Numerical Simulation of Climate Change Impacts on the Coast of Oman

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Abstract

It is well known that there is an apparent increase in the intensity and frequency of extreme weather events, such as tropical cyclones (IPCC, 2023). This will lead to a significant effect not just on the infrastructure and the economic activities but also on the coastal environments. On the other hand, an increase in the population along the coastal areas in such a country as the Sultanate of Oman will also increase the risk and the hazard. It has been noticed extremely heavy rainfall during the most recent tropical cyclone, Shaheen (October 3 2021). It is also recorded along the Omani coast's extremely high waves during this storm event. Some other tropical cyclones in the past also indicated an essential effect on the Omani coast (Shawky et al., 2021). In this regard, the development of a fundamental understanding of the hydrodynamic behaviour along the coastal system during these events has been necessary. Moreover, the tropical cyclone track and wind speeds have been recorded only for a few temporal spans. This leads to better reliable estimations of such a kind of event. The state-of-the-art process-based numerical model will be utilized to hind cast the hydrodynamic developments from several tropical cyclone events along the Omani coast. A well-calibrated and validated flow model has been set up using Deft3D, a world leader's software (Lesser et al., 2004). Furthermore, the impact of wind-induced waves has been investigated using the SWAN wave model (Booij et al., 1999; Ris et al., 1999). In this paper, four well-known tropical cyclones in the Indian Ocean will be simulated. The four tropical cyclones were selected due to their historical significance and the amount of destruction they caused on the Omani coast. The investigation results showed significant tropical cyclones' effects on the Omani coasts due to their intensity and the cyclones' pattern. Overall, the numerical models that are showing good descriptions of climate change can be valuable tools for comprehending and predicting the influences of climate change on the Omani coast and can be employed to support in the decision-making.

Keywords: Sultanate of Oman; Numerical models; Tropical cyclones

1 Introduction

Many researchers and scientists declared that the climate is changing, leading to climate-related hazards like rising sea levels and increases in the intensity and frequencies of tropical cyclones (TC) and storm surges (IPCC, 2023). According to the world meteorological organization (WMO), between 1970 and 2019, globally, about 11072 disaster events have been imputed only to weather, climate and water-related (WMO, 2020). Over the last 50 years, the recorded weather, water, and climate hazard events showed about 79%, 56% of deaths and about 75% of economic losses. Moreover, it has been recorded in the last ten years, i.e. between 2010 and 2019, there is an apparent increase in the tendency of disasters associated with weather, climate, and water by 9% compared to the previous decade and almost 14% between 1991 and 2000 (WMO, 2020).

Intense cyclones, tropical storms and hurricanes often hit the coast of Oman. This kind of weather phenomenon is called a sea hurricane. Storm surge-driven waves travelling off the shore cause significant damage in erosion phenomena. Besides destroying forests, buildings and coastal infrastructure, it also causes widespread pollution of drinking water sources and flooding (WMO, 2020). Moreover, Oman has a coastal line about 3165 km in length connecting the Arabian/Persian Gulf, the Sea of Oman and the Arabian Sea (Shawky et al., 2021). Therefore, Oman's location is more exposed to TCs, especially when about 7% of the global TCs are from the Indian Ocean (Leijnse et al., 2022).

Many researchers studied the effect of the TCs, based on remote sensing analysis and assessments, on the coast of Oman. Besides, the most recent studies cover mainly local regions of the Omani coast due to the need for more available data. Fritz et al. (2010) modelled the storm surge of Gonu using the Advanced Circulation Model (ADCIRC). The study has been conducted for non-spatial analysis (Fritz et al., 2010). Shawky et al. (2019) utilized geospatial techniques to model cyclone risk on the southern coasts of Oman. Hereher et al. (2020) recounted cyclones and tsunamis using the coastal vulnerability index (CVI). Likewise, Shawky et al. (2021) described a single risk index using a geospatial modelling technique. As it is known, the CVI assessment estimates a simplified index as one number indicating the coastal lines' vulnerability to the impact of climate changes. Mainly six physical processes, geomorphology, coastal slope, rate of relative sea-level rise, rate of shoreline erosion/accretion, mean tide range and mean significant wave heights are used to estimate CVI ranked from 1 (low) to 5 (high) (Al-Sariri, T., 2014). On the one hand, previous studies mentioned could help decision-makers and governors quantify the risk. On the other hand, these index numbers still need to describe the weather-related risks adequately. It will be challenging to use them in many engineering applications depending on water levels or wave parameters due to TCs.

In this study, a state-of-the-art hydrodynamics model developed by Deltares in Delft, Netherlands (Lesser et al., 2004) coupled with the wave model SWAN (Booij et al., 1999; Ris et al., 1999) is used to simulate storm surge, and wave conditions due to several TCs happened in the past. In particular, a good description of the sea state (tides and wave conditions) using well-calibrated numerical models will improve the estimation of the CVI.

2 Area of Study

The study area covers the entire Omani coastal line. The Sultanate of Oman is the third country located in the south-eastern quarter of the Arabian Peninsula, covering about 309000 km^2 (Hereher et al., 2020). The coastline stretches out over a distance of about 3165 km, from the Strait of Hormuz to the border with Yemen (Al-Sariri et al., 2014). Oman is classified as hyper-arid, with less than 100 mm rainfall, from the arid desert climate, 100 to 200 mm rainfall, to semi-arid, with 250-500 mm rainfall in different parts of the country (Al-Sariri et al., 2014).

The unique location of Oman (Fig. 1) during Tropical Cancer makes the climate conditions vary throughout the country. Nevertheless, two main seasons occur, winter from November to April and Summer from May to October; the wind speed leans moderate (Hereher et al., 2020). For low-land regions, the wind speed is generally between 2 and 3 m/s (2 m above the ground). In general, the wind speed is not varying too much during the year, excluding some tropical cyclones generated in the Indian Ocean. Moreover, a strong wind along the Arabian Sea during the Monsoon also leads to tropical cyclones (Dibajnia et al., 2010). In the study area, it has been observed since 1945 about 29 tropical cyclones storms (Sarker, 2017). Most of the tropical cyclones occurred, namely pre-monsoon (May) and post-monsoon (October to November), and in some cases, TC events were also recorded between June and September (Evan et al., 2011; Fritz & Okal, 2008).

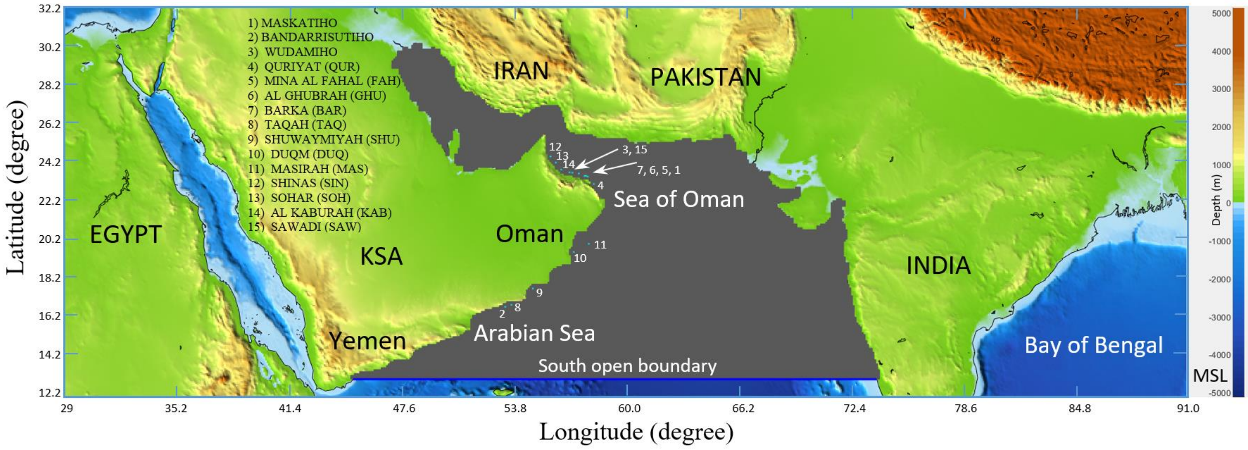

Fig. 1: Area of study (models' grid, open boundary, and observation points)

3 Purpose and Methodology of the Present Study

Studies of the TC and their effects on the coastal regions along the Omani coast have been exploratory, and a detailed study is required. Therefore, this paper presents a 2DH model for flow based on Delft3D software developed by Deltares coupled with SWAN wave models. The flow model was used to compute current velocities and water levels at several locations along the Omani coast. The flow model was set up for astronomical conditions, calibrated and validated using relevant tide gauge measurements at different locations in the area. Moreover, the current-induced wind has been intensively studied. The wave and flow models were then coupled to study only the wave-induced wind due to TC's without considering the swell waves. The methodology which has been pursued, the flow and wave model's setup and TC's events, can be described in the way that the wind and pressure fields are used from ERA5 (Hersbach et al., 2018) data sets to force the hydrodynamics and wave models. The results for the wave heights extracted from these models are evaluated using several statistical techniques, which will confirm the effects of the selected TCs on the coastal regions. Additionally, the two models, when completed, should help arrive at decisions about the coastal protection (long-term) and contingency and evacuation plans (short-term) due to TC's events.

4 Tropical Cyclone Hazards

It is well known that the tropical Indian Ocean is mainly described by surface warming more than other tropical cyclones in the northeast Pacific and north Atlantic. Moreover, TCs in the Indian Ocean are highly possible due to global warming (Charabi, 2010). Therefore, the TCs in the Indian Ocean have gotten more attention from researchers since 2007, since it has been observed that about 2 to 4 TCs per year (Bakker et al., 2022).

In a recent paper, the IBTrACS data set (The International Best Track Archive for Climate

Stewardship), which was developed by National Climatic Data Center (NCDC) from National Oceanic and Atmospheric Administration (NOAA) and World Data Center for Meteorology from World Meteorological Organization (WMO) is used for the TC's tracks and intensity (Knapp et al., 2018). In June 2007, the TC Gonu was one of the strongest cyclones that attacked the coast of Oman and the whole Indian Ocean. However, it only caused significant damage and about 50 deaths in Oman and has been described as the worst national disaster (Charabi, 2010). According to the Indian Meteorological Department, cyclone Gonu developed from a lasting area with high sea surface temperatures east of the Arabian Sea. The maximum wind speed recorded was about 270 km/h (June 1), and then it changed its direction toward the north entering the Gulf of Oman and dispersing on June 7. In 2007, Gonu was the second named TC in the Indian Ocean and categorized as Category 5 according to the Saffir–Simpson hurricane wind scale (SSHWS) (Saffir, 1973; Mohanty et al., 2014).

In June 2010, almost 3 years after Gonu, the Phet cyclone developed between the Arabian Sea and the Indian Ocean. It was the third described TC in the region, with a maximum wind speed of about 155 km/h (June 2). It started as a thunderstorm off the southwest of the Indian coast in the south-eastern Arabian Sea (Mohanty et al., 2014).

In October 2019, the super TC Kyarr developed (October 24) from a low-pressure region close to the Equator. The TC Kyarr showed an extremely strong TC in the North of the Indian Ocean and was denoted as the first strong TC after Gonu in 2007. The maximum wind speed that has been recorded was about 250 km/h. It has been noted that Kyarr did not cause severe damage because its path is offshore and almost parallel to the coastal lines along the affected areas. Moreover, Kyarr was merged with another TC (Maha), which makes for the first time two simultaneous TCs in the Arabian Sea (Mohanty et al., 2014). After two years since Kyarr occurred, the most recent TC Shaheen impacted the Omani coast in October 2021. Shaheen was named the fourth TC during the cyclone season in the Indian Ocean. Although the maximum wind was recorded at about 110 km/h, it caused great damage, especially along the Omani coast. It can be noted that the track of Shaheen starts from the east-central Bay of Bangel (it is named TC Gulab) towards the west of the Arabian Sea (named Shaheen). Additionally, Shaheen delivered extreme rainfall exceeding normal records. As a result, it caused flooding across many regions in Oman and High waves along the coastlines (Mohanty et al., 2014).

5 Flow and Wave Models Set Up

Due to the tropical cyclones, coupled 2DH flow and wave models are used to simulate the climate change impacts on the coast of Oman. Delft3D model is used in this study that Deltares, Netherlands have developed (Deltares, 2018). The model can solve the two- and three-dimensional unsteady shallow water equations by implementing a hydrostatic pressure approximation. The flow model is also able to simulate unsteady flow resulting from tides only, tidal and metrological forcing (wind-driven flow), wind shear, wave forces, density-driven flow, and atmospheric pressure changes in coastal regions, rivers, and estuarian areas (Lesser et al., 2004; Deltares, 2018). Moreover, the model is designed to solve the numerical equations for Cartesian or spherical unstructured grids using Generalized Lagrangian Mean (GLM) or Eulerian equations (Lesser et al., 2004). All the numerical formulations can be found in detail in the paper from (Lesser G.R. et al., 2004) or in a short description in the paper from Talal et al., 2022 (Etri et al., 2022). To include the effects of the waves on the hydrodynamics of the coastal processes, the SWAN wave model is coupled with the flow model. The well-known SWAN model is designed to simulate the sea state by calculating the wave action density (Booij, et al., 1999; Ris et al., 1999). The great benefit of coupling Delft3D flow and SWAN wave models is that the wind included in the simulation is only a result of the TCs. On the one hand, this goal can be achieved by controlling the hydrodynamic inputs of the wave model under the Delft3D platform, which would be difficult to do under a standalone SWAN model. On the other hand, no wave conditions were applied along the open boundaries of the wave model.

For the flow and the wave models, an unstructured grid with a resolution of about 2 km (about 0.018^o) has been used (Figure 1). The setup of the models has been done using the tool Delft Dashboard (DDB) from Deltares. The DDB is mainly a MATLAB-based tool using several open-source datasets (Van Ormondt et al., 2020). Three of the most important input parameters are the bathymetry, astronomical tides, and wind of the TCs. Therefore, the available GEBCO08 gridded bathymetry data set is utilized (IHO, 2018). The grid resolution for this data set is about 30 arc seconds (1 km) which consists of the proposed grid (2 km) for flow and wave models. For the astronomical tides, DDB provides complete data from the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO (Van Ormondt et al., 2020). In addition, ERA5 hourly data on single levels from 1959 to the present has been imposed for the wind inputs for both the flow and the wave models. ERA5 wind and wave data set is the 5th version of ECMWF reanalysis, not only for the wind and wave but also for the global climate and weather for the last 4 to 7 decades. The data covers a period from 1950 to the present and a horizontal resolution of 0.25^o and 0.5^o for the atmosphere and ocean waves, respectively (Hersbach et al., 2018). For the flow model, the open boundaries were selected to be only one open boundary as astronomical tide components are imposed at the south of the domain with enough distance to avoid any numerical instability close to the Omani coast (Figure 1).

6 Results and Discussions

To determine whether the results of the flow and wave models are showing good descriptions for climate change and to reach a high degree of confidence in the results of the models, an extensive study was conducted for sensitivity, calibration, and validation. In these stages, acceptable numerical and physical parameter settings were reached, as shown in Table 2. Also, to guarantee an independent evaluation of the model results from the TC's events, the period in December 2018 is used. For this purpose, 15 observation points along the Omani coast have been used.

Table 2: Flow and wave model settings

Parameter	Value	Description
Δt_{Flow}	5	Flow computational time step (minute)
Δt_{Wave}	60	Wave computational time step (minute)
C_d	0.0025 to 0.005	Wind drag coefficient
NDir	36	Directional bins
FreqMin and FreqMax	0.033 to 0.5	Frequency ranges (Hz)
NFreq	30	Frequency bins
BedFricCoef (jonswap)	0.067	Bottom friction (m^2s^{-3})

As seen in Table 2, using a frequency range from 0.033 to 0.5 Hz will allow wave periods from 2 to 33.3 s. One important point should be mentioned that due to the grid resolution (about 2 km), the wave model cannot represent nearshore wave conditions like wave shoaling, refraction, and wave breaking. Because of this, the observation points and the wave analysis have been extracted for water depths not less than 30 m, as proposed by (Leijnse et al., 2022). This is valid since the effects of the local wind-induced setup are not significant on such a large simulation scale.

Usually, the flow model simulations' quality is evaluated using the mean square error (MSE) and mean absolute error (MAE). In this study, it is highly recommended to use the MAE, which is more suitable and practical for evaluating the hydrodynamic models (Sutherland et al., 2004). For the quality of the wave model, the evaluation using the qualification proposed by Van Rijn et al. (2003), will be implemented (Van Rijn et al., 2003). It can be noted that the proposed qualification is converting the values of the root mean absolute error (RMAE) of the significant wave heights into qualification categories from Bad to Excellent.

The flow model results showed a good performance for the astronomical Semi-diurnal (M2, S2, N2, and K2) and diurnal components (K1, O1, P1, and Q1) in terms of amplitude and phase. In this regard, simulations for one year (2018) have been carried out. The comparison between the modelled and the estimated tidal components in the observation points showed differences between less than 1cm to 23cm for the amplitude and from 42 to 270o for the phase. Therefore, it can be confirmed that the astronomical tides imposed along the open boundary represent the tide conditions reasonably. Since this paper focuses on the TC's effects, further improvements in the tide conditions will not significantly change the wave conditions. In addition to the tidal analysis, a time series analysis for the tide with the wind as a driven force of the flow model has been carried out in December 2018. It is crucial to evaluate the flow model preference under the wind effect since the hydrodynamic conditions from the flow model will be used as input for the wave model. Since the area of interest is located along the Omani coast, only four stations are used to analyse the wind effects on the water level of the flow model results. The selection is based on the available water level measurements from the previously mentioned IHO tide observation points. The four stations (QURIYATIHO, MASKATIHO, BANDARRISUTIHO, and WUDAMIHO) cover a significant part of the south-eastern to the north-western coastline in the area of interest. The water levels in the four stations showed a good agreement between the measured and the modelled flow by using the wind from ERA5 wind datasets as driven forces. The calculated MAE in the four stations varies from 1 to 6 cm. Moreover, the results showed an excellent agreement in the phase without having any phase lag in any of the four stations.

The encouraging results from the flow model will reflect positively on the wave model, especially since the wave model is considered an essential element in studying the impact of hurricanes along the coasts of Oman. As the flow model was simulated in December 2018, the wave model was carried out for the same period. The wave model runs only using the hydrodynamics from the flow model (online coupling), including the wind speed and direction, without imposing any wave conditions at the open boundaries. In this way, the results from the wave model will only illustrate the effects of the TCs without any interaction with the swell waves. As mentioned before, the qualification proposed by (Van Rijn et al., 2003) will be used to evaluate the wave model preference. A comparison between the modelled and the measured wave data has been made using the ERA5 dataset. Although the ERA5 wave dataset is too coarse in terms of spatial (0.5o by 0.5o) and temporal (3 hours) resolution, it can be used for such analysis. Therefore, significant wave heights analysis took place in the 15 observation points, which showed RMAE values between 0.01 and higher than 0.3 (Bad to Excellent). It should also be clear that the high RMAEs are mainly observed at the shallow observation points depths where the ERA5 dataset accuracy is low (ocean waves).

For the quality of the simulations from the coupled flow and wave models, the effects of the TCs on the Omani coast can now be described with high confidence using the ERA5 wind dataset. For this purpose, four simulations of the selected TCs have been executed. Initially, time series analysis of the wave model results from the four TCs will cover the significant wave heights and wave peak periods at 15 observation points. Here, the simple analysis will take place by plotting the significant wave heights (Hs) vs the time in terms of days, neglecting the months and the years. This way, it will be possible to compare all the TC's effects on the Hs at the 15 observation points. Moreover, water levels from the flow model will be used for the same TCs at the 15 stations to describe the tide conditions (Neap-Spring). The model results showed that Gonu, Phet, and Shaheen mainly occurred during the spring tide in contrast with Kyarr, which occurred during the neap tide.

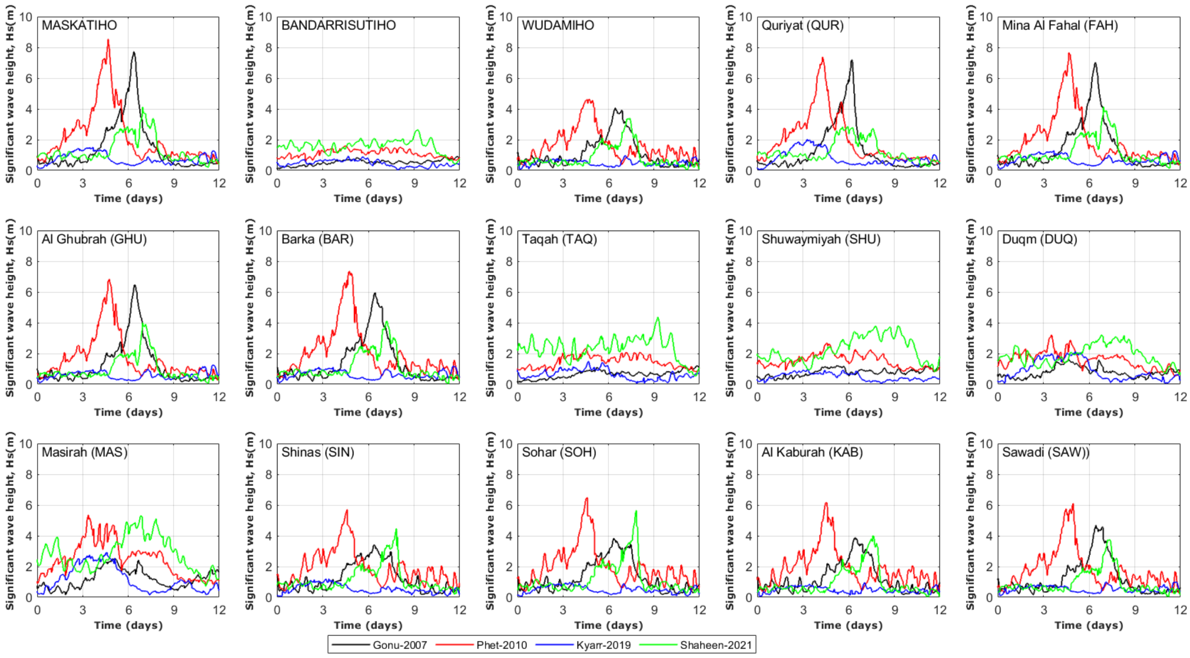

Fig. 2: Significant wave heights (Hs) in meters for the four TCs

Figure 2 shows the significant wave heights (Hs) from the wave model results in the 15 observation points. It can be seen clearly that the effects of the TCs on the Hs can be divided into 3 patterns. Pattern 1, low effects along the Arabian Sea, at the most south-western part of the Omani coast (BANDARRISUTIHO, TAQAH (TAQ), and SHUWAYMIYAH (SHU)). Pattern 2, medium effects at DUQM (DUQ) and MASIRAH (MAS). Pattern 3, significant effects at the rest of the 15 observation points along the Sea of Oman. This is valid for Gonu 2007, Phet 2010, and Shaheen 2021 TCs. It can be seen that Gonu 2007 and Phet 2010 caused extreme wave conditions (between 4 and 8m) in pattern 1 observation points. The observation of the Hs results from Gonu, and Phet TCs showed similar wave heights and event duration behaviour. It can be seen that both of the TCs reached 8m wave heights for a duration of 3 to 4 days. This will lead to more pressure due to events on the coastal structures. The more important point can be added that the Phet TC can be compared, even worse than the well-known TC Gonu. On the other hand, the TC Kyarr 2019 showed fewer effects on the Hs. However, a high wind speed is recorded, which could be mainly due to the cyclone's path following parallel to the Omani coast and in conjunction with neap tidal conditions. This leads to wave heights of less than 2 m at the 15 observation points. The Hs model results reveal the most critical effects due to TC Shaheen almost along the Omani coast from the north to the south. In pattern 1 region, the Hs can be recorded in the order of 4m. In pattern region 2 the wave heights were recorded between 2 and less than 4m, and in pattern 3 region about 2 m. It can be noted that the durations of the extreme wave conditions in all regions take from 4 to 5 days. In this case, the TC Shaheen can be considered the most severe event of the four simulated TCs. This is not due to high wind speed but to the path that the wind is following, the duration of the event and, additionally, the spring tidal conditions.

7 Conclusion

A 2DH flow model from Deltares and a wave from the SWAN model were set up along the Omani coast. The two models simulations have accounted for the tides for the hydrodynamics and wind for the wave models. The two models were calibrated in December 2018, and the model results showed that the models are capable of predicting wave conditions with acceptable accuracy. Four TCs, namely, Gonu 2007, Phet 2010, Kyarr 2019, and the most recent cyclone Shaheen 2021, have been simulated. The wave results clearly described the TC's events and their effects along the Omani coast. The results showed a clear tendency to increase the intensity of the TCs in the last two decades. Moreover, it has also been confirmed that the duration and the path of the TC event play an important role in studying the TCs. Additionally, the model's results showed a significant effect due to neap-spring tides on the wave conditions along the coast of Oman. The model's results improve the understanding of the TC's effects on the most exposed regions along the Omani coast. It can also be seen that not only the well-known TCs with 4 or 5 SSHWS categories (Gonu, Phet, and Kyarr) reveal extreme wave conditions but also TCs with 1 SSHWS category (Shaheen).

Although it has been found that the flow and the wave models, in general, are appropriate for describing the wave conditions due to TC's improvements, using field measurements is recommended. It is also highly recommended to generate reliable synthetic TCs using wind and pressure estimations to be used with flow and wave models.

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Cite as: Etri T., Al-Rawas G., Sana A. & Nikoo M.R., “Numerical Simulation of Climate Changes Impacts on The Coast of Oman Sea”, *The 2nd International Conference on Civil Infrastructure and Construction (CIC 2023)*, Doha, Qatar, 5-8 February 2023, DOI: https://doi.org/10.29117/cic.2023.0151