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A high-resolution mapping of wind energy potentials for Mauritius using Computational Fluid Dynamics (CFD)

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Abstract. A wind energy assessment is an integrated analysis of the potential of wind energy resources of a particular area. In this work, the wind energy potentials for Mauritius have been assessed using a Computational Fluid Dynamics (CFD) model. The approach employed in this work aims to enhance the assessment of wind energy potentials for the siting of large-scale wind farms in the island. Validation of the model is done by comparing simulated wind speed data to experimental ones measured at specific locations over the island. The local wind velocity resulting from the CFD simulations are used to compute the weighted-sum power density including annual directional inflow variations determined by wind roses. The model is used to generate contour maps of velocity and power, for Mauritius at a resolution of 500 m.

Keywords: Computational Fluid Dynamics (CFD); WindSim; complex terrains; wind power map; Mauritius Island

1. Introduction

With the ever increasing demand of energy and the awareness of the environmental impact, renewable sources are being looked upon as the trivial solution for future developments in many countries. These sources include solar, wind, geothermal and so on. Nowadays, the wind energy technologies have reached such a mature level that it is being used as one of the main sources for producing electricity in many countries including Germany, Spain, United States, China and India (Ahmed *et al*. 2010). In Mauritius, the Government recently took the initiative to set up "The Maurice Ile Durable" project. Its main thrust is to educate people on the importance of using renewable energy systems and also to find means of reducing effectively the dependencies of the country on fossil fuels in the generation of electricity by the year 2028. Mauritius possesses vast renewable resource potentials for the production of electricity. These include solar, wind, wave, geothermal and biomass. The present research work explores the wind energy potential in detail for Mauritius. In order to assess the wind energy potential of Mauritius, knowledge of the wind flow patterns and its average velocity over the island is essential. Wind data collection systems installed over the island and on-site measurements taken over sufficiently long-term periods help

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in this endeavor. But, the accuracy in the prediction of the wind power can be unreliable, especially when the wind flow is very turbulent with high shear factor in complex hilly terrains. It is therefore critical to predict the flow around such complex and mountainous regions accurately in order to gain optimum energy output. Due to the difficulties involved in direct measurements of wind over such type of terrains, alternative methods such as computer simulations have become extremely useful (Hunt *et al.* 1991, Palma *et al.* 2008). The current standard approach for this component in a wind assessment involves the use of linear models such as WasP (Wind Atlas Analysis and Application Program). However, one can encounter problems in evaluating wind characteristics when the region becomes complex, that is, where hills and steep mountains are present. Therefore, in this paper, the use of Computational Fluid Dynamics (CFD) is explored since Mauritius has a relatively complex topography.

A CFD model is concerned with finding numerical solutions to the wind flow patterns by solving the governing equations for fluid flow over a given domain in which the topography of the site can be specified. It can therefore provide comprehensive solutions, which are highly reliable, cheap and less time-consuming, for the flow field. In addition, it allows better understanding of the physics of the fluid flow, including turbulence effects, without recurring to measurements of the flow variables at the site of interest. The model output (wind velocity, pressure, etc.) can be used to effectively assess the wind power potential of the site. The wind energy sector is slowly but progressively incorporating CFD as a complement to the traditional linear models for complex terrain, forest and wake modeling. Modern CFD tools have already proved essential for modeling wind flows over complex rural terrains (Kalmikov *et al*. 2010, Wakes *et al.* 2010). They can provide location, height and time specific wind information. According to Unchai and Janyalertadun (2014), CFD modeling provides the possibility of replacing field measurements in the near future. There are numerous commercial CFD software which have been adapted for simulating wind flow patterns and which are able to provide an estimate of the wind power. Most of the packages work accurately when the terrain is flat or consists of gentle hills. However, some software fails to give accurate results when the terrain is complex with mountainous regions (Moreno *et al*. 2003). That is why, for modelers, different test cases have to be performed before adopting a particular software.

A brief review of the wind energy literature reveals that in recent years, there has been an increasing development of suitable numerical models for computing the wind flow over a given region (Gravdahl *et al*. 2012). Llombart *et al*. (2007) compared the accuracy of the linear model WasP and WindSim (which solves the complete set of Navier Stokes equations). They concluded that WindSim produced more precise results in complex terrains than the linear model. Similarly, same deduction has been reached by Albrecht and Klesitz (2006) when they compared the linear model with WindSim. Moreover, they noted that the larger the domain, the better results are generated by WindSim. Berge *et al.* (2006) have adopted one year of measured wind data from a complex site in Western Norway to WaSP and to CFD software WindSim and 3D Wind. This study has demonstrated that the CFD models provided information about the turbulent characteristics of the flow unlike the linear model. A similar conclusion has been reached by Schaffner and Gravdahl (2003), when they compared CFX-4 and WindSim to the linear WaSP model. Gravdahl and Harstveit (2006) have validated WindSim software results with measured data for the flow of wind along the Norwegian coast, resulting in a good correlation. Recently, Wang *et al.* (2014) have demonstrated that a CFD simulation for flow around hills must incorporate turbulence effects to obtain realistic results.

Most of the works mentioned above have only compared the CFD software WindSim to linear models. Recently, Dhunny *et al*. (2015) have analyzed the output response of some commonly used commercial as well as open-source CFD software in the study of wind flow over complex hilly terrains. The cases of the well-known Bollund and Askervein hills were considered. The software utilized were OpenFOAM and WindSim. After performing several comparative tests and flow scenarios using each CFD software, the authors concluded that WindSim yielded results which were close to measured data. Therefore, for the simulation of wind flow over Mauritius, which has a very complex orography (see Fig. 1), the software WindSim has been adopted.

2. Materials and methods

2.1 Description of study area

Fig. 1 depicts the aerial view of the tropical Island of Mauritius which spans over a range of 60 km in the North-South direction, and 42 km in the east-west direction. Mauritius is surrounded by the Indian Ocean and has coral reefs populating almost all around it, making the beaches one of the world's leading tourist attraction. The central plateau is characterized by mountain ranges not over 825 m. The north is generally flat terrain, with mostly sugarcane crops.

The climate of the island is very humid year round, typical for a tropical island. It has two seasons; winter and summer, each for a period of 6 months. The summer season starts from November to April while winter is from May to October. The island is affected by heavy rainfall during the summer period. Overall, the wind potential around the island varies from region to region which makes this study all the more interesting and challenging.

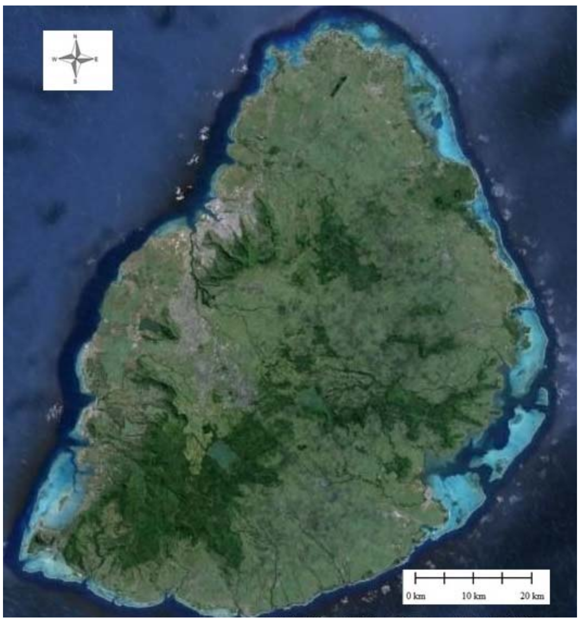

Fig. 1 Aerial view of the island of Mauritius (Google Earth, 2014)

2.2 Digital map

The digitalization of the aerial view obtained from Google Earth, (Fig. 1) has been performed by Global Mapper software with the actual global features taken into consideration and scaled to fit the real size of the configuration as shown in Fig. 2, with a terrain resolution of 500 m. Detailed urban features have not been taken into consideration. Hence, the simulation domain is assumed to consist of sea, forests and concrete (dense urban locations). Consequently, the island has been divided into three roughness locations, which are represented by different data of roughness heights. For forest canopy it is taken to be 0.8 m, 0.001 for sea and 0.1 for concrete (Troen and Petersen 1989). The digitalized map has then been converted to the required format for the WindSim CFD software.

2.3 Mathematical model

The Navier-Stokes equations govern the fluid flow in the Atmospheric Boundary Layer and are described in terms of mass and momentum conservation equations. In this work, the flow was assumed to be steady and turbulent. The velocity is denoted by $\overline{u} = \left(u_x, u_y, u_z\right)^T$, pressure by *p*, density by ρ and fluid kinematic viscosity by *v*. By decomposing the variables into mean value and oscillating value (eg. $u_i = \overline{u_i} + u_i'$ where *i=x, y* or *z*) to describe turbulent flows, the Reynolds-Averaged Navier-Stokes equations (RANS) are obtained (Launder and Spalding 1974)

$$\overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \overline{u'_i u'_j}\right] \tag{1}$$

Turbulence effects were modeled by the *k*-ε transport equations, where *k* is the turbulent kinetic energy and *ε* is the dissipation rate of kinetic energy. These equations are formulated as follows

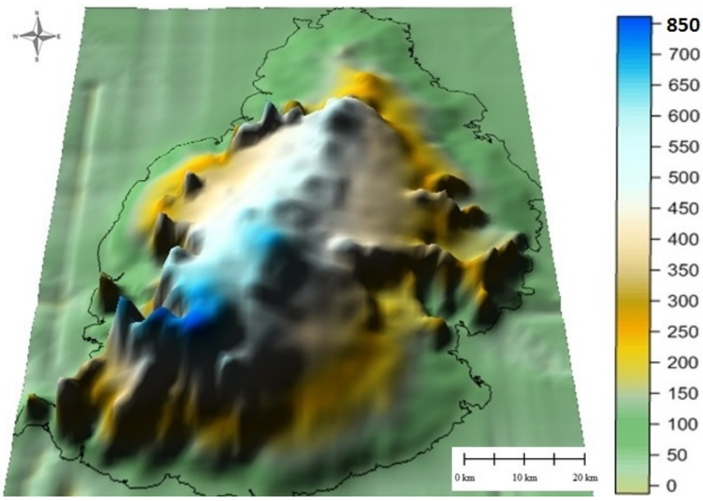

Fig. 2 The island of Mauritius with its height contour (in m) above sea level

$$\frac{\partial}{\partial x_j}\left(k\overline{u_j}\right)=\frac{\partial}{\partial x_j}\left[\left(\frac{\nu_i}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_k-\varepsilon \tag{2}$$

$$\frac{\partial}{\partial x_j}\left(\varepsilon\overline{u_j}\right)=\frac{\partial}{\partial x_j}\left[\left(\frac{\nu_i}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_1P_k\frac{\varepsilon}{k}-C_2\frac{\varepsilon^2}{k} \tag{3}$$

$$\nu_i=C_\mu\frac{k^2}{\varepsilon} \tag{4}$$

where the constants C_μ, σ_ε, σ_k, C_1 and C_2 are defined in table 1. The variable P_k, which is the turbulent kinetic energy production is given by

$$P_k=\nu_i\left(\frac{\partial\overline{u_i}}{\partial x_j}+\frac{\partial\overline{u_j}}{\partial x_i}\right)\frac{\partial\overline{u_i}}{\partial x_j} \tag{5}$$

3. Computational model

3.1 CFD parameters

A large enough computational domain was designed for the CFD simulations of the island to avoid artificial acceleration of the flow. The criteria chosen for the domain size followed the work of Loureiro *et al*. (2007). Hence, the inlet boundary was extended a distance of 7.5*H*; the lateral and outflow boundaries were extended a distance of 10*H* from the island shores, with *H* being the height of the tallest entity, which in our case was the highest mountain peak. The boundary height was taken to be 1000 m above it.

Grid dependency tests have been performed with different cell sizes to ensure reliability of mesh used. The final model employed a uniform horizontal grid size of 500×500 m^2 while the vertical grid size varied with from ground at 9.8 m to a maximum of 565 m at the top boundary. This resulted into a total of 1,400,000 cells for all 12 directions of wind flow. It should be mentioned that a test case for a 3D hill has been performed by the authors to verify the viability of the above mentioned characteristics before applying to the model. Figure 3 show the horizontal grid resolution of the terrain.

Table 1 Constants for *k*-*ε* turbulence model.

C_μ	σ_k	σ_ε	C_1	C_2
0.09	1.0	1.3	1.44	1.92

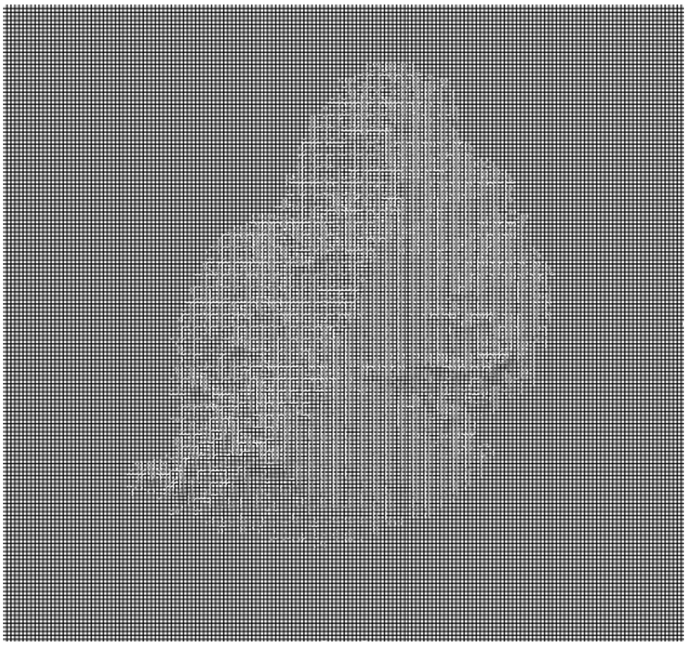

Fig. 3 The horizontal grid resolution (1,400,000 cells)

3.2 Boundary conditions

To ensure that a good model of the actual scene was replicated, conditions at the boundaries were set carefully. At the inlet of the domain up to the boundary layer height, the wind profiles are taken to be logarithmic due to the fact that the atmosphere was considered to be neutral, whereby the thermal stratification was not taken into account (Gravdahl *et al*. 2012).

$$u(z) = \frac{u^*}{k_1} \log\left(\frac{z}{z_o}\right) \tag{6}$$

where u^* is the frictional velocity; z is the height above the ground level, z_o is the roughness height and k_1(=0.4) is the von Karman constant. The bottom of the domain was specified as the wall functions including the roughness heights for each entity and fixed pressure was applied to the top of the domain. The outlet boundaries were set as Pressure outlet, which kept the pressure constant. It was assumed that the flow was fully developed at these boundaries. The pressure outlet boundary condition requires the specification of a static pressure at the outlet boundary. This approach ensured that the solutions were not non-physical. The velocity of wind at the outlet was then calculated by extrapolation of values from the inner cells.

3.3 Numerical solver

Eqs. (1) to (5) were discretized using the control volume approach. In this method the differential equations were integrated over the control cells to form a set of finite differential equation. The second order upwind discretization scheme was employed for the diffusion and convective transport terms. The resulting algebraic equations were solved using the Semi Implicit Pressure Linked Equations (SIMPLE) iterative algorithm of Patankar and Spalding which was integrated into the commercial software WindSim. It is based on the segregation of momentum and continuity equations. The second order upwind discretization scheme employed for the diffusion and convective transport terms. Convergence was achieved when the residuals reached a minimum value of 10^{-7} for the velocities in all 3 directions and 10^{-8} for turbulent kinetic energy and turbulence dissipation rate.

3.4 Climatology data

Before solving the meshed terrain by numerical method, we needed to find from which direction the wind is predominant and which type of wind speed was present year round so that we can obtain our initial wind velocity for our model. All this information was obtained from long term wind data recorded from weather stations. We integrated this climatology into our model using the averaged value. In our case, the wind speed and direction from long term data was obtained from the Utah Climate Centre (UCC) and the Mauritius Meteorological Services (MMS). These were the mean daily data for the meteorological stations of Vacoas (for a period of 37 years starting from June 1977 to July 2014) and for Plaisance international airport (42 year period starting from June 1972 to July 2014). It is worthwhile mentioning that MMS is the authorized government organization for all meteorological activities in the island. This organization provides accurate and timely weather information and meteorological products for the general welfare of the citizens of the Republic and is also the Early Warning Centre for natural disasters affecting the island. MSS records meteorological data such wind speed and stores the values in the UCC database.

The AWS (1997) wind resource assessment handbook was used as a guide for data filtering. The data were checked thoroughly for homogeneity, outliers and missing records before being processed for the study. Errors and missing data as well as cyclonic winds (wind exceeding 40 m/s) were eliminated. We hence restricted our study for flow of wind on any normal day. Figs. 4 and 5 display the mean wind daily data during that period for both sites. Figs. 6 and 7 show the wind roses at Plaisance and Vacoas respectively. These diagrams depict the dominance of the south east trade winds, which prevail year round. Therefore, the sector which needs to be considered is the South East one (150 degrees). The whole dataset for both stations are statistically described in Table 2. It can be observed that the mean value of the wind speed is higher for Plaisance than for Vacoas. The Standard Deviation, which describes by how much the data differ from the mean, is nearly the same for both stations.

Table 2 Statistical description of wind data for Plaisance and Vacoas

Statistics	**Estimates (m/s)**	
	Plaisance	**Vacoas**
Mean	4.0	3.6
Standard Deviation	1.8	1.6

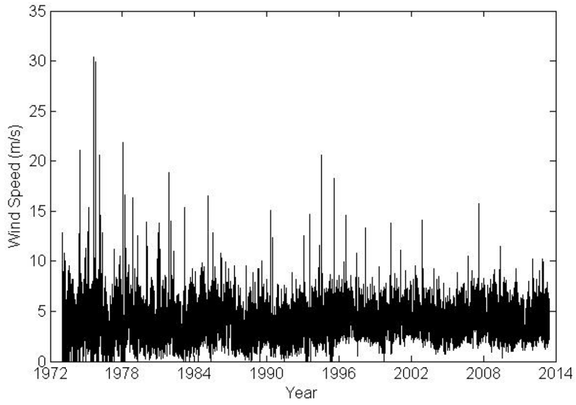

Fig. 4 Wind speed at Plaisance

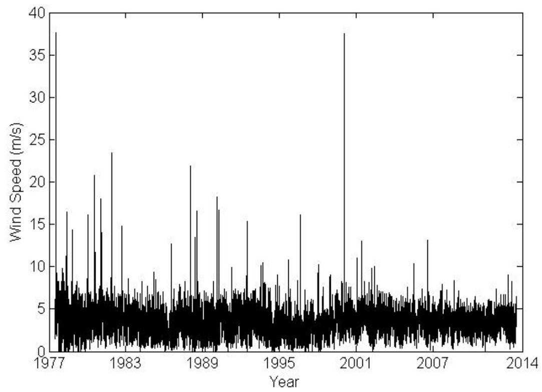

Fig. 5 Wind speed at Vacoas

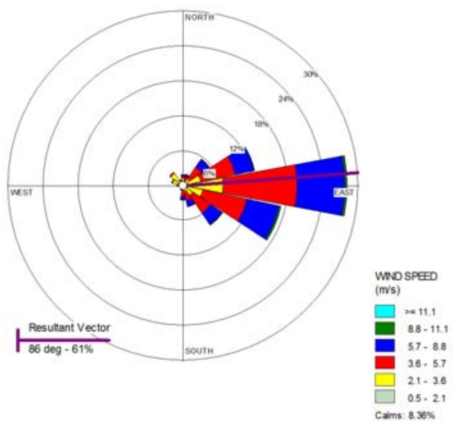

Fig. 6 Wind Rose at Plaisance

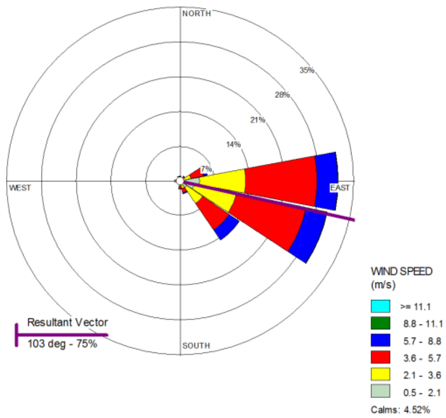

Fig. 7 Wind Rose at Vacoas

4. Results and discussion

4.1 Comparative study of CFD simulations with On-site measurements

Mauritius has seven main weather stations scattered around the island (Fig. 8).Thirteen years of data at Pamplemousses, Domaine des Pailles, Fort Williams, FUEL and Medine was analyzed and filtered for the validation of the model. Simulated data was compared with the measured data at the mentioned stations. Based from the results in Table 3, it can be observed that the software over predicted the results; this is due to the fact that in the simulated model no urban features have been taken into considerations. It should be mentioned that FUEL and Pamplemousses yielded the maximum error factor. This is probably due to the large gap of missing data at those two particular locations. The missing data was due to the malfunction of the wind measuring equipment; it took the MMS a lot of time (around two months) to repair/replace the equipment. Overall for a resolution of 500 m, the model has been successfully validated.

Table 3 The model validation

Weather stations	Mean Wind Speed (m/s)		
	Measured	Simulated	% Error
Medine	2.8	3.2	14.3
FUEL	2.5	3.1	24
Pamplemousses	3.0	3.6	20
Fort Willliams	3.2	3.8	18.7
Domaine des Pailles	3.1	3.6	16.1

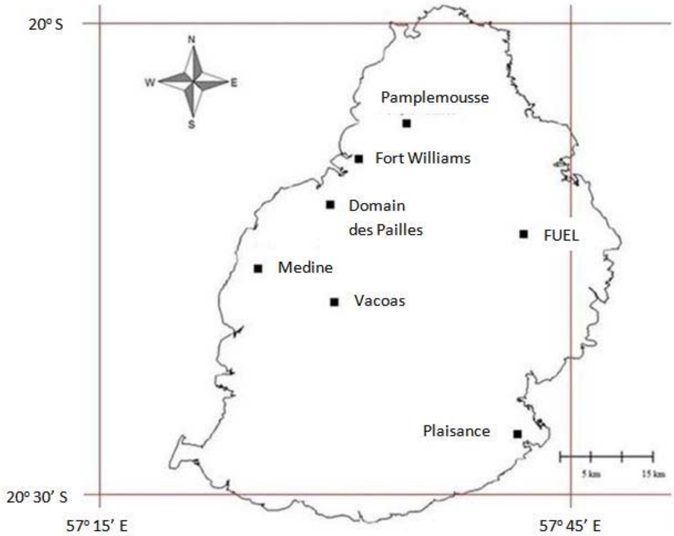

Fig. 8 Meteorological stations of Mauritius

4.2 Spatial analysis

The model was simulated in 3D for the South East (150°) trade winds as it prevails essentially year-round as shown from the wind roses (Figs. 6 and 7). Fig. 9, displays the steady state results as velocity vectors. It shows that around each mountain range, there is a region of high velocity. To further observe the wind activity over the island in more details, the wind speed distributions at different heights were analyzed.

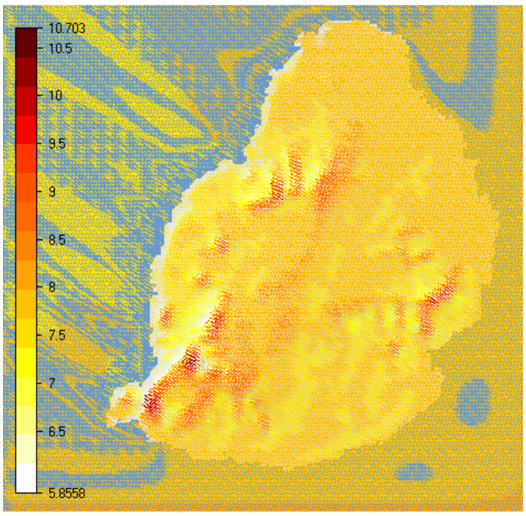

Fig. 9 Velocity vectors at a height of 30 m. The color scale represents the wind speed in m/s

The frequency distribution of the wind speed covering the domain at different elevations was scaled (u_{ref} = 9 m/s) and displayed in Figs. 10(a) to 10(d). The South Western region was observed to have high velocity of around 11 m/s, this region is known to be generally very windy since the presence of a mountain range accelerates the wind speed. The surrounding South West location has an average velocity of 8-9 m/s. At a height of 60 m and above, the wind velocity remains stable as there are no obstacles to disturb the flow of wind, though the highest peak fluctuated between 8.5 m/s to 10.5 m/s, which is suitable for wind farm development.

4.3 Predicted power output

One of the many outcomes from this study is the setting up of a power map, whereby the annual energy output in any place around the island can confidently be estimated from our simulated results. The WindSim software allows the prediction of wind power for a particular wind turbine. For instance an 80 KW wind turbine with hub height of 30 m will generate energy which can be processed at that particular height. The power output has been computed and the Energy per square meter per year (in Wh/m^2) is given in Eq. (7).

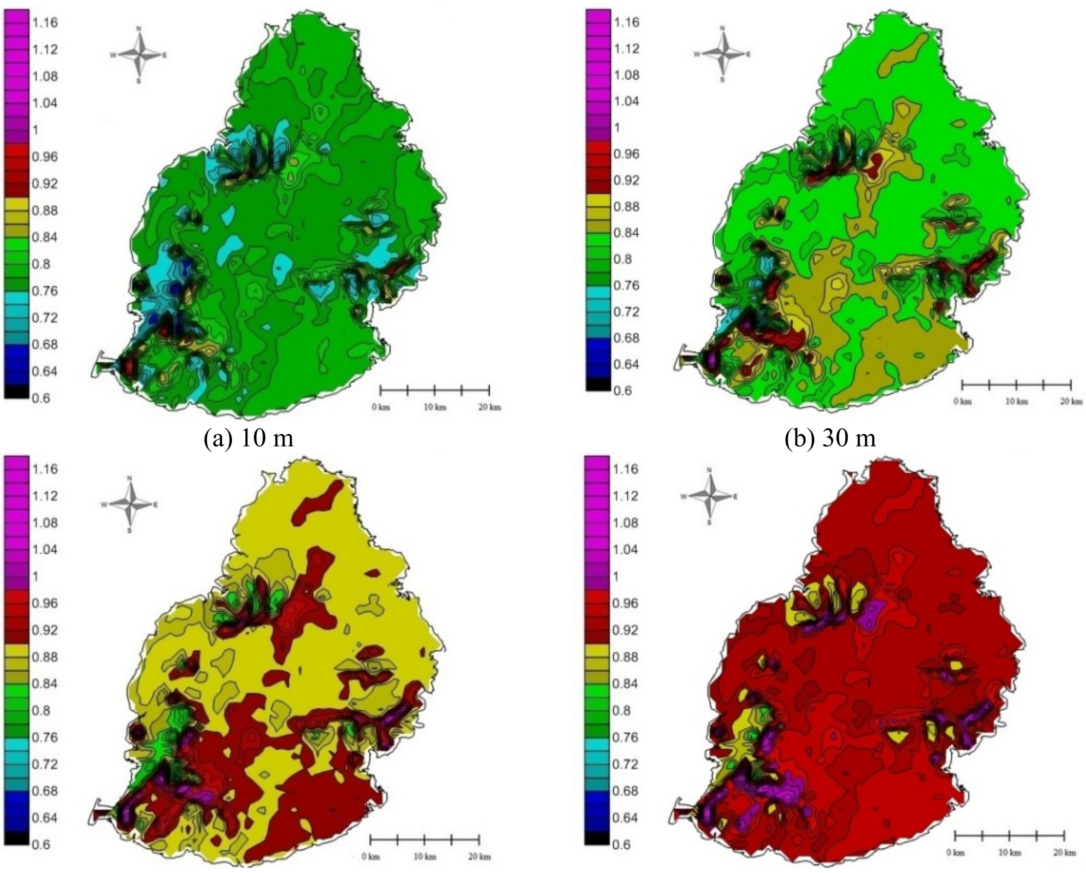

Fig. 10 Simulated scaled multi-level wind maps over the island of Mauritius. The color scale is dimensionless (u_{ref} = 9 m/s)

$$E = \frac{1}{2}\rho u^3 8760 \qquad (7)$$

where, E is the energy per square meter, ρ is the air density, u is the mean wind velocity and 8760 is the total number of hours in a year.

Fig. 11 displays the annual power map for Mauritius at a height of 30 m. This power map, gives a clear indication of the optimum sites for the erection of wind farm projects. In this case also, if at any one particular area, it is decided to install wind turbines, downscaling can be performed and more refined work can be done. Based from this power map, a wind farm can be built at Plaine Sophie, (20°22’0” South and 57°28’60” East at 588 m above sea level) located south from Vacoas. The wind speed is around 8 m/s at this location with an expected power yield of around 280 MWh/year for wind farms. Moreover, there is space available for the construction of wind farms as this site is vegetated with exotic species. High wind speed also occurs almost year round on the upper central plateau where space can be made available for wind farm development. For locations, where wind velocity is sufficiently high but has no space for wind farm development, micro wind turbines can be envisaged. It is also observed that the maximum velocity obtained is on the mountain peaks and hence wind farm can be erected on mountain slopes. The placement of a 5 MW wind turbine can be placed on the South East coast of Mauritius (for example Ile aux Far), to supply energy to settlement areas.

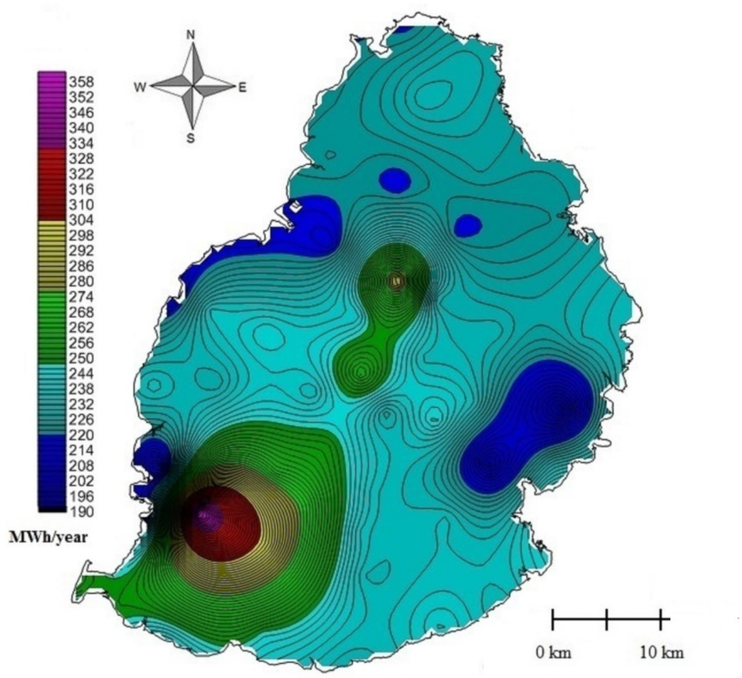

Fig. 11 Wind power map of Mauritius at 30 m

5. Conclusions

The WindSim software has been validated with experimental data. The latter has shown the capability to reproduce the flow of wind over the Island. A wind map of the island to find the high velocity zone has never been created in the past; hence the study mainly aims at finding the estimated annual wind energy output at specific locations which has high wind velocity (hot spots). One of the main outputs of this study has been the creation of a detailed high resolution wind resource map for the analysis of wind potential in Mauritius. It will be used to indicate the possible areas apt for the wind energy development. This work can be further enhanced by refining any areas which shows good potential for wind turbine erection and by inserting the urban features.

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