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A Novel Framework for Estimating Probable Maximum Tropical Cyclone with Sparse Records

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ABSTRACT:

Tropical cyclones (TCs) pose a significant threat to critical infrastructure (e.g., nuclear power plants) located in coastal regions, as they are accompanied by concurrent high winds, heavy rainfall, and storm surges that can cause catastrophic flooding and damage. Thus, such infrastructures must be designed to withstand the most severe TC, to ensure their safety under the worst-case scenario. For this purpose, the design basis event (flood/wind) can be obtained based on the Probable Maximum Tropical Cyclone (PMTC) that can make landfall in the coastal region. The PMTC is defined as a hypothetical steady-state cyclone having the highest maximum sustained wind speeds (V_{max}) that can reasonably occur in an ocean basin. Conventionally, a probabilistic approach involving frequency analysis of historical cyclone records is utilized to arrive at V_{max} of PMTC as a quantile corresponding to a very high return period (e.g., 1000,10000 years) (Kumar et al., 2023). The V_{max} estimates are validated by comparing them with a theoretical maximum value of V_{max}, which corresponds to the maximum potential intensity of a cyclone that can originate in the ocean basin from the available thermal energy, with no inhibiting factors. In literature, an empirical linear regression relationship has been established between V_{max} of historical cyclones and the corresponding mean sea surface temperature (SST) in the genesis region. The relationship can be utilized to estimate the theoretical maximum V_{max} corresponding to a high mean SST under a climate change scenario.

The estimates of V_{max} of PMTC obtained using the existing methods (probabilistic approach, linear regression relationship) have uncertainty due to sparse records of TCs in an ocean basin. We propose a novel framework to reduce this uncertainty in analysis with sparse records. It involves estimation of V_{max} of PMTC using the non-parametric Bethlahmy method adapted for probable maximum precipitation literature (Bethlahmy, 1984; Jaya and Srinivas, 2023). Furthermore, estimation of the theoretical maximum V_{max} is based on a quantile regression relationship newly developed between V_{max} and SST of the cyclone genesis region. The efficacy of the framework is demonstrated over the Bay of Bengal basin in the North Indian Ocean, which is a breeding ground for intense TCs during pre-monsoon and post-monsoon seasons. The V_{max} of PMTC is also estimated corresponding to the different El Niño Southern Oscillation (ENSO) phases, as they are known to modulate the frequency and intensity of TCs in the North Indian Ocean.

The results indicated that the proposed framework outperforms the existing methods. The V_{max} estimates obtained using the Bethlahmy method of the framework had a higher median value and lower uncertainty (interquartile range) than those obtained from the existing probabilistic approach in the literature (Kumar et al., 2023). Furthermore, a more reliable estimate of the theoretical maximum V_{max} was obtained using the newly developed quantile regression relationship in the framework than the existing linear regression relationship. The error in the estimated median V_{max} of PMTC (348.8 kmph) with respect to its theoretical maximum value (395.04 kmph) was least for the proposed Bethlahmy method. Similar findings were obtained when the proposed framework was applied to the TCs during different ENSO phases. Overall, the proposed framework can be considered as a promising alternative for reliably estimating the PMTC parameter in ocean basins with sparse records.

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