph	Compatibility coefficients
H	Humidity from meteorological stations, %	hi	High of the palm grove, m
Hmin	Minimum humidity, %	ΔP	Difference in pressure, N/m
Hh	Humidity per hour, %	V	Wind Velocity, m/h
Hp	Palm grove humidity, %	Mp	Air mass in the palm grove, Kg
Hd	Desert humidity, %	M1, M2	Air mass at points 1 and 2, Kg

1. Introduction

Among all the extreme environments worldwide, deserts cover over 50 million km^2 (Larousse, 2016), equivalent to 33% of all

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continental areas around the world. Moreover, all these deserts share most of the following characteristics: scarcity of rainfall, scarcity of fauna and flora, high solar radiation, very low humidity, and high temperature, with average daily temperatures year-round ranging from 20°C to 30°C and an annual variation of up to 60°C (von Willert, 1992; Gritzner, 2016; Encarta, 2009). However, despite all these harsh environmental characteristics, the inhabitants have adapted to desert climates by finding a magic formula that creates the wonder of the world (the oasis). A three-part system creates the oasis: the water, a built environment, and a palm grove. By creating several natural phenomena such as forest breeze, cool island, and the oasis effect, these three elements make oases strong enough to withstand extreme environmental conditions; moreover, presence of water and vegetation give rise to the oasis effect as one of the most significant phenomena in the oasis system, offering a comfortable microclimate for inhabitants (Potchter *et al*., 2008).

In fact, hot desert oases are the most famous in the world with their fictional scene comprising camels, lakes, palms, and sand dunes. Furthermore, the main components of an oasis (water, a built environment, and a palm grove) live in a stable environmental state; Therefore, oasis offers a lesson in sustainable human settlements (Ahriz, 2003;Ahriz, 2018). The first component (water) can be a lake, a river or a well; the second component (built environment) is the inhabitant's residence, and the final component (palm grove). The palm grove is also a three-part system with three different heights of agricultural system: the lowest level (comprised of plants, herbaceous flora, humid soil, and fruited trees), the intermediate level, and the highest level which protects palms against solar radiation (Shahidan and John, 2008). Each component affects the harsh desert climate, but their interrelation enables the oasis to survive.

Moreover, all these phenomena, especially the vegetation climatic behavior in urban environments, have been the focus of many studies using several methods and approaches. Particularly, over the past decades, several studies have employed digital simulation as the most significant method. Moreover, some of these studies have discussed the simulation of tree impacts on the streets and the microclimate (Shashua-Bar *et al*., 2010) while others have predicted the influence of gardens and urban parks on the local climate (Brown *et al*., 2015); few works, on the other hand, have investigated the impact of large green surfaces on the whole city climate or the Meso-scale (Grimmond *et al*., 2011).

According to Krayenhoff (2014), in 1979, John Norman gave rise to several models of vegetation climatic behavior; he developed the CUPID software based on the SVAT model. During the past decades, developers have used several ideas, concepts, and theories to advance other models in this field, yet few have dealt entirely with vegetation. As a matter of fact, this period began with three models: (a) the Green CTTC model developed by (Shashua-Bar and Hoffman, 2002), (b) LUMPS model developed by (Grimmond and Oke, 2002), and (c) SUEB model developed by Fortuniak *et al*. (2003). Furthermore, all these models were developed based on the statistical method while the next step was the process-based method with more complexity and highly accurate predictions. Prior to the present study, only five models in the world made use of this innovative approach: (a) DA-SM2-U developed by (Dupont *et al*., 2004) where the thermal drag phenomenon was integrated to predict the urban climate in rural environments, (b) VUCM model developed by (Lee and Park, 2008), which is the first single layer model which considers the impact of vegetation on wind velocity and different thermal exchanges, (c) TEB_Veg developed by (Lemonsu *et al*., 2012) where they ingrate the thermal exchanges between vegetation and urban built environment on the original TEB model of Masson (2000), (d) BEP_Tree developed by (Krayenhoff *et al*., 2015) is the most recent model which makes use of the multi-layer system.

This research begins by hypothesizing that the palm grove is able to generate a more comfortable microclimate compared to that of the desert, a phenomenon called the oasis effect; however, the actual problems are the limits of this phenomenon and how we might benefit from its advantages. These scientific issues guided us in developing a new model, SPUCAL (Simulation Platform of Urban Climate in Arid Lands), as an innovative vision to predict, calculate, and simulate the impact of palm grove on the microclimate (Ahriz, 2017;Ahriz, 2018). To reach the main objective of this research, we presented and simulated several forms, structures, and sizes of the oasis.

2. Environmental benefits of the palm grove structure on the urban built environment

Like other types of flora, the palm grove affects the microclimate of desert oases in several ways (de Abreu-Harbich *et al*., 2015; Ahriz *et al*., 2017; Lehmann *et al*., 2014; mei *et al*., 2016;

MLIH et al., 2016; NOUMI, 2015; Shahidan and John, 2008; Ahriz, 2018). Based on these studies, we can summarize the palm grove benefits as follows: (a) provision of shade, humidity, and temperature regulation, (b) modification of wind direction, (c) absorption of smell and gas, and (d) noise attenuation.

2.1. Impact on wind

2.1.1. Sand winds

Generally, sand winds are very strong; therefore, we utilized many types of palm grove to repel and deflect them (Fig. 1. Repulsed and deflected winds by the palm grove (Ahriz *et al.*, 2017)); furthermore, to deflect winds above the urban canopy, we could employ the wind springboard (Figure 2) (Ahriz *et al.*, 2017; Lei and Aifeng, 2016; Ahriz, 2018).

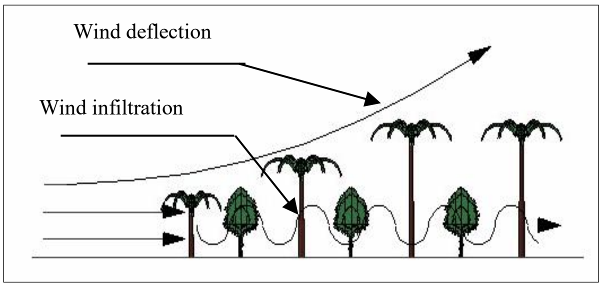

Fig. 1. Repulsed and deflected winds by the palm grove (Ahriz *et al.*, 2017)

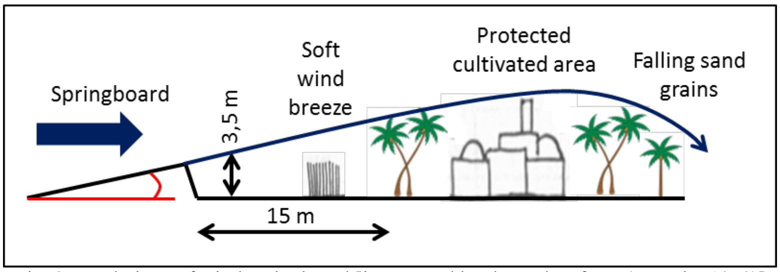

Fig. 2. Technique of wind springboard [interpreted by the author from (Toutain, 1979)]

2.1.2. Hot and dry winds

Hot and dry winds are slower and less powerful than sand winds; in this regard, the three vegetated layers under the palm parasol humidify the winds and reduce the air temperature (Fig. 3. Impact of the palm grove upon hot & dry winds (Ahriz *et al.*, 2017)) (Shahidan and John, 2008). Moreover, Potchter *et al.* (2008) described the oasis effect as a climatic modification owing to the presence of a wetland in a dry area.

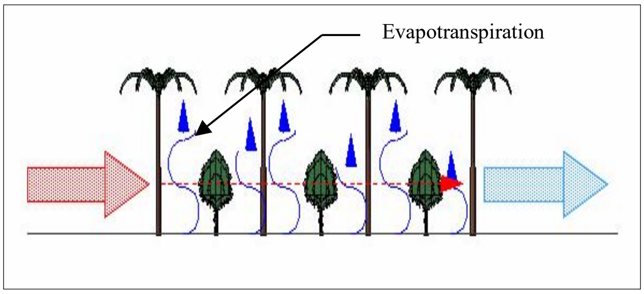

Fig. 3. Impact of the palm grove upon hot & dry winds (Ahriz *et al.*, 2017)

2.2. Impact on humidity and air temperature

Many types of trees, shrubs, plants, and grass can produce quantities of water through evapotranspiration, thereby increasing humidity and reducing temperature (Ahriz, 2003; Picot, 2004; Lehmann *et al.*, 2014; Ahriz, 2018). Furthermore, on hot summer days with no air movement, the built space warms up faster than the surrounding palm grove, creating a low-pressure area that withdraws cool air from the palm grove (Fig. 4. The breeze of forest phenomenon in an oasis, by authors); Otto (2000) called this phenomenon “the breeze of the forest”.

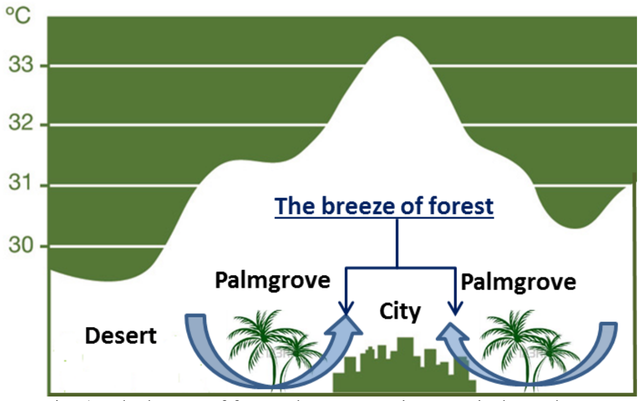

Fig. 4. The breeze of forest phenomenon in an oasis, by authors

2.3. The oasis effect as a cooling phenomenon

The oasis effect reduces the air temperature because of the existing moisture source (water surface or a green area) (Potchter *et al*., 2008). Some researchers have attributed this phenomenon to the evaporative cooling effect (Oke, 1987;Potchter *et al*., 2012;Zhang *et al*., 2008) whereas others have ascribed it to the cooling effect phenomenon (Givoni, 1991). Therefore, an isolated moisture source is always cooler than the adjacent areas (Potchter *et al*., 2008).

3. Research Aim and Method

This paper investigates the oasis effect as a cooling effect; The research method depends on the experimental method which is divided into three stages: (a) recording facts, (b) building a preliminary theory, and (c) conducting the experiments. In the first stage, we used the Righ Valley, an oasis region in the Algerian Sahara, as a case study to collect and record the required information.

To analyze the climatic context, a suitable set of climatic data is required for the location under investigation (Mohamed, 2013; Mohamed, 2014; Mohamed and Gado, 2006; Mohamed *et al*., 2005). The method involves employing synthesized climatic data generated by the Meteonorm software, which interpolates the climatic data needed for a specific location using the data from the nearest meteorological station to this location. Therefore, we rescaled the interpolated data using the Data Synthesis feature of the Weather Tool software.

The second stage involved analyzing the literature to draw up a preliminary theory regarding the case study. In the third stage, we performed a digital simulation of the palm grove behavior through the use of SPUCAL_oec as an innovative model for estimating the oasis effect on microclimate.

4. SPUCAL_oec as an innovative digital model for the oasis effect simulation

SPUCAL (Simulation Platform of Urban Climate in Arid Lands) is an innovative digital platform developed by the main author in 2013. This platform is able to simulate various microclimatic elements such as Tmrt, T, H, SOL_rad, and others; moreover, SPUCAL can help designers, researchers, and scientists interested in arid lands to design a sustainable and comfortable outdoor built environment.

The oasis effect calculator (OEC) is a calculator-based program developed by the first author in an M.Phil. thesis (Ahriz, 2003). In 2017, this program was developed into a simulation software package (SPUCAL_oec) defended in a PhD thesis (Ahriz, 2018). To obtain accurate results, the mathematical model is based on many complex theories, physical rules, and climatic curves, including many physical parameters specific to arid lands. Furthermore, we organized the model into three main steps: the first one involves acquiring climatic data concerning the desert and the second calculates the climatic data in the palm grove’s center; finally, the software can predict the new microclimatic data generated by the palm grove owing to the oasis effect (see the SPUCAL_oec algorithm, (Fig. 5. SPUCAL_oec algorithm, by authors)).

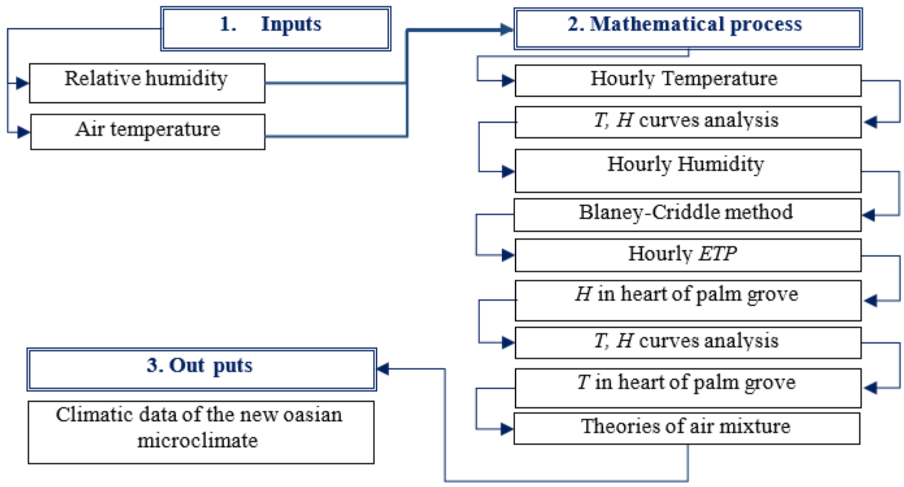

Fig. 5. SPUCAL_oec algorithm, by authors

4.1. Estimating the hourly average air temperature

We initially based this model on the Szokolay chart digitization (Ahriz, 2003), which requires Tmax and Tmin inputs. Next, the model can estimate T every hour using formulas extracted from the chart demonstrated in (Fig. 6. Digitization of Szokolay chart (Ahriz 2003)).

$$T_h = T_{max} - \hat{T}_h \quad (1)$$

$$\hat{T}_h = \tan \propto \cdot h^{14.6} \quad (2)$$

$$tan \propto = (T_{max} - T_{min})/h^{14.6} \quad (3)$$

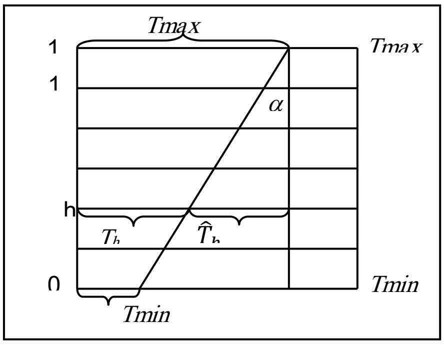

Fig. 6. Digitization of Szokolay chart (Ahriz 2003)

4.2. Calculation of hourly air humidity

Secondly, this step was based on the theory of compatibility between T and H graphs, with Tmax corresponding to Hmin and Tmin to Hmax.

$$P_h = \left({(T_h - T_{min})}/{(T_{max} - T_{min})} \right) \cdot 100\% \quad (4)$$

$$H_h = {(P_h \cdot (H_{min} - H_{max}))}/{(100 + H_{max})} \quad (5)$$

4.3. Predicting air humidity in the palm grove's center

In this step, the model is able to predict the quantities of water generated every hour in the palm grove by evapotranspiration using a corrected Blaney-Criddle method (FAO, 2016):

$$ETP_h = 0.0416 \cdot (0.46 \cdot T_h + 8.13) \quad (6)$$

The next step is the conversion of ETP from mm to g/m^3: if ETP = 1 mm, then ETP = 100 g/m3. The model is then able to predict H in the palm grove's center:

$$H_{p.h} = H_h + H_{etp.h} \quad (7)$$

$$H_{etp.h} = ETP_h / H_{sat.h} \quad (8)$$

4.4. Physical corrections

4.4.1. Night correction factor

Doorenbos and Pruit (PNNL, 2016) developed the night correction factor to correct the Blaney-Criddle formula and other formulas. Specifically, the factor corrects nocturnal ETP which decreases due to the halt in photosynthesis and respiration at night. Furthermore, this factor takes into account the cultivated area as demonstrated in (Table 1).

Table 1. Night corrector factor (Oliver 1973)

Cultivated area (hectare)	Night corrector factor
01	0.14
10	0.16
100	0.21
≥ 1000	0.25

4.4.2. Oasis effect correction factor

Scientifically, the contrast between an irrigated wetland and a dry area creates the oasis effect (Potchter *et al.*, 2008); furthermore, as demonstrated in (Fig. 7. Oasis effect correction factor [interpreted by the author from (Guyot 1997)]), this factor corrects the nocturnal ETP through accounting for the cultivated area and the vegetation cover thickness (Guyot, 1997).

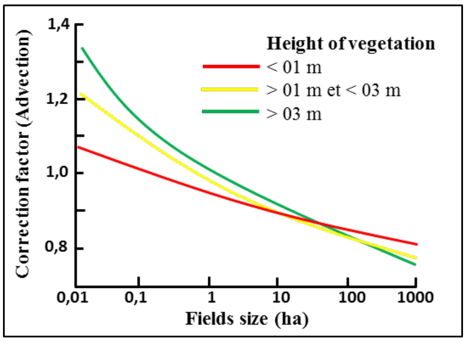

Fig. 7. Oasis effect correction factor [interpreted by the author from (Guyot 1997)]

4.5. Predicting air temperature in the palm grove's center

In this step, the model predicts hourly T in the palm grove's center using the compatibility reverse theory between the T and H graphs:

$$T_{p.h} = T_{max} - \left[(H_{min} - H_{p.h}) \cdot (T_{max} - T_{min}) / (H_{min} - H_{max})\right] \quad (9)$$

4.6. Final results

Finally, the model can predict T and H outside the palm grove using air mixture theories, psychometric tables, and mass conservation principles. Additionally, the linear air mixture graph provides high-precision mathematical formulas for predicting T and H at any point (X) outside the palm grove at a distance (D). Accordingly, we can calculate the D equidistance via estimating the air velocity using the difference in pressure phenomena:

$$\Delta P = |0.043 \cdot hi \cdot (T_d - T_p)| \quad (10)$$

$$V = 10^{-1} \cdot \sqrt{(0.7 \cdot \Delta P)} \quad (11)$$

Then, we can predict the climatic data at point 1 by:

$$(T_d - T_1) \cdot M_1 = (T_1 - T_p) \cdot M_p \quad (12)$$

$$(H_p - H_1) \cdot M_p = (H_1 - H_d) \cdot M_1 \quad (13)$$

Afterwards, the climatic data at point 2 can be predicted by:

$$(T_d - T_2) \cdot M_1 = (T_2 - T_1) \cdot M_1 \quad (14)$$

$$(H_1 - H_2) \cdot M_1 = (H_2 - H_d) \cdot M_2 \quad (15)$$

Finally, the same formulas can be utilized for other points X until the climatic data comparable to the desert are obtained**.**

5. Case Study

Located in the northeastern Algerian Sahara, the Righ Valley is the second largest oasis in the world with over 4,000,000 palms, 26 villages, and 10 new cities distributed adjacently to the Righ River over 170 linear kilometers between longitude 5.50°E to 6.10°E and latitude 32.50°N to 34.50°N (Figure 9). Furthermore, three huge sub-oases constitute the Righ Valley: Touggourt, Djamaa, and El Meghaier. As demonstrated in (Table 2) and (**Error! Reference source not found.**), the climate is hot and dry, the average temperature exceeds 20°C for over six months, and the annual rainfall is below 100 mm,.

Table 2. Climatic data of Djamaa from the meteorological station of Touggourt, 2016

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T max (°C)	14.1	19.9	21.8	25.3	32.1	38.7	42.3	41.2	34.3	27	22.4	16.5
T min (°C)	4.3	7.7	9.8	10	19.2	24.6	27.1	26.2	22.7	16.6	10.3	5.7
H max (%)	71	69	63	57	55	51	50	51	53	64	70	77
H min (%)	49	40	36	35	30	23	21	24	32	36	38	43

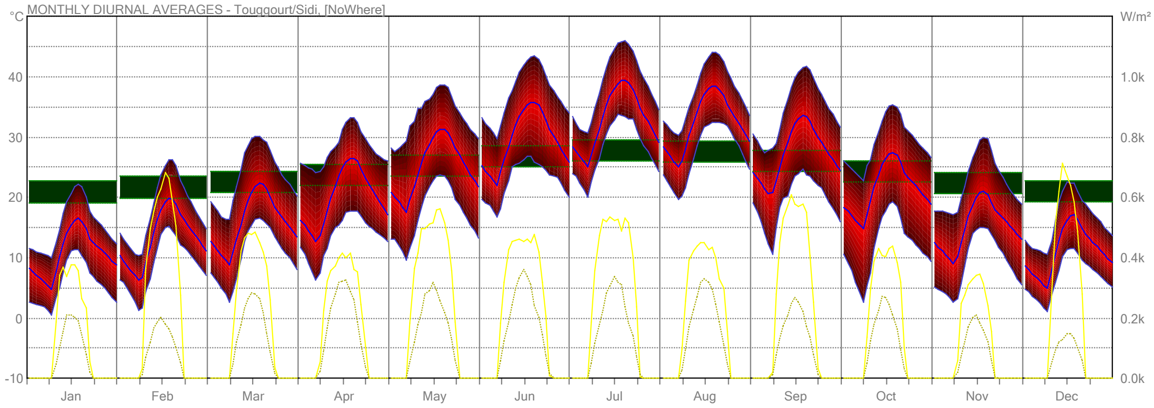

Fig. 8. Hourly air temperature of Djamaa in Righ Valley, after Weather Tool, by authors

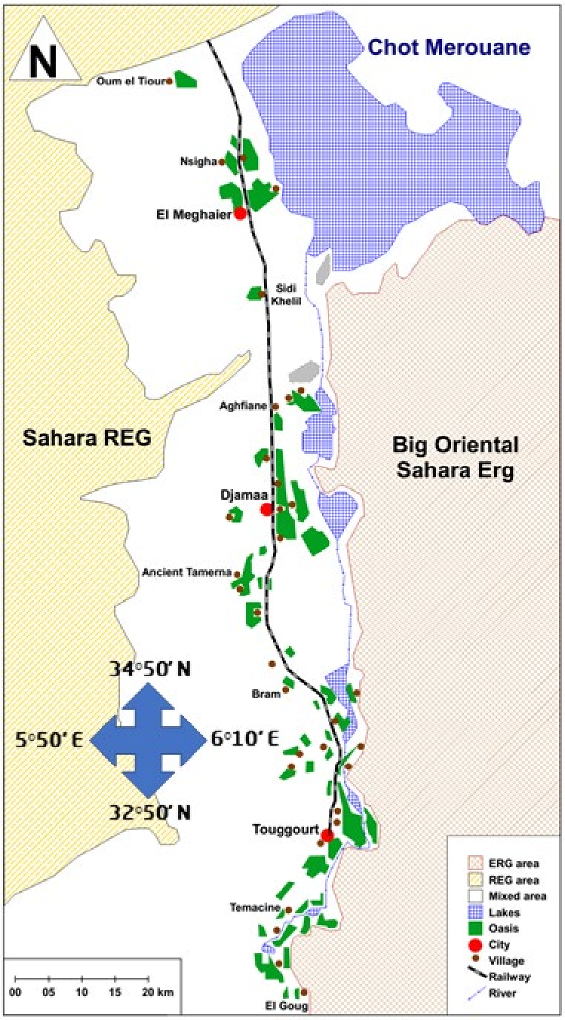

Fig. 9. Map of the Righ River [interpreted by the author from Nesson *et al*. (1973)]

6. Results and Discussion

The present study is a numerical application of the model on two oases with different configurations: the first one is Djamaa city with a palm grove on one side and the second is the Mazher oasis with palm groves on both sides. The purpose was to evaluate the limits of the oasis effect as a cooling phenomenon on desert climate. After acquiring the climatic data from the meteorological station, the first step was to predict the climatic data in the palm grove's center. (Fig. 10. ΔT (°C) between the desert and the palm grove, by authors and 11) demonstrate the differences between the desert and the palm grove regarding T and H. The results showed that the temperature was reduced by about 2°C at night year-round due to the halt in photosynthesis and respiration at night. Then, T decreased by a further 3°C at sunrise and sunset. The difference could reach 3°C to 5°C during the day and 6°C as a maximum in April (Fig. 10. ΔT (°C) between the desert and the palm grove, by authors). Humidity increased by approximately 4% at night year-round because the photosynthesis and respiration stop at night. Afterwards, H increased by 6% at sunrise and sunset. The difference could reach 6% to 10% during the day and 12% as a maximum in April (Fig. 11. ΔH (°C) between the desert and the palm grove, by authors).

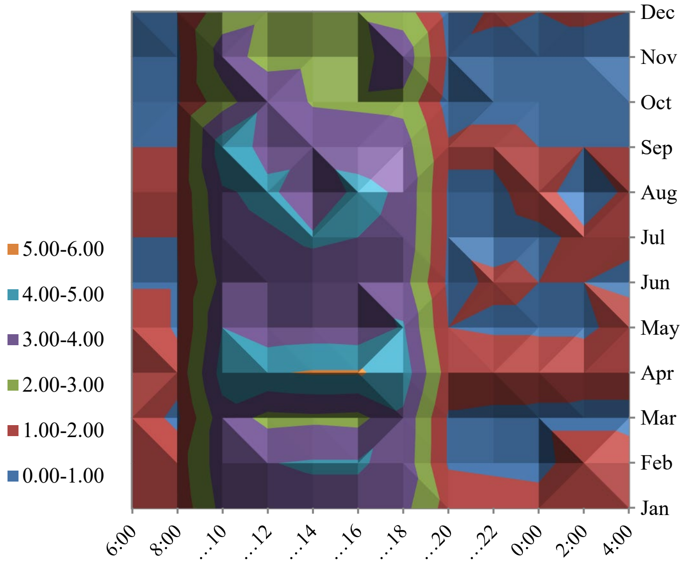

Fig. 10. *ΔT* (°C) between the desert and the palm grove, by authors

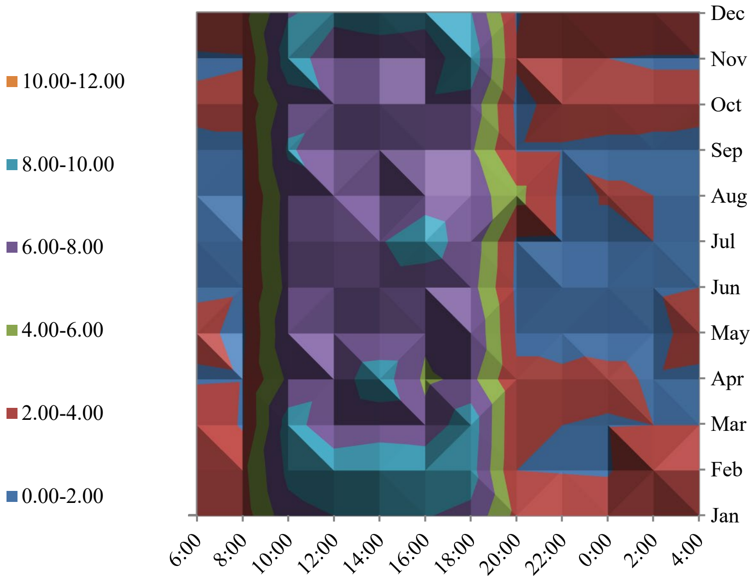

Fig. 11. *ΔH* (°C) between the desert and the palm grove, by authors

The next step was to predict T and H at any point (X) outside the palm grove using the formulas given earlier. The graphs of April presented below demonstrate a great variation in temperature and relative humidity between the desert climate and the climate in the oasis center. Finally, we simulated the climatic data for the two configurations. In the first type, with a palm grove on one side, T reached 25°C for nine hours per day in April (Fig. 12. April's temperatures (°C) at point (X) in one side palm grove type, by authors); however, in the second type, with a palm grove on both sides, T reached 25°C for only four hours per day (Fig. 13. April's temperatures (°C) at point (X) in besides palm grove type, by authors). As for relative humidity, H in the first case increased to 35% for six hours per day (Fig. 14. April's Humidity (%) at point (X) in one side palm grove type, by authors) while in the second case, it peaked between 40% and 45% (Fig. 15. April's Humidity (%) at point (X) in besides palm grove type, by authors).

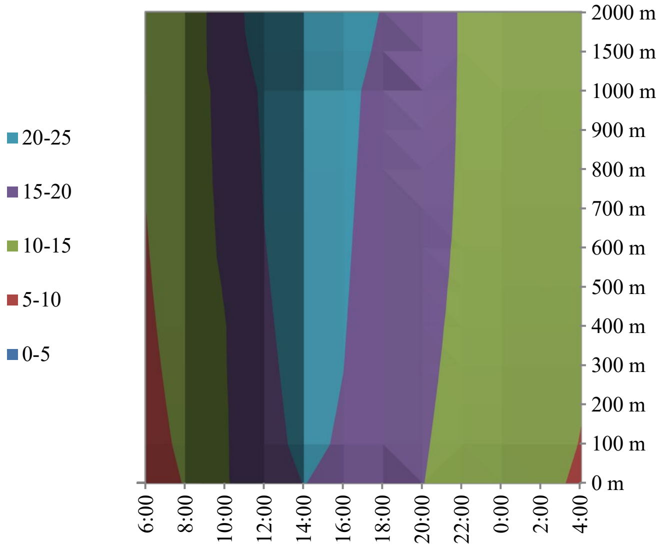

Fig. 12. April's temperatures (°*C*) at point (*X*) in one side palm grove type, by authors

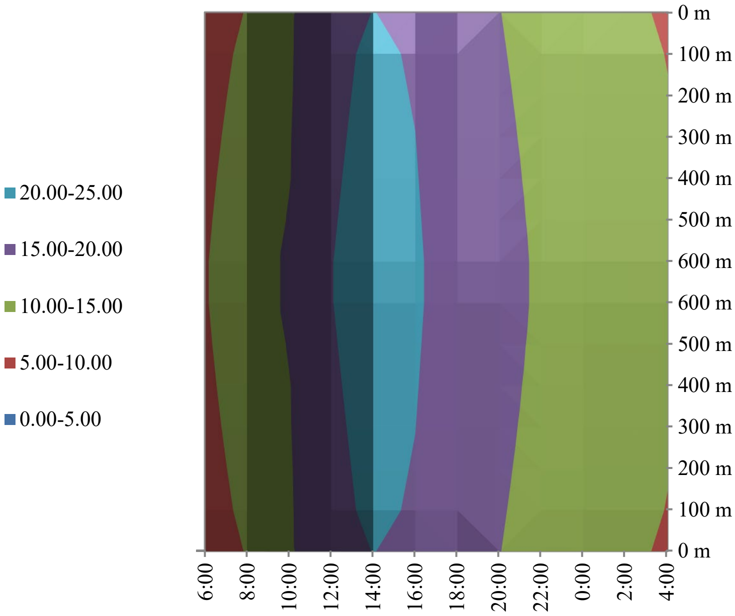

Fig. 13. April's temperatures (°*C*) at point (*X*) in besides palm grove type, by authors

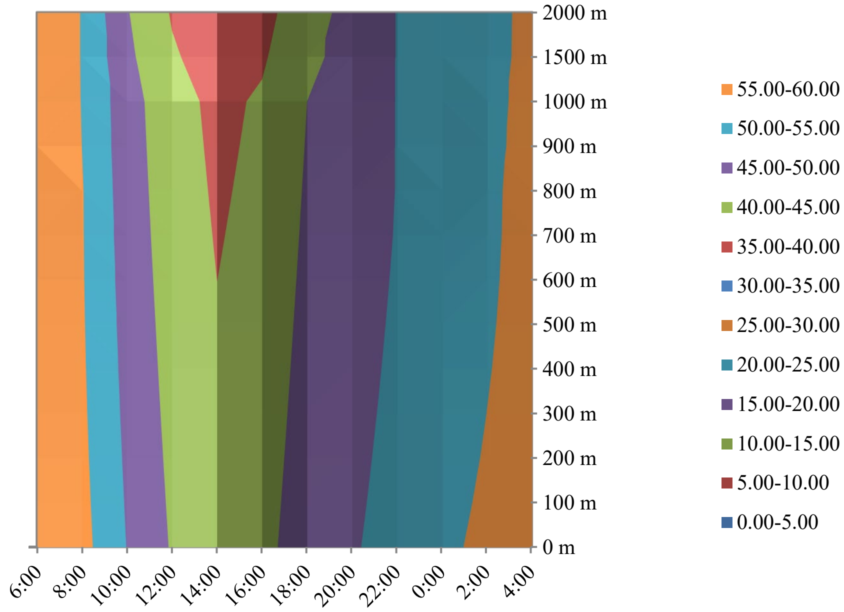

Fig. 14. April's Humidity (%) at point (*X*) in one side palm grove type, by authors

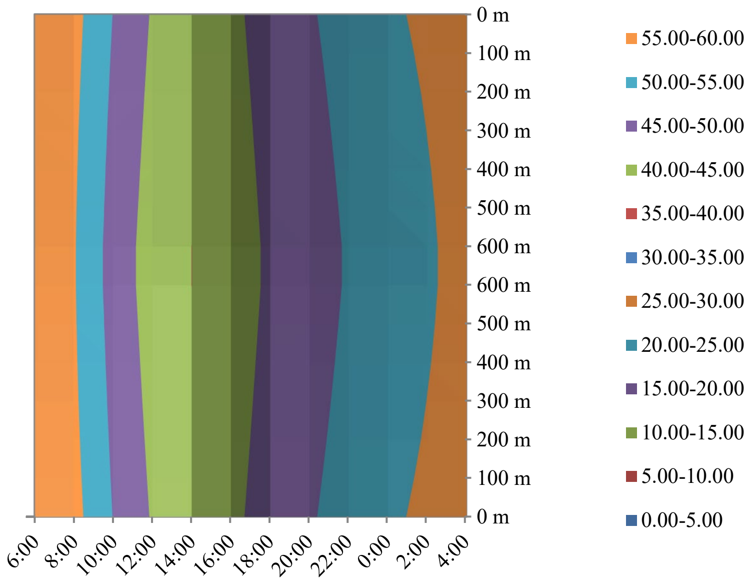

Fig. 15. April's Humidity (%) at point (*X*) in besides palm grove type, by authors

7. Conclusions

The SPUCAL_oec model was employed on two oases types: the one-side palm grove type and the both-side palm grove type. Therefore, this experiment was divided into two fundamental steps: the first one was to predict the oases effect in the palm grove's center based on the climatic data in the desert area; the results showed that the temperature was reduced by about 2°C at night year-round and by 3°C at sunrise and sunset. Furthermore, the difference could reach 3°C to 5°C during the day and 6°C as a maximum in April. Additionally, humidity increased by about 4% at night year-round and by 6% at sunrise and sunset. Moreover, the difference could reach 6% to 10% during the day and 12% as a maximum in April.

The final step was to estimate the oases effect at any point (X) outside the palm grove using the formulas previously presented. In the first type, with a palm grove on one side, T reached 25°C for nine hours a day as a maximum in April; however, in the second type, with a palm grove on both sides, T reached 25°C for only four hours per day. As for relative humidity, H in the first case increased to 35% for six hours per day as a maximum while in the second case, it peaked between 40% and 45%.

Finally, we demonstrated that the oasis effect has a large impact on the oasis microclimate. Additionally, this effect can be as large as 6°C of temperature reduction and 12% increase in relative humidity.

8. Future work

At present, a new version of the platform is in development, taking into account the flora design of streets and other Saharan botanic types. Furthermore, in the near future, we will advance an innovative model to simulate the effect of vegetation on architectural microclimate.

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