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Wave resource assessment and climate change impacts in Reunion and Mauritius

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ABSTRACT

This study assesses wave energy resources in two remote, yet populated islands in the Indian Ocean, i.e., Reunion and Mauritius. The suitable areas for future consideration for development were specified using the criteria defined for the sustainability of wave energy, including high energy potential and low intra-annual variation and long-term change in the future due to climate change. For climate projections, a super-high-resolution climate model was used to simulate the wave characteristics in both historical and future periods. The wave model has been downscaled on a local scale using the boundary condition generated by a parent model covering the whole Indian Ocean. The results show that in both islands, the wave power is the highest in the southeast and southern parts. There is higher stability for wave power in terms of monthly fluctuations in the southern parts of both islands. However, the north of Mauritius and south of Reunion show a lower future change in available mean wave power. In general, the southwest of Reunion and northwest of Mauritius are suggested to be more suitable locations for future development of wave energy farms considering their potential and sustainability.

KEYWORDS

wave energy; climate change; future projection; Reunion; Mauritius; Indian Ocean

1 INTRODUCTION

Ocean renewable energies (OREs) are considered as a promising alternative to fossil fuels resources, thus contributing to the reduction of Greenhouse gas emissions and climate neutrality targets. In particular, wave energy can supply an important part of the electricity demand where providing the energy is challenging even with popular renewables such as wind and solar energy due to the limitation of land use (e.g., Rusu and Guedes Soares, 2012; Vicinanza et al., 2013; Sierra et al., 2017). Other forms of OREs include ocean current energy, ocean thermal energy conversion (OTEC), salinity gradient (or the so-called blue energy), offshore wind, and tidal energy. However, except for offshore wind and wave energy, the other types of OREs are limited to particular areas due to their nature (Neill and Hashemi 2018). With its high density and lower visual and environmental impacts, wave energy can add to the diversity of the renewable energy mix. The exploitation of wave energy may furthermore pave the way for innovative solutions in terms of coastal protection (e.g., against erosion, coastal surge and marine inundation, etc.), desalination, hydrogen production, pumping, and heating processes (Rodriguez-Delgado et al. 2019a; b; Zheng et al. 2017).

Although OREs have been considered a measure to tackle global warming, the ocean climate is also highly affected by climate change (Kamranzad and Takara 2020). Therefore, such uncertainty due to changes in ocean climate should be taken into account in future planning for renewable energy exploitation. Wave climate projections are traditionally investigated based on the comparison of future and historical wave data. Thus, the future projections of wind climate are available from Global Climate Models (GCMs), whereas the historical data may be retrieved from the same GCMs, re-analysis hindcasts, or any long-term observations. The wind data extracted from GCMs can be used as an input for wave models to simulate the future wave climate. The former generation of Coupled Model Intercomparison Project (CMIP) models, i.e., CMIP3 models, were the model ensemble for the Intergovernmental Panel on Climate Change (IPCC)'s Fourth Assessment Report (AR4) with the Special Report on Emissions Scenarios (SRES) (Nakićenović and Swart, 2010). The SRES were replaced by Representative Concentration Pathways (RCPs) in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Moss et al. 2010) and Shared Socioeconomic Pathways (SSPs) in the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al. 2016).

Aside from the uncertainties associated with climate change projections, the numerical wave modeling itself contains inaccuracies mainly associated with the inaccuracy in input wind data, and the results of wave predictions are sensitive to the input winds (e.g., Teixeira et al., 1995; Ponce de León and Guedes Soares, 2008; Holthuijsen et al., 1996; Alizadeh et al., 2019; Alizadeh et al., 2020; Salah et al. 2016). Hence, a reliable high-resolution wind field is required for accurate wave modeling. This concerns especially the local scales where an increased spatial resolution is needed to optimize the selection of location/technology for the installation of wind and wave farms (Kamranzad and Hadadpour 2020; Kamranzad and Lin 2020; Karunarathna et al. 2020a; b; Etemad-Shahidi, et al., 2011).

This paper assesses wave energy resources and their sustainability considering the climate change impacts in Reunion and Mauritius islands located in the southern Indian Ocean, west of Madagascar. These two islands are excellent case studies for wave energy assessment due to their vicinity to vast resources in the Indian Ocean and the growing energy demand associated with an increasing population, especially in Reunion Island (INSEE, 2011). However, the electricity supply still relies on a significant proportion of fossil fuels resources. Thus, in 2015, petrol, coal, and gas generated more than 85% of the primary energy consumption within these islands territories (ORE 2016; Selosse et al. 2018b). In Mauritius, where population growth is approaching zero, its density is among the highest globally (Bowman 2021). Although Mauritius has been highly dependent on fossil fuels (83.6% in 2015) (Bundhoo 2018), the long-term energy strategy forecasts a share of 35% of electricity production by renewable energies by 2025 (Ministry of Renewable Energy and Public Utilities, 2009). A previous study by the authors in the Indian Ocean indicated that Reunion and Mauritius are among the promising areas considering their high wave energy potential, low monthly variation of the resources, and higher stability in terms of future changes (two conditions liable to reduce the intermittency of energy production and facilitate its integration into the grid) (Kamranzad et al. 2020). Further local studies specifically assessed the wave characteristics and energy potential and its viability in Reunion (e.g., Selosse et al., 2018a,b; Praene et al., 2012; Lecacheux et al., 2012) and Mauritius (e.g., INSEE, 2011; Ministry of Renewable Energy and Public Utilities, 2009) based on refined available estimated resources. However, assessing the sustainability of the wave energy resource and the role of climate change in selecting the proper locations for energy exploitation around these islands has not been carried out. This paper studies the wave resources as a promising energy supply for these two islands and investigates the sustainability of resources considering climate change impacts. For this purpose, a super-high-resolution wind field obtained from CMIP5 climate projections is exploited to drive a numerical wave model which generates the high-resolution wave characteristics in historical and future periods in the study area. The spatio-temporal variation of wave energy is investigated in both periods, and a sustainability index is implemented to identify the suitable locations for further downscaling and future development plans. The methodology, including the case study, data, and modeling, is described in Section 2. Section 3 contains the results and discussions, and Section 4 provides the summary and conclusions.

2 Materials and Methods

2.1 Study Area

The study area is located in the southern Indian Ocean, including the Reunion and Mauritius islands (Figure 1). These islands are both located in the east of Madagascar island. Reunion Island is an overseas region of France, whereas Mauritius island belongs to the Republic of Mauritius. Reunion is home to a human population of around 859,959 residents (https://www.insee.fr/en/accueil), while Mauritius's population has been estimated to be around 1.27 million

("Worldometer"). Both islands are isolated in the southern Indian Ocean, and the minimum distance from the closest major populated land (i.e., Madagascar) is around 680 km and 870 km for Reunion and Mauritius, respectively (according to Google Earth). Reunion and Mauritius cover furthermore the areas of 2,512 km^2 and 2,040 km^2, respectively. The length of the coastline is about 207 km and 150 km for Reunion and Mauritius, respectively.

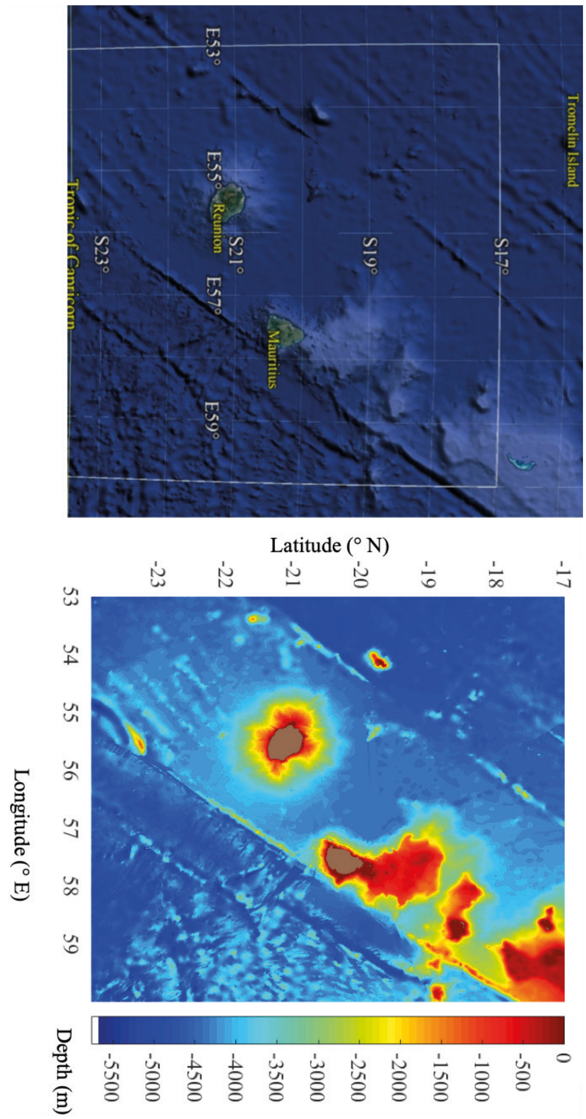

Figure 1. Location of the computational domain (top) and bathymetry of the study area (bottom).

2.2 Dataset

Wave characteristics in the study area, including Reunion and Mauritius islands, were generated in two time slices, (i) 1979–2003 (historical run) and (iii) 2075–2099 (future run). These two time slices are therefore of equal length covering a period of 25 years, thus meeting the Technical Specification set up by the Marine Renewable Energy Technical Committee (TC114) of the International Electrotechnical Commission (IEC), which recommends a minimum period of ten years for wave energy resource assessment (IEC, 2015). A super-high-resolution wind dataset of MRI-AGCM3.2S (Mizuta et al. 2012) provided by the Japan Meteorological Research Institute (MRI) was used as an input for the wave model. This wind dataset has spatial and temporal resolutions of 20 km and 1 hour, respectively in both historical and future periods, and has been widely used in generating the wave dataset in the Indian Ocean area (e.g., Kamranzad and Lavidas, 2020, Kamranzad and Mori, 2019). RCP (Representative Concentration Pathway) 8.5 projection was utilized as the future scenario of the wind field. Bathymetry data obtained from the General Bathymetric Chart of the Oceans (GEBCO) with a 30 arc-sec spatial resolution was also used in numerical wave modeling.

The numerical model used is Simulating WAves Nearshore (SWAN) Cycle III version 41.31 developed by Delft University of Technology (Booij et al. 1999). The computational domain covers the area between 53°E - 60°E in longitude and 17°S - 24°S in latitude (Figure 1). The spatial and temporal resolution of the computational grid was 0.05° and 30 minutes, respectively, while the output grid was defined covering the area between 54.5°E - 58.5°E in longitude and 18.5°S - 22.5°S in latitude and with spatial and temporal resolutions of 0.05° and 6 hours, respectively.

The formulations of Komen et al. (Komen et al. 1984) and Hasselmann et al. (Hasselmann et al. 1985) were considered as the source terms for the wind energy and nonlinear 4-wave interaction (quadruplets), respectively. In addition, Komen et al. (1984) and Hasselmann et al. (1973) formulas were used for whitecapping and bottom friction, respectively. The rate of whitecapping dissipation was considered as 2.36e−5 (default value), the friction coefficient was 0.038 according to the JONSWAP formulation, and the breaking coefficient was also considered as 1 for the proportionality coefficient of the rate of dissipation, and 0.73 for the breaker index. The frequency domain in the computational grid included the range from 0.03 to 1 Hz with 36 bins on a logarithmic scale, and the directional computational grid consisted of 36 bins of 10 degrees. The boundary condition of the model has been provided by the parent model covering the Indian Ocean (Kamranzad et al. 2020) and has been calibrated and verified against remote-sensing satellite observations (Kamranzad and Mori 2019a).

The wave energy and power are obtained from the wave characteristics generated by the numerical model. The wave energy density (E) is calculated using (Hughes and Heap 2010):

$$E = \frac{1}{16} \rho g \,(SWH)^2 \tag{1}$$

in which ρ, *g*, and *SWH* are the water density, gravitational acceleration, and significant wave height, respectively. The wave power (*P*) is calculated as:

$$P = ECg = ECn \tag{2}$$

where C_g, *C*, and *n* are the wave group velocity, the phase speed of the wave, and the ratio of the wave group speed to the phase speed, respectively. *C* can be calculated as the ratio of wavelength ($gT^2/2\pi$ for deep water) to the wave period (*T*), and *n* is considered approximately equal to 0.5 for deep water condition. Hence, equation (2) can be re-written as:

$$P \approx 0.49 \,(SWH)^2\, T \tag{3}$$

The actual sea state includes a large number of regular waves. Hence, a variance spectral density function is used to describe a mixture of different amplitudes, frequencies, and directions. Therefore, the energy period (T_e) is introduced to calculate the wave power (deep water approximation) (Abbaspour and Rahimi, 2011):

$$P \approx 0.49 \,(SWH)^2\, T_e \tag{4}$$

Equation 4 thus expressed the available wave energy flux for deep waters in kW/m (Guillou, 2020). T_e can be obtained based on the wave peak period multiplied by a factor, which for instance, is 0.9 for a standard JONSWAP spectrum with a peak enhancement factor of γ = 0.33 (Abbaspour and Rahimi, 2011). T_e is equal to the parameter T_{m-10} in SWAN outputs and is calculated by m_{-1}/m_0. m_n is the n-th moment of the energy density spectrum (E(f)) in which *f* is the frequency (SWAN scientific and technical documentation, 2019):

$$m_n = \int_0^{\infty} f^n E(f)\, df \tag{5}$$

The deep water approximation was used to calculate the available wave power in all output grid points of the domain. Based on the wave power generated in both historical and future periods, the results, spatio-temporal analysis, and stability of resources are discussed in the next section.

3 RESULTS AND DISCUSSION

The generated wave characteristics in the two periods -historical and future- and the calculated wave power were used for the spatio-temporal assessment. Figure 2 shows the annual mean values of various wave parameters, including SWH, swell wave height (HSWELL), mean wave period (MWP), and wave power (P) in the historical period and their relative future changes (in percentage) during 2075–2099. Figure 3 represents the mentioned values in nearshore areas of Reunion and Mauritius. The nearshore area has been defined by two grid points around the land on the outputs (i.e., the distance of around 0.1°). According to Figure 2, the dominant wave direction is from S-SE, and hence, the presence of the islands reduces the wave power in their northern side due to the sheltering effect. The wave power in the southern side of the islands is around 25 kW/m which is reduced to around 10 kW/m on the northern side, implying a reduction of around 60% due to the sheltering effect. The reduction in SWH from the southern (around 2.2 m) to the northern side (around 1.2 m) of the islands is about 45%, while it is about 60% and 25% for HSWELL and MWP. It indicates that the reduction of HSWELL has a higher impact on reducing P from the southern to the northern side of the islands. Comparing the future and historical periods shows that according to RCP 8.5, SWH, HSWELL, MWP, and P may decrease in the future. However, the reduction does not exceed 10% for P and HSWELL and 5% for SWH and MWP in the domain. In nearshore

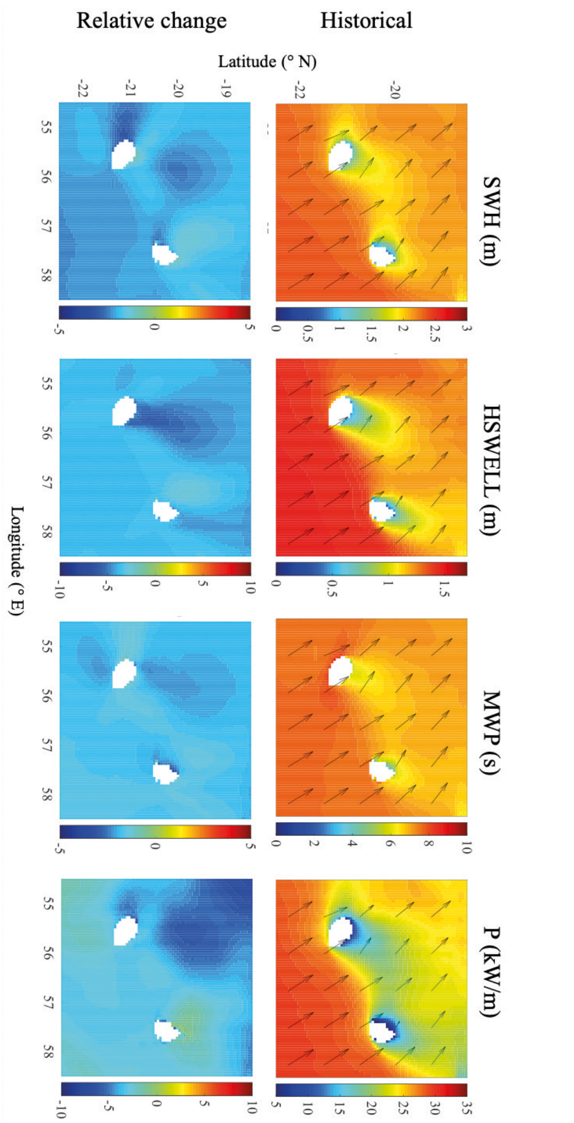

Figure 2. Annual mean values of various wave parameters (right column) and their relative change (%) in the future (left column). Arrows show the wave propagation direction.

areas (Figure 3), the future decrease in all parameters does not exceed 2-3%, while for HSWELL it is more than 5%. Extracted from a global study, Camus et al. (2017) also showed a future reduction in SWH there. The largest relative reduction in wave power and HSWELL exists in the north of the Reunion. Figure 4 shows the seasonal variation of P and its relative change (in percentage) in different seasons. MAM, JJA, SON, and DJF correspond to March-April-May (austral

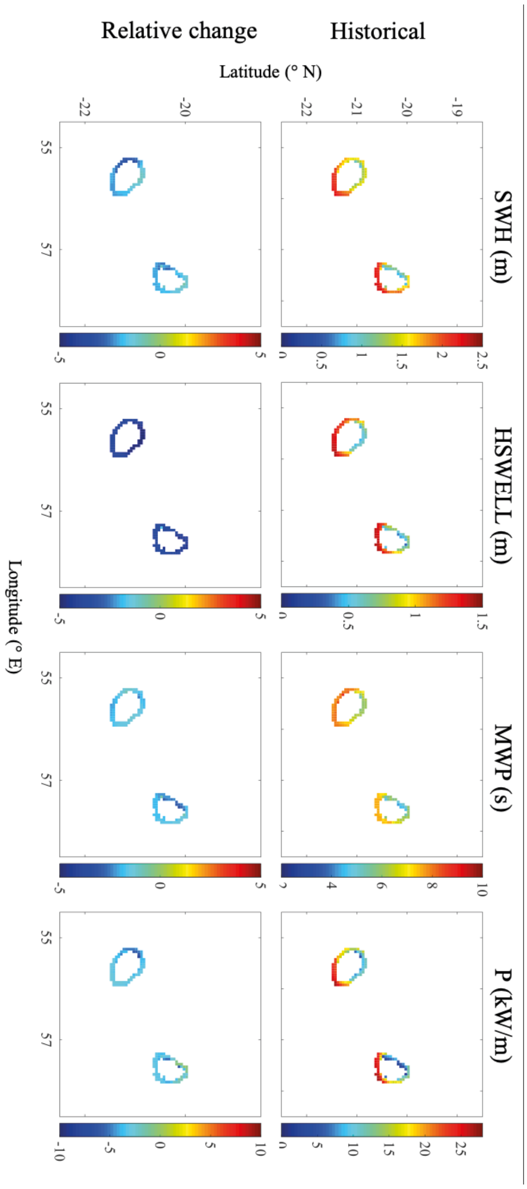

Figure 3. Annual mean values of various wave parameters (right column) and their relative change (%) in the future (left column) in nearshore areas.

autumn), June-July-August (austral winter), September-October-November (austral spring), December-January-February (austral summer), respectively. According to this figure, the highest mean seasonal wave power of about 35 kW/m can be found during austral winter in the southern parts of the islands. The wave power fluctuates seasonally and reaches the lowest values of 25 kW/m and 13 kW/m during SON in the southern and northern sides of the islands, respectively. Figure 4 indicates that the future change in austral winter and spring wave power is nearly negligible, while there is a slight increase (about 10%) during austral autumn and a decrease of about 10% during austral summer in future available wave power in the northern part of the domain, according to RCP8.5. This decrease of the mean seasonal wave power during austral summer appears particularly marked in the northern part of Reunion.

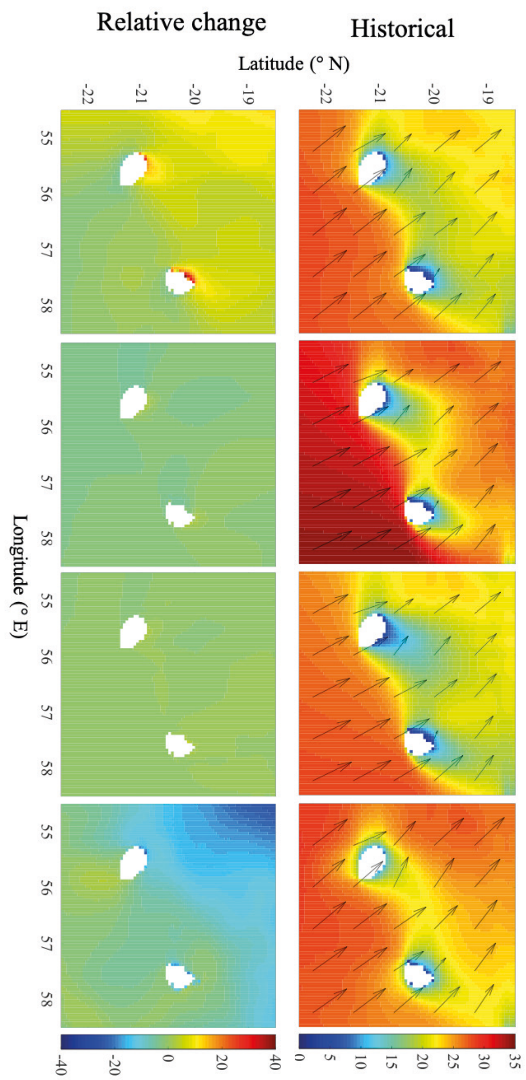

Figure 4. Seasonal variation of mean wave power (kW/m) (right column) and the relative change (%) in the future (left column). Arrows show the wave propagation direction.

In order to investigate the short-term variation of the wave energy resource, the Monthly Variability Index (MVI) was calculated based on the ratio of the difference between the maximum and minimum monthly average wave power and the mean annual wave power (e.g., Camus et al., 2017).

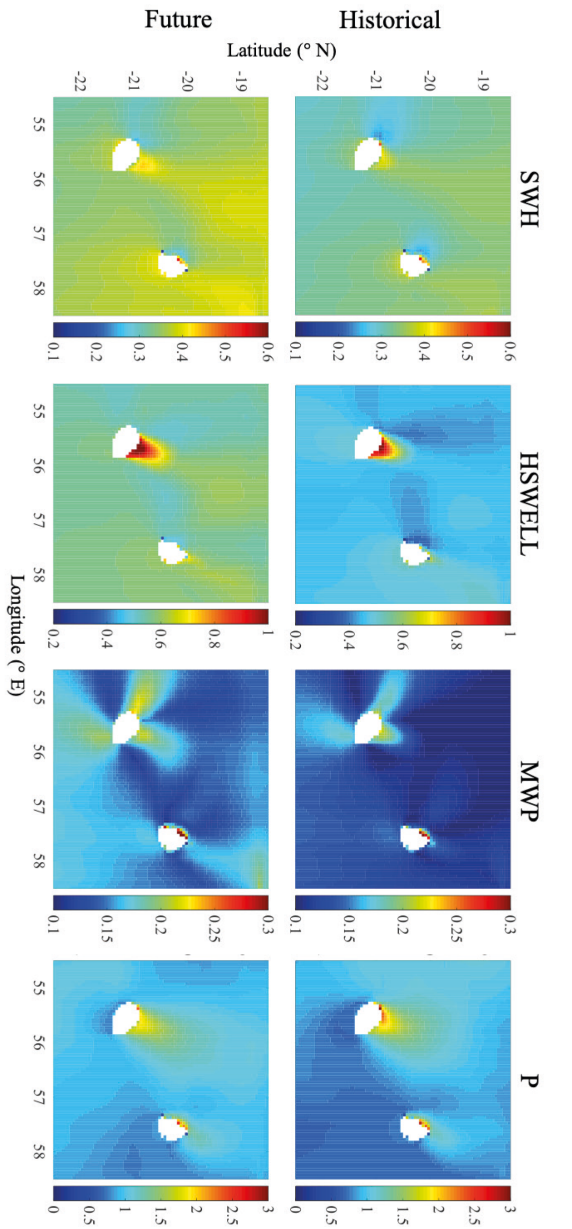

Figure 5. MVI values for wave power in historical period (right column) and in the future (left column).

Lower amounts of MVI imply higher stability in terms of monthly variation, whereas higher values account for increased temporal variability and, therefore, unattractive conditions for the implementation of wave energy converters (Guillou and Chapalain, 2018). Figure 5 shows the spatial distribution of MVI for various wave parameters in both historical and future periods. According to this figure, MWP shows the lowest monthly variability in the domain in both historical and future periods. However, the monthly variability of the wave period was found to be increased around Reunion in the future. For all parameters, the comparison of MVIs for historical and future periods exhibits an increase in monthly variability, implying lower stability of future resources.

Climate Stability Index (CSI) has been defined by both short-term variation (MVI) and long-term change (relative change) of specified parameters (Kamranzad et al. 2020; Kamranzad and Mori 2019b):

$$CSI = \frac{X_H}{\left|(MVI_F - MVI_H) \times MVI_H \times (X_F - X_H)\right|} \tag{6}$$

where H and F represent historical and future periods, respectively, and X refers to the annual mean values. Therefore, the higher values of CSI account for a higher stability of the wave parameters in both short- and long-terms. CSI was calculated based on the results discussed in the previous sections and shown in nearshore areas of the domain (Figure 6). According to Figure 6, CSI shows higher stability of wave power in the south and southwest of Reunion and in the north, northwest, and west of Mauritius. This result is consistent with previous studies, showing that the south of Reunion is a suitable location for wave energy extraction (Camus et al., 2017; Guillou et al., 2020; Guillou and Chapalain, 2018; Kamranzad and Mori, 2019). Although the stability of SWH is higher in the north and northeast of Reunion, swells also demonstrate stable conditions in its southwest. This shows that the stability of wave power is more dependent on the stability of swell than on the resultant of seas and swells and also wave period. Such an outcome can be due to the domination of swell in the southern ocean, which also propagates toward the northern Indian Ocean (SWAN scientific and technical documentation, 2019; Davy et al., 2016). A part of the nearshore regions around the islands, where wave power appears to be the more stable, finally corresponds to energetic locations. This concerns especially the northern part of Reunion and Mauritius.

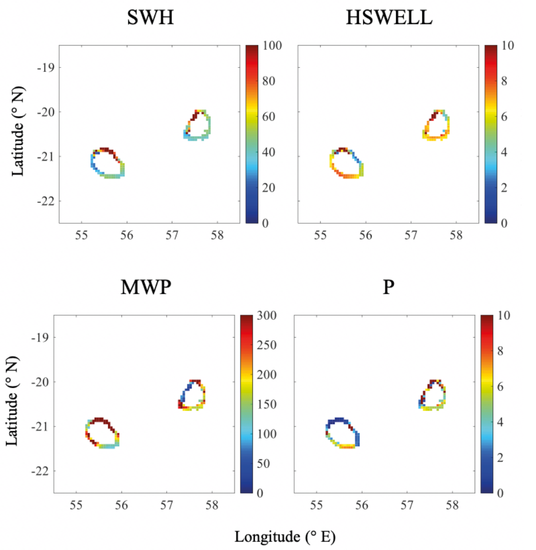

Figure 6. CSI values for different wave parameters in nearshore areas

4 SUMMARY AND CONCLUSIONS

Super-high-resolution wind data were used to generate the downscaled high-resolution wave characteristics around Reunion and Mauritius islands in the southern Indian Ocean. Such high-resolution wave data provided the opportunity of assessing the wave climate and energy seasonally and directionally for two 25-yearly periods, i.e., historical (1979–2003) and future (2075–2099) periods. The future projections were estimated based on the RCP8.5 scenario, and the boundary conditions were obtained from a previous study covering the Indian Ocean. The analysis showed that considering the dominant wave propagation direction (from south and southeast), the islands play an important role in reducing the wave energy in their northern side (sheltering effect). A reduction of around 45% and 25% was found in significant wave height and wave period, respectively, due to wave propagation from the energetic southern parts to the northern part of the islands. Such a reduction causes a considerable reduction of around 60% in available wave power in the northern side of the islands due to the sheltering effect. The results also indicated that the spatial change of wave power is more dependent on swell climate rather than locally generated waves (wind seas).

The seasonality of wave climate was also investigated around the Reunion and Mauritius islands, and the results demonstrated the highest available wave power to reach around 35 kW/m during austral winter (JJA), which is reduced to the lowest value of 13 kW/m during austral spring (SON) in the northern side of the islands. Monthly variability of the resources was also investigated, and the results showed a nearly stable condition for the wave period.

The comparison between the wave characteristics in historical and future periods showed a reduction in the amount of all wave parameters and, consequently, wave power. However, the most predictable reduction in the domain was found to be about 10% for wave power and swell wave height found in the north of Reunion. The future reduction in nearshore wave power does not exceed 3%. The future change in the seasonal variation of wave power is negligible during austral winter and spring, while there is an increase and decrease of about 10% in wave power during austral autumn and spring, respectively. The analysis also demonstrated an increase in monthly variability (i.e., lower stability) of wave characteristics in the future.

In order to consider the impact of both short-term variability and long-term change in the suitability of locations around the islands for wave energy extraction, the CSI factor was finally implemented and applied to wave power characteristics. The results showed that the stability of wave climate in terms of monthly variation and relative future change is various in different areas around the islands and for different parameters. For instance, the significant wave height shows higher CSI values in the north and northeast of Reunion, whereas swells are more stable in the southwest areas. In addition, the south and southwest of Reunion and the north, northwest, and west of Mauritius demonstrate higher climate stability for wave power. This again highlights the stronger relationship between the stability of wave power and the stability of swells, which is due to the domination of swells in the study areas. Such an outcome can be used in climate projections of the wave energy based on the projection of swell climate in swell-dominated areas.

The results of this study emphasize the importance of assessing the long-term stability of wave climate and resources as a key element for future planning and for the installation of wave farms. Further analysis can be conducted for the updated projection scenarios and based on ensemble models to reduce the uncertainties associated with future projections.

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