

Grey swan tropical cyclones

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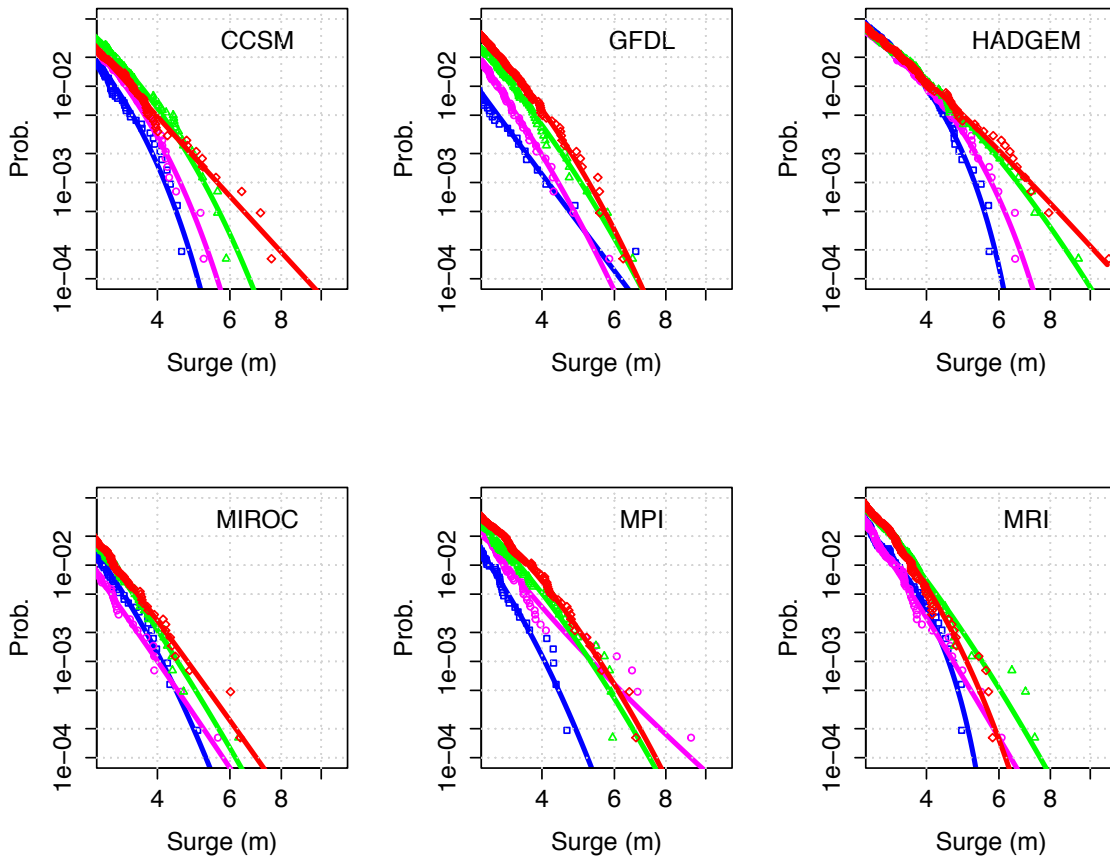


Figure S1. Generalized Pareto distribution (GPD) fit (curves) of the upper tail of the surge levels (dots) for Tampa, in the climate of 1980-2005 (blue), 2006-2036 (pink), 2037-2067 (green), and 2068-2098 (red), projected using each of the 6 climate models for the IPCC AR5 RCP8.5 emission scenario. The full distributions are shown in Fig. 3 of the main article.

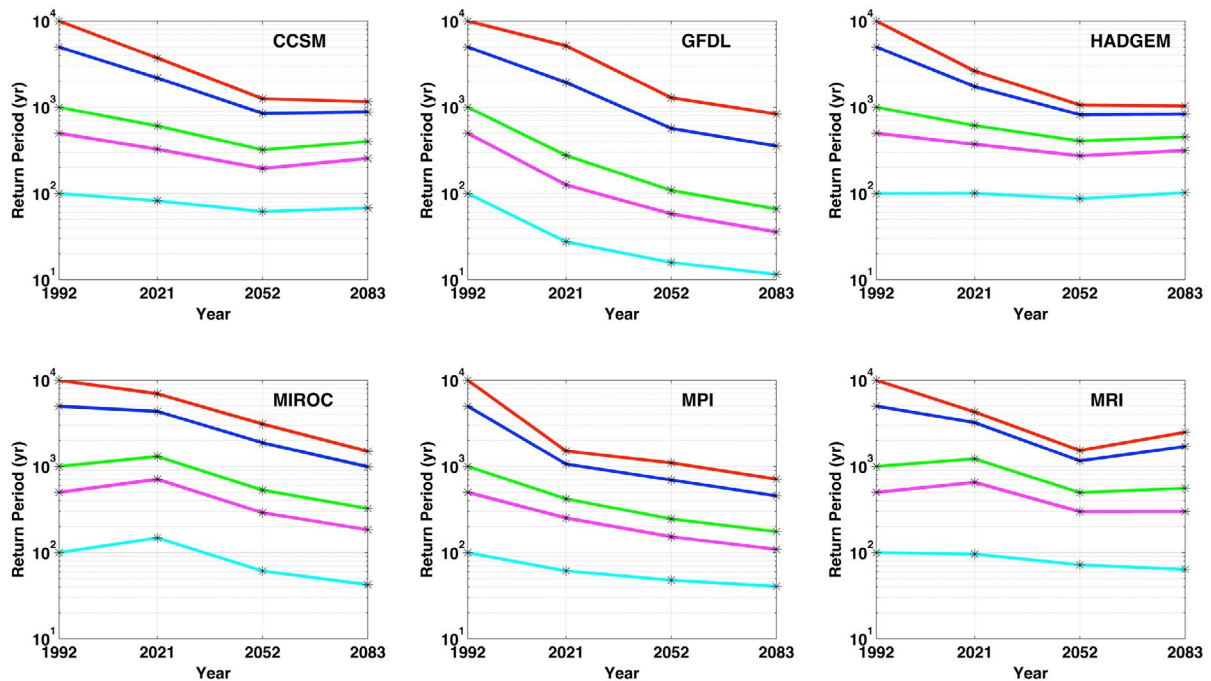


Figure S2. The change of return period of a 10,000-year (red), 5,000-year (blue), 1,000-year (green), 500-year (pink), and 100-year (cyan) event from the late 20th century to the late 21st century, projected for Tampa, using each of the 6 climate models for the IPCC AR5 RCP8.5 emission scenario. Black stars show the estimated return periods for the climates of 1980–2005 (control), 2006–2036 (early 21st century), 2037–2067 (middle), and 2068–2098 (late), marked at the center year of 1992, 2021, 2052, and 2083, respectively. These estimates are consistent with those in Fig. 3 of the main article. Linear interpolation is applied between the marked points in this figure.

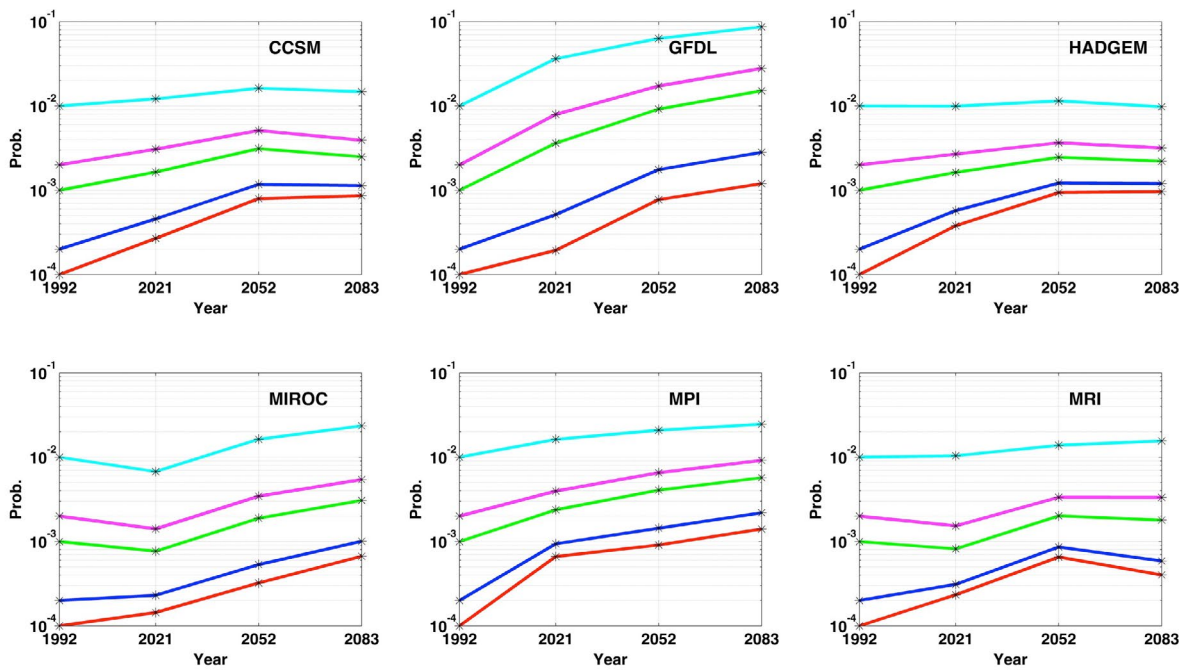


Figure S3. Same as Fig. S2, but presented as the change of annual exceedance probability (the reciprocal of the mean return period).

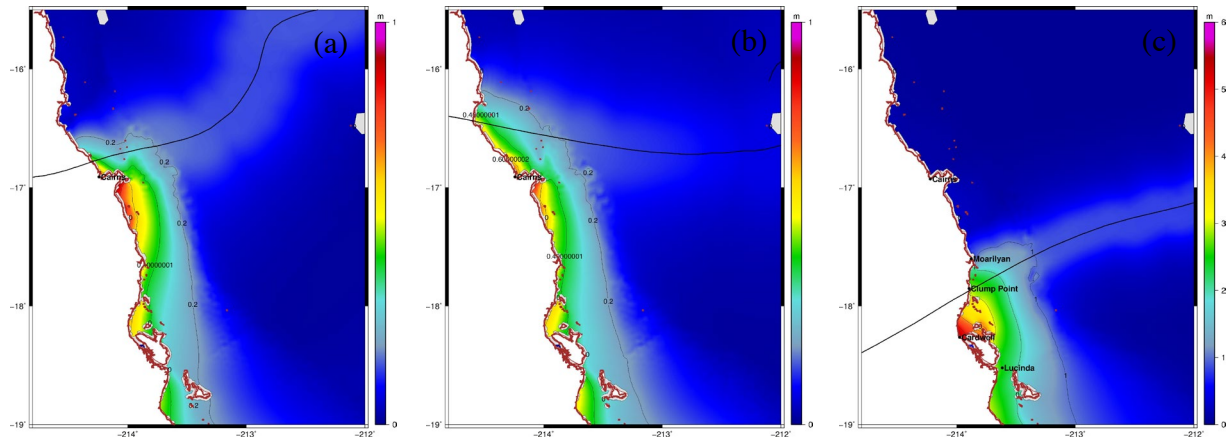


Figure S4. Simulated surges for three historical storms in the Cairns region. (a). Cyclone Justin of 1997. The simulated surge at Cairns is 0.69 m (the observation is 0.63 m). (b). Cyclone Rona of 1999. The simulated surge at Cairns is 0.67 (the observation is 0.63 m). (c). Cyclone Yasi of 2011. The simulated surges at Moarilyan, Clump Point, Cardwell, and Lucinda are 1.03 m, 2.88 m, 5.45 m, and 2.48 m, respectively (the observations are 1.30, 2.97, 5.33, and N/A due to tidal-gauge failure). The shaded contours show the simulated surge height (m; above MSL). The black curve shows the storm track. (The observed storm surge is estimated as the difference between the observed maximum water level, obtained from the State of Queensland, Department of Science, Information Technology, Innovation and the Arts, and the predicted astronomical tide, obtained from the Australian National Tidal Center.)

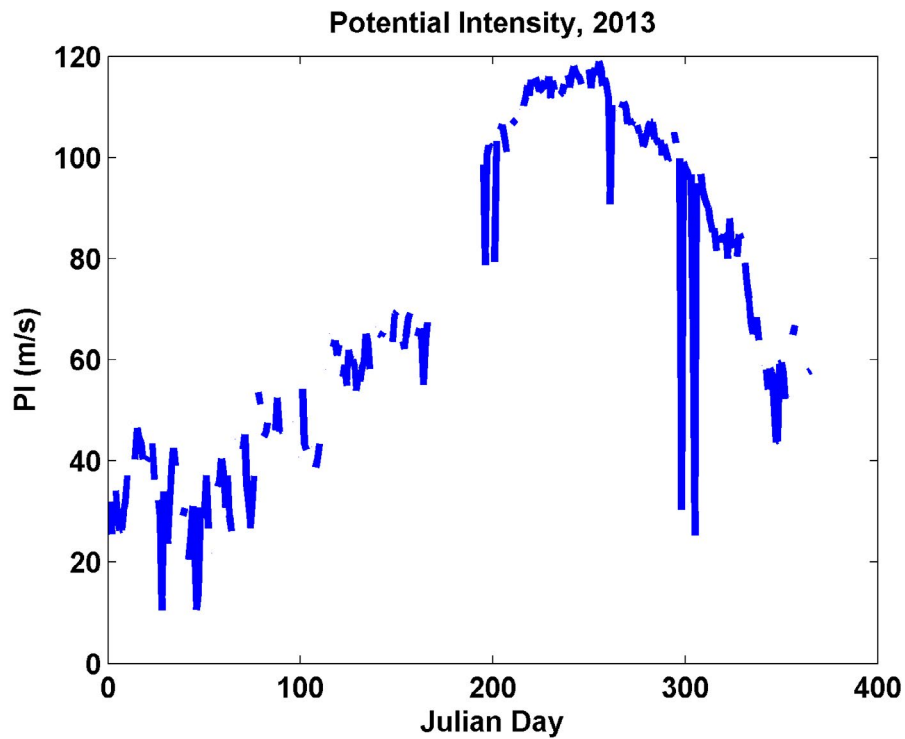


Figure S5. Daily potential intensity (PI) in the Persian Gulf during the year 2013. Data applied in the calculation includes the atmospheric sounding at Dammam, Saudi Arabia, for 12 GMT each day (obtained from the University of Wyoming atmospheric data website) and monthly mean Hadley Center SSTs averaged over the whole Persian Gulf and linearly interpolated to the day. The blank sections represent days with missing soundings.

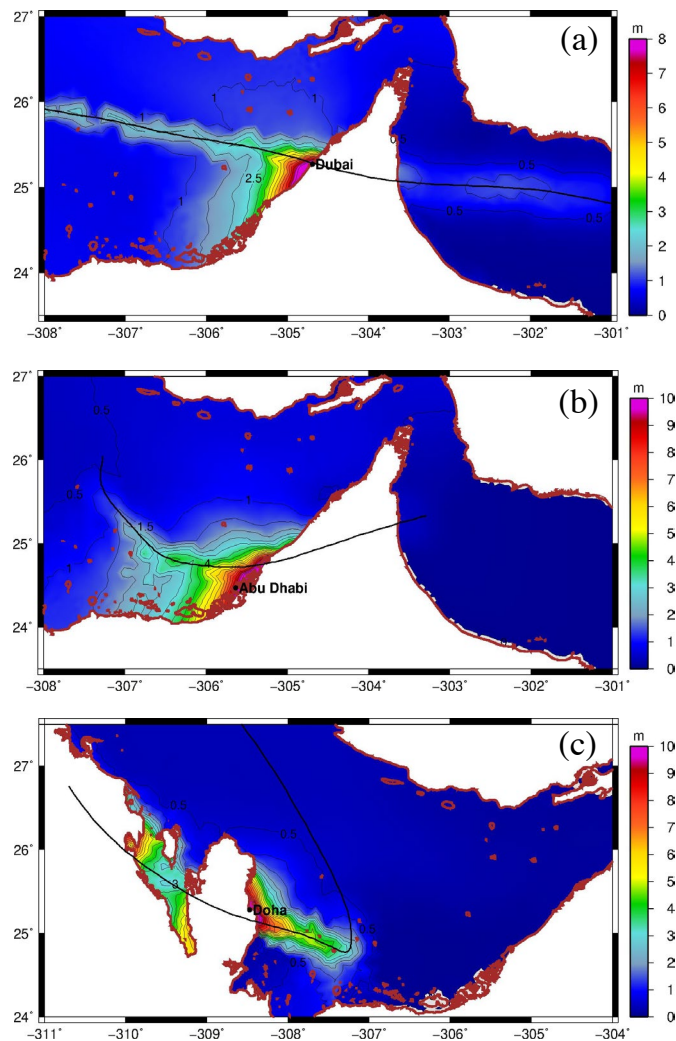


Figure S6. Three grey swan TC surge events for three major cities in the Persian Gulf, based on the NCEP/NCAR reanalysis climate of 1980–2010. (a). The “worst” surge event (among 3100 events) inducing a maximum surge of 7.1 m for Dubai. (b). The “worst” surge event (among 3100 events) inducing a maximum surge of 9.5 m for Abu Dhabi. (c). The “worst” surge event (among 3100 events) inducing a maximum surge of 9.1 m for Doha. (The higher surges in Abu Dhabi and Doha compared to Dubai are mainly induced by their different local geophysical features; the lower resolutions in the numerical mesh may have also led to overestimates; see Methods.)

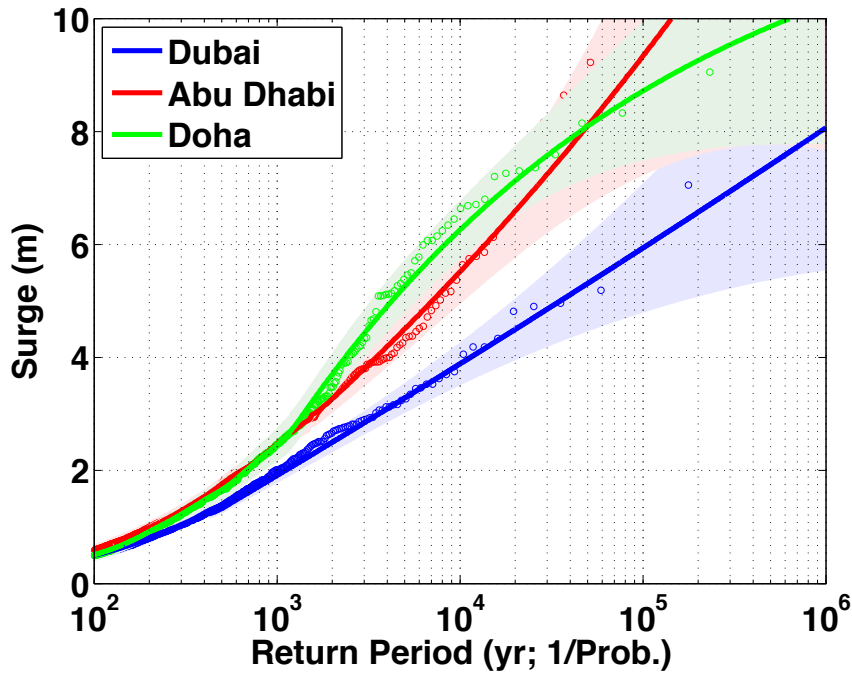


Figure S7. Estimated storm surge level as a function of return period for Dubai (blue), Abu Dhabi (red), and Doha (green), each based on 3100 synthetic events in the NCEP/NCAR reanalysis climate of 1980-2010. The associated annual frequencies of the synthetic events are 0.032, 0.024, and 0.025 for Dubai, Abu Dhabi, and Doha, respectively. The dots show the synthetic data, and the shading shows the 90% statistical confidence interval. (The return level curve for Dubai is very similar to that obtained based on the MERRA reanalysis, as shown in Fig. 5c in the main article.)