WAVES AND STORM SURGES OF TROPICAL CYCLONES OVER THE ARABIAN SEA: FUTURE PROJECTIONS AND UNCERTAINTY ANALYSIS

Zahra Ranji[1], Mohsen Soltanpour[2], and Tomoya Shibayama[3]

The present study aims to address the future projection of waves and storm surges of Tropical cyclones over the Arabian Sea, using the atmosphere-ocean numerical models and CMIP5 climate models. A Pseudo Global Warming (PGW) approach was utilised to implement the future climate and a WRF-FVCOM-SWAN framework was utilized to estimate the changes of a historical event in the future climate. The uncertainties included in different parts of the framework can lead to remarkable changes in this future estimation and are required to be addressed and quantified for a more appropriate estimation. Different factors such as forcing, boundary condition, and physics play a significant role in the uncertainties of wave and surge models. The study revealed that the wind forcing provided by the WRF model is the governing factor with the highest importance.

Keywords: Uncertainty analysis; climate change; tropical cyclones; Wave; Strom surge

INTRODUCTION

Tropical cyclones (TCs) are associated with a number of various hazards such as extreme wind, storm surge and large wave, which can individually threaten the coastal residents and infrastructures. Different atmospheric variables such as vertical wind shear stress control the TC characteristics. These parameters are remarkably changing in past years because of climate change. As an example, rare TC tracks and intensities, e.g., cyclone Shaheen-Gulab (Terry et al., 2022), are recently observed in the Arabian Sea.

Various factors can affect the surge and wave height, including TC characteristics, coastline shape, ocean bathymetry, and local features (Pattanayak et al., 2016). While it is demonstrated that TCs of the Arabian Sea are intensifying (Evan and Camargo, 2011), and the extreme waves and surge heights are remarkably dependent on the characteristics of TCs (Camelo et al., 2020), limited numbers of research that studied TCs generated waves and surges are available (e.g., Pattanayak et al., 2016).

Two approaches exist to consider the uncertainties associated with the estimation of TC-generated waves and surges:

- The impacts of uncertain parameters on real-time forecasting (e.g., Bastidas et al., 2016), including the wind field, model resolution, and input parameters.
- The effect of uncertainty on the future projection of TC-generated waves and surges, including GCM physics, the spatial pattern of SST, and global warming scenarios (Yang et al., 2020).

Considering the first approach, Lin and Chavas (2012) stated that the wind parameters are more effective on the surge height, in comparison with the sea surface drag. Zhong et al. (2010) examined the effect of uncertainties of atmospheric models on the accuracy of the simulated storm surge and indicated that even small errors in modeling TC parameters (more importantly TC track and forward speed) will lead to large errors in storm surge estimation. Similarly, Toyoda et al. (2022) recommended utilizing an ensemble of perturbed TC track for better capturing the maximum surge height. Warder et al. (2021) also computed the rise of uncertainty level by bathymetry and bottom friction, which is negligible compared to the meteorological input. On the other hand, there are other studies (e.g., Yazdandoost et al., 2021) that attempted to improve forecasting, using the statistical approach, disregarding the uncertainty sources.

Following the second approach, Mori et al. (2021) applied a statistical method, with lower computational costs, for the long-term assessment of storm surge. They concluded that the CMIP5 worst scenario (i.e., RCP 8.5) lead to higher surge height, with the largest range of uncertainty. Yang et al. (2020) estimated the uncertainties of future projection of the potential extreme surge height under the effect of future SST conditions and global warming scenarios.

Murakami et al. (2013) examined the effect of physics and SST change patterns on the variation of TC frequencies. They indicated that finer model resolution results in the stronger decrease of TC occurrence. Walsh et al. (2016) further recommended improving the regional TC projections by reducing the uncertainties of climate model simulation.

---

[1] Civil engineering Department, K.N.Toosi University of Technology, Tehran, Iran, zranji@mail.kntu.ac.ir
[2] Civil engineering Department, K.N.Toosi University of Technology, Tehran, Iran, soltanpour@kntu.ac.ir
[3] Civil engineering Department, Waseda University, Tokyo, Japan, shibayama@waseda.jp

Although numerical simulation is a useful tool to simulate the characteristics of future TCs, using the variability provided by GCM datasets, these methods, e.g., Pseudo Global Warming (PGW), have their own uncertainties. The uncertainty analysis, which requires a large ensemble set, is thus necessary to estimate future TCs and their subsequences such as giant waves and surges (Mori et al., 2021). Following Ranji et al. (2022), this study aims to estimate the changes of TC generated waves and surge heights, in a changing climate of the Arabian Sea, together with addressing the uncertainties associated with numerical models to estimate their changes.

STUDY AREA

The Arabian Sea, located in the northern Indian Ocean (Figure 1), is experiencing an increase in intensified TCs in recent years. Most of the TC landfalls happen either in the western Omani coastline or the eastern coastlines of India/Pakistan. Since a limited number of TCs reach the vicinity of the Iranian coastline, this coast can be considered as a risk free region. However, there have been exceptions in terms of intensity, e.g., Gonu (2007) as the highest record on strength, and rare track, e.g., Shaheen/Gulab (2021), which propagated close to the Iranian coastlines and caused significant damages to the coastal infrastructures. The present research highlights the importance of studying the intensified waves and surge heights in the structural design of the coastal properties, as well as providing an estimation about the future projection of TCs parameters over the Arabian Sea, in particular along the Iranian coastlines.

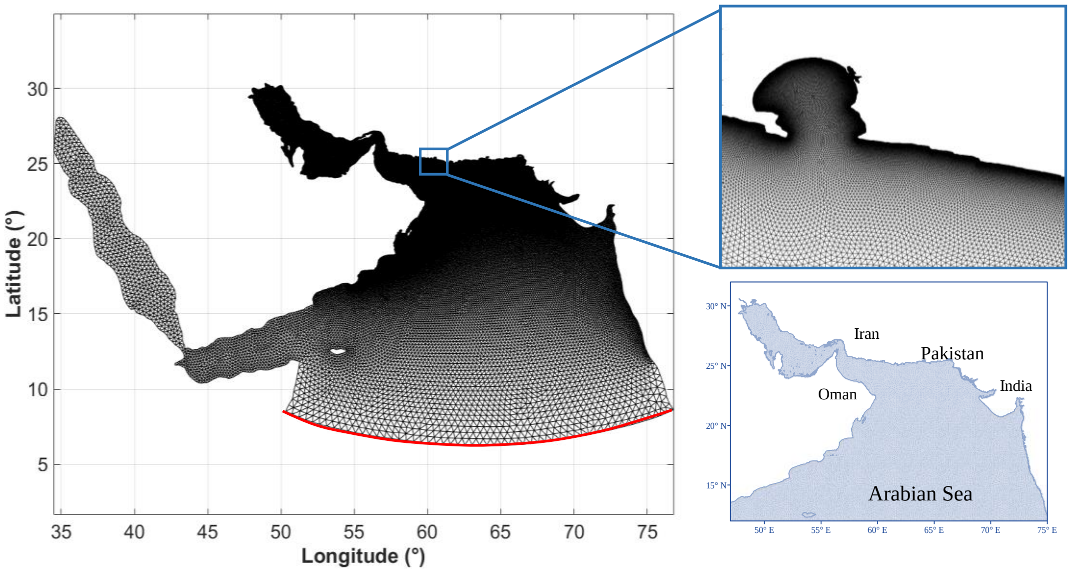

Figure 1. The study area (top right) and computational grid of SWAN and FVCOM (red line represents the open boundary)

METHODOLOGY

Future projection of TCs can be estimated using PGW approach, in which the GCM-based signals are imposed on the initial and boundary condition of historical event simulation. Through this process, simulation of the future intensification/weakening of historical TCs becomes feasible. However, several sources of uncertainties contribute to the presented projection. To address the uncertainties, Ranji et al. (2022) performed an intercomparison of 20 GCMs of CMIP5 in the baseline period to create the best GCMs ensemble that represents the fitted signals over the Arabian Sea. Using Weather Research and Forecasting (WRF) model, they used the PGW approach for future TCs projection. Using the configured model and several scenarios, a discussion of uncertainties was provided. The simulated wind and pressure fields of this study are employed here to derive the Simulating WAves Nearshore (SWAN) model and Finite Volume Community Ocean Model (FVCOM).

Figure 1 presents the domain and computational grid of the numerical models. A combination of GEBCO data and local hydrography maps at ports and coastal areas is used for the bathymetry. The boundary condition (red line in Figure 1), is selected from WWIII data (MMAB, 2016) and TPXO atlas model (Egbert and Erofeeva, 2002), for SWAN and FVCOM models, respectively. Model calibration is conducted using the measurements of local waves and storm surges in the baseline periods (Soltanpour et al., 2018).

Different scenarios of the simulated wind and pressure fields of the cyclone Phet (Ranji et al., 2022) are applied to the numerical models as the external forcing.

RESULTS AND DISCUSSION

RCP4.5 in the far future is only considered to simulate the future projection of wave parameters as it is the most intense case and the closer track to the baseline. Figure 2 presents a comparison of wave parameters, i.e., significant wave height, peak period, and mean wave direction, in the baseline and far future period.

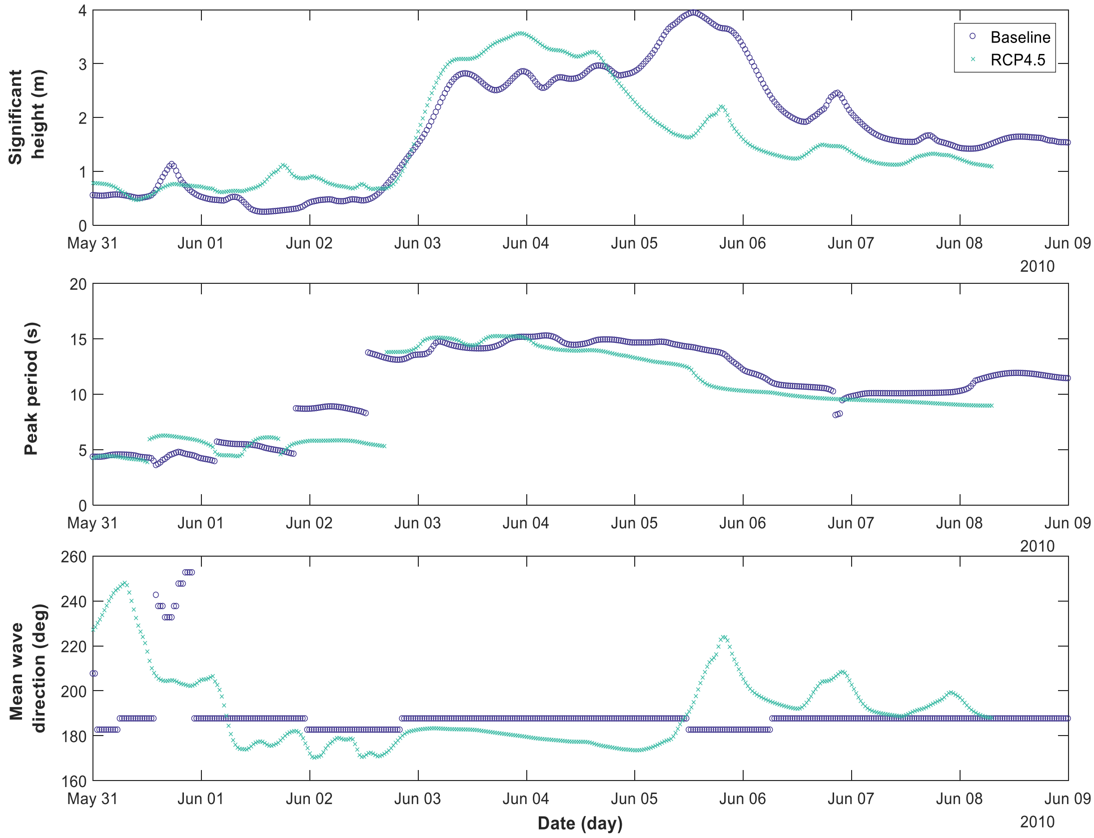

Figure 2. Simulated wave height (top), peak wave period (middle), and wave direction (bottom) of cyclone Phet for present climate (dark blue) and the far future climate for RCP 4.5 (Persian green).

The increase and decrease of significant wave height are both observed, which can be partially related to the different simulated tracks in the baseline and far future period. The approximately 25% increase of the peak wave period occurs when both tracks overlap. On the other hand, the wave height decrease is related to the time that the shifts between the tracks become remarkable. Since the simulated track in the far future shifts to a far distance from the Iranian coastline and the buoy location, the associated wave height decreases. The peak periods in the baseline and far future are almost similar. Mean direction, on the other hand, shows a relatively large difference in these two periods. However, it is minimized at the time of the TC's arrival and the dominance of local wind waves. In order to further study the future projection of the wave heights, two dimensional variation of the maximum significant wave height is depicted and compared in Figure 3. An increase of 10% in maximum wave height is observed nearby the TC’s eye.

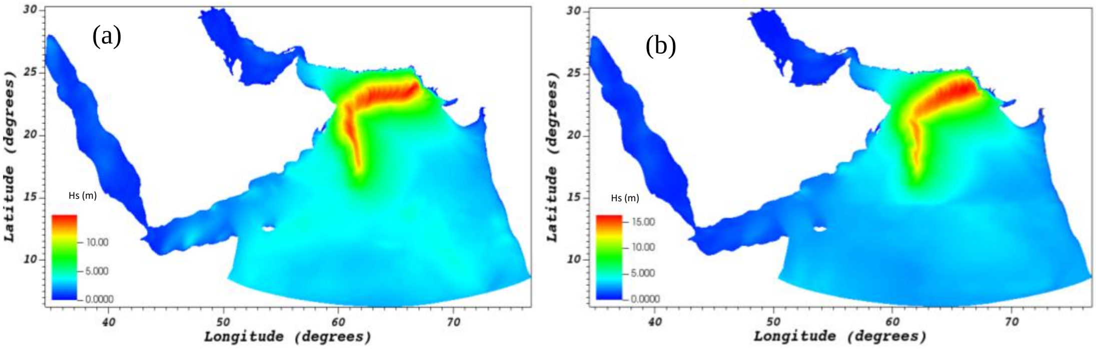

Figure 3. Maximum significant wave height of cyclone Phet for a) present climate and b) far future climate of RCP4.5

As the computed wave height for the future climate depends on different sources of uncertainty (i.e., forcing, grid size, boundary condition, bed roughness, wave breaking, and physics scheme), an attempt to examine the importance of each source is performed. Several scenarios are simulated to conduct the sensitivity analysis. Figure 4 shows the changes of maximum significant wave height in comparison with the standard simulation (see Figure 3-b). It is observed that the wind forcing has the highest impact on the simulated wave height. Thus, the uncertainties of future wind field need to be quantified, as discussed by Ranji et al. (2022). Grid size is the second factor that affects the future projection of the wave height. Although different discretization of the shelf slope and topographic variation result in a different projection of wave height, it is expected that the range of variation becomes negligible by further refining the grid.

The model physics, bed roughness, wave breaking parameters, and boundary condition are other important uncertainty sources for a wave model.

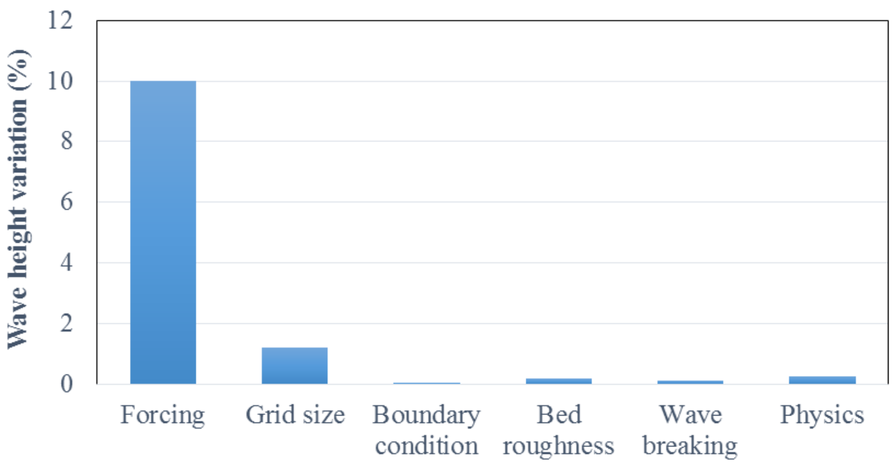

Figure 4. Sensitivity analysis of uncertainty sources for the wave model

To estimate future projection of surge height, FVCOM model are derived by wind and pressure inputs from future simulation of WRF. Figure 5 depicts the unremarkable intensification of the surge height in the vicinity of Iranian coastlines. The spatial pattern of maximum surge height in Figure 6 shows the overall increase of the surge height in the far future. At the landfall location of TCs, i.e., Pakistani coastlines, an increase of 50% is observed. In general, it is concluded that small intensification of TCs can lead to a remarkable increase of the surge height, specifically near the landfall location.

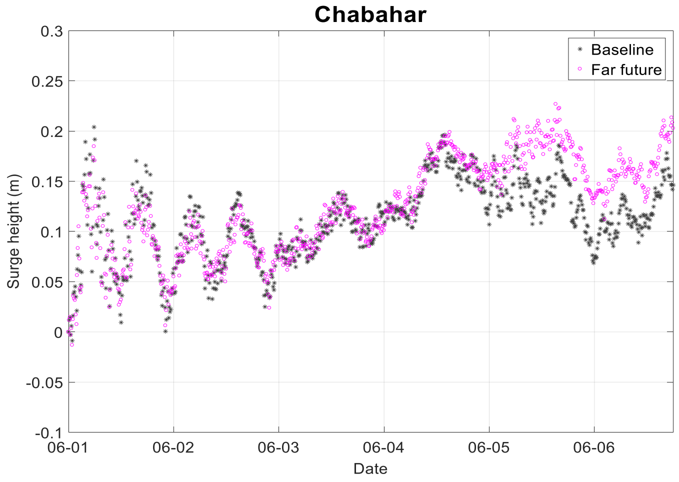

Figure 5. Simulated surge height of cyclone Phet for present climate (gray) and the far future climate for RCP 4.5 (pink)

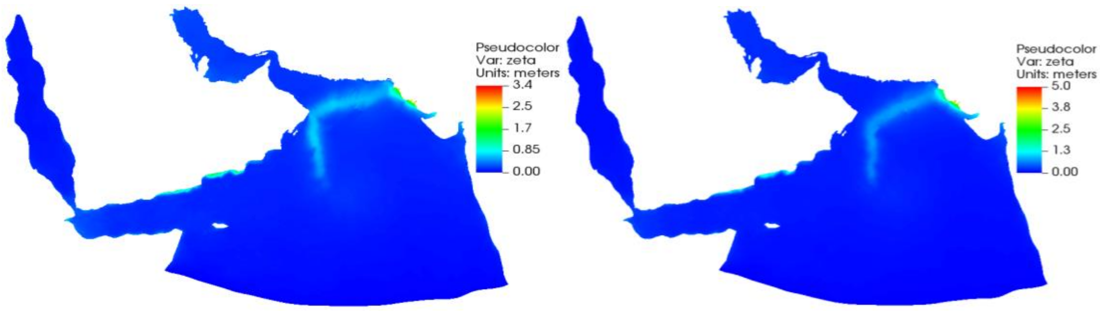

Figure 6. Maximum surge height of cyclone Phet for a) present climate and b) far future climate of RCP4.5

Similar to the wave model, the surge model is more sensitive to the driving forces and horizontal/vertical resolution of the computational grid (Figure 7). On the other hand, the bed roughness, boundary conditions, and turbulence models are less effective on the surge height.

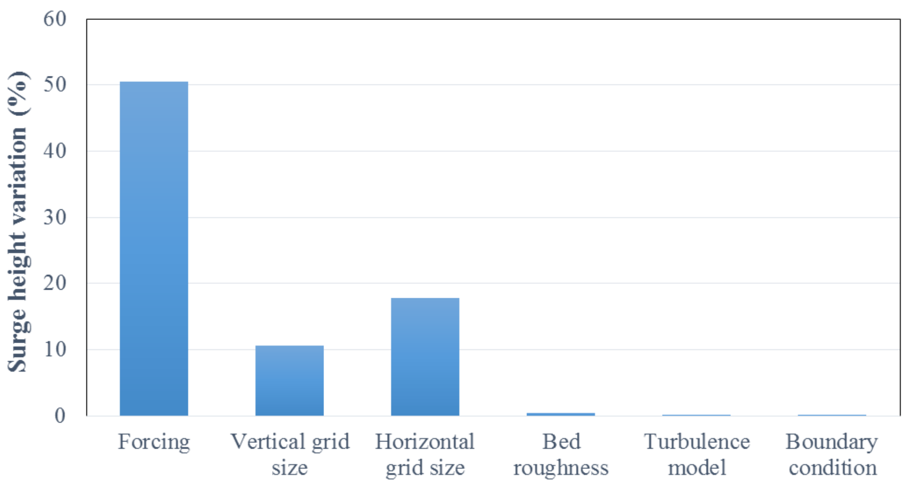

Figure 7. Sensitivity analysis of uncertainty sources for the surge model

CONCLUSION

Using the PGW approach, future projection of TC-generated waves and surges was presented. An increase of 10% in the maximum wave height was observed near the TC's eye. Along the Pakistani coastlines near the landfall location of TC, 50% increase in surge height was also observed.

It was concluded that small intensifications of TCs can lead to a remarkable increase in the surge and flooding, particularly in the vicinity of the landfall location. The major uncertainty, associated with the future projection of waves and surges, rises from the driving forces, rather than the configuration of numerical models. The uncertainties of the winds and pressure fields (e.g., input signals variables, and spatial variation of signals) need to be well addressed in order to have a more reliable projection.

Quantification of uncertainties requires a different combination of effective factors and a higher number of TC simulations. A higher number of TCs is also required for better projection of waves and surge heights in the future climate. Limited number of simulations were conducted in this study that affects the accuracy of the projection of waves and surge heights in the future climate. For better projection of TC-generated waves and surge heights, it is recommended to apply a regional climate model over the Arabian Sea, which is able to detect future TCs.

ACKNOWLEDGMENTS

The authors are grateful for the former collaboration of Dr. Cartwright and Dr. Zarifsanayei (Griffith University) in the former research, which was utilized in the current research. The collaboration and support received from Dr. Haghshenas (Tehran University) is also appreciated.

REFERENCES

Bastidas, L. A., Knighton, J., and Kline, S. W. 2016. Parameter sensitivity and uncertainty analysis for a storm surge and wave model. *Natural Hazards and Earth System Sciences*, *16*(10), 2195–2210. https://doi.org/10.5194/nhess-16-2195-2016

Camelo, J., Mayo, T. L., and Gutmann, E. D. 2020. Projected Climate Change Impacts on Hurricane Storm Surge Inundation in the Coastal United States. *Frontiers in Built Environment*, *6*(December). https://doi.org/10.3389/fbuil.2020.588049

Egbert, G. D., and Erofeeva, S. Y. 2002. Efficient Inverse Modeling of Barotropic Ocean Tides. *Journal of Atmospheric and Oceanic Technology*, *19*(2), 183–204. https://doi.org/10.1175/1520-0426(2002)019<0183:EIMOBO>2.0.CO;2

Evan, A. T., and Camargo, S. J. 2011. A Climatology of Arabian Sea Cyclonic Storms. *Journal of Climate*, *24*(1), 140–158. https://doi.org/10.1175/2010JCLI3611.1

Lin, N., and Chavas, D. 2012. On hurricane parametric wind and applications in storm surge modeling. *Journal of Geophysical Research: Atmospheres*, *117*(D9), n/a-n/a. https://doi.org/10.1029/2011JD017126

MMAB. 2016. *WAVEWATCH III Model Data Access*. https://polar.ncep.noaa.gov/waves/ensemble/download.shtml

Mori, N., Ariyoshi, N., Shimura, T., Miyashita, T., and Ninomiya, J. 2021. Future projection of maximum potential storm surge height at three major bays in Japan using the maximum potential intensity of a tropical cyclone. *Climatic Change*, *164*(3–4), 25. https://doi.org/10.1007/s10584-021-02980-x

Murakami, H., Sugi, M., and Kitoh, A. 2013. Future changes in tropical cyclone activity in the North Indian Ocean projected by high-resolution MRI-AGCMs. *Climate Dynamics*, *40*(7–8), 1949–1968. https://doi.org/10.1007/s00382-012-1407-z

Murakami, H., Wang, Y., Yoshimura, H., Mizuta, R., Sugi, M., Shindo, E., Adachi, Y., Yukimoto, S., Hosaka, M., Kusunoki, S., Ose, T., and Kitoh, A. 2012. Future Changes in Tropical Cyclone Activity Projected by the New High-Resolution MRI-AGCM. *Journal of Climate*, *25*(9), 3237–3260. https://doi.org/10.1175/JCLI-D-11-00415.1

Pattanayak, S., Mohanty, U. C., and Dube, S. K. 2016. The Storm Surge Prediction over Bay of Bengal and Arabian Sea: A Review. In *Advanced Numerical Modeling and Data Assimilation Techniques for Tropical Cyclone Prediction* (pp. 691–723). Springer Netherlands. https://doi.org/10.5822/978-94-024-0896-6_27

Ranji, Z., Zarifsanayei, A. R., Cartwright, N., and Soltanpour, M. 2022. Climate change impacts on tropical cyclones of the Arabian Sea: Projections and uncertainty investigations. *International Journal of Climatology*, *42*(10), 5121–5141. https://doi.org/10.1002/joc.7523

Soltanpour, M., Ranji, Z., Shibayama, T., Ghader, S., and Nishizaki, S. 2018. NUMERICAL SIMULATION OF TROPICAL CYCLONES AND STORM SURGES IN THE ARABIAN SEA. *Coastal Engineering Proceedings*, *1*(36), 11. https://doi.org/10.9753/icce.v36.papers.11

Terry, J., Al Ruheili, A., Boldi, R., Gienko, G., and Stahl, H. 2022. Cyclone Shaheen : the exceptional tropical cyclone of October 2021 in the Gulf of Oman. *Weather*, *77*(10), 364–370. https://doi.org/10.1002/wea.4193

Toyoda, M., Fukui, N., Miyashita, T., Shimura, T., and Mori, N. 2022. Uncertainty of storm surge forecast using integrated atmospheric and storm surge model: a case study on Typhoon Haishen 2020. *Coastal Engineering Journal*, *64*(1), 135–150. https://doi.org/10.1080/21664250.2021.1997506

Walsh, K. J. E., McBride, J. L., Klotzbach, P. J., Balachandran, S., Camargo, S. J., Holland, G., Knutson, T. R., Kossin, J. P., Lee, T., Sobel, A., and Sugi, M. 2016. Tropical cyclones and climate change. *WIREs Climate Change*, *7*(1), 65–89. https://doi.org/10.1002/wcc.371

Warder, S. C., Horsburgh, K. J., and Piggott, M. D. 2021. Adjoint-based sensitivity analysis for a numerical storm surge model. *Ocean Modelling*, *160*(February), 101766. https://doi.org/10.1016/j.ocemod.2021.101766

Yang, J., Kim, S., Son, S., Mori, N., and Mase, H. 2020. Assessment of uncertainties in projecting future changes to extreme storm surge height depending on future SST and greenhouse gas concentration scenarios. *Climatic Change*, *162*(2), 425–442. https://doi.org/10.1007/s10584-020-02782-7

Yazdandoost, F., Zakipour, M., and Izadi, A. 2021. Copula based post-processing for improving the NMME precipitation forecasts. *Heliyon*, *7*(9), e07877. https://doi.org/10.1016/j.heliyon.2021.e07877

Zhong, L., Li, M., and Zhang, D.-L. 2010. How do uncertainties in hurricane model forecasts affect storm surge predictions in a semi-enclosed bay? *Estuarine, Coastal and Shelf Science*, *90*(2), 61–72. https://doi.org/10.1016/j.ecss.2010.07.001