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Grey Swan Tropical Cyclones

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9 **Abstract**

10 We define “Grey swan” tropical cyclones as high-impact storms that would not be predicted
11 based on history but may be foreseeable using physical knowledge together with historical data.
12 Here we apply a climatological-hydrodynamic method to estimate grey swan TC storm surge
13 threat for three highly vulnerable coastal regions. We identify a potentially large risk in the
14 Persian Gulf, where TCs have never been recorded, and larger-than-expected threats in Cairns,
15 Australia, and Tampa, Florida. Grey swan TCs striking Tampa, Cairns, and Dubai can generate
16 storm surges of about 6 m, 5.7 m, and 4 m, respectively, with estimated annual exceedance
17 probabilities of about 1/10000. With climate change, these probabilities can increase
18 significantly over the 21st century (to 1/3100-1/1100 in the middle and 1/2500-1/700 towards the
19 end of the century for Tampa). Worse grey swan TCs, inducing surges exceeding 7 m in Dubai
20 and 11 m in Tampa, are also revealed with non-negligible probabilities, especially towards the
21 end of the century.

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32 **Introduction**

33 The term “Black swans”^{1,2} is a metaphor for high-consequence events that come as a surprise.
34 Some high-consequence events that are unobserved and unanticipated may nevertheless be
35 predictable (though perhaps with large uncertainty). Such to-some-extent-predictable, low-
36 probability, high-impact events may be referred to as “grey swans”^{3,4} (or, sometimes, “perfect
37 storms”⁵). Unlike truly unpredicted and unavoidable black swans, which can be dealt with only
38 by fast reaction and recovery, grey swans-although also novel and outside experience-can be
39 better foreseen and systematically prepared for^{4,5}.

40 Tropical cyclones (TCs) often produce extreme wind, rainfall, and storm surges in
41 coastal areas. Storm surges are especially complex functions of TC characteristics (track,
42 intensity, and size) and coastal features (geometry and bathymetry), and they are also the most
43 fatal and destructive aspect of TCs (see ref 6 for a comprehensive review of global TC surge
44 observations and impacts). Hence, storm surge is an appropriate and practical metric for
45 identifying grey swan TCs. The most infamous TC disasters early in this century were
46 attributable to storm surges, but they should not be considered grey swans, as they had been or
47 could have been anticipated based on historical observations and/or experience. Hurricane
48 Katrina (2005), the costliest U.S. natural disaster, generated the highest U.S recorded surge
49 inundation (~ 10 m)⁷, but its impact on New Orleans, due largely to the levee failure, had been
50 anticipated by various studies⁸. Cyclone Nargis (2008), the worst natural disaster in Myanmar’s
51 history and one of the deadliest TCs worldwide, struck Myanmar’s Ayeyarwady River Delta at
52 an unusually low latitude (near 16° N) and induced extreme surges (over 5 m); however, the
53 catastrophic fatalities in the hardest-hit areas were largely due to the lack of evacuation plans and
54 cyclone awareness⁹, although intense tropical cyclones had been active in the Bay of Bengal and

55 made landfall in Myanmar (e.g., in 2006). Hurricane Sandy, which devastated the U.S. Northeast
56 coast in 2012, set the record-high storm tide (3.4 m) at the Battery in New York City (NYC);
57 however, its storm surge (2.8 m) at the Battery was much lower than those of the 1821 NY
58 hurricane (4.0 m)^{10,11} and more severe grey swan TCs (4.5-5 m) that had been simulated for the
59 region^{12,13}. Typhoon Haiyan (2013), the deadliest TC in Philippine history and probably the most
60 powerful TC to make landfall worldwide, generated extreme water levels up to 8 m near the
61 most affected Tacloban area¹⁴, but the water level was comparable to those induced by earlier
62 storms, including a similarly severe typhoon that struck the area in 1897 (7.3 m)¹⁵.

63 Prediction of a grey swan TC, by definition, is meaningful and practically useful only
64 when associated with some likelihood/probabilistic statement, e.g., the probability of exceeding
65 the storm surge level induced by the TC in a year is 10^{-3} . The Monte Carlo (MC) method, based
66 on numerous synthetic simulations, is an important way to assess the probability of grey swan
67 TCs. Most current MC methods^{16,17,18} simulate synthetic TCs using (quite limited) historical TC
68 statistics. In contrast, a statistical-deterministic model¹⁹, which is independent of the TC record,
69 simulates TC environments statistically and generates TCs in the simulated environments
70 deterministically. This statistical-deterministic approach may sometimes be more reliable, as
71 observations of the large-scale TC environment are often better constrained than those of TC
72 characteristics in areas with very limited TC history. It is also more likely to generate unexpected
73 but realistic grey swan TCs, because, rather than extrapolating historical TCs, it applies physical
74 knowledge of TCs and ample observations of the large-scale environment. Moreover, as the
75 synthetic TC environments can be generated for any given climate state, this model can simulate
76 grey swan TCs not only in the current and past climates but also in projected future climates²⁰.
77 As TC activity may vary with changing climate^{21,22,23,24}, the model enables quantitative projection

78 of how grey swan TCs will evolve in the future. This statistical-deterministic TC model has been
79 integrated with hydrodynamic surge models²⁵ into a climatological-hydrodynamic method¹³,
80 which has been shown to generate extreme storm surges that are far beyond historical records but
81 are compatible with geological evidence²⁶. The method has been used to study storm surge risk
82 and mitigation strategies for NYC^{27,28}, and it is applicable to any coastal city. Here we apply the
83 method to another three highly vulnerable regions: Tampa in Florida, Cairns in Australia, and the
84 Persian Gulf; we identify their grey swan TCs as the synthetic TCs that are associated with
85 extremely low annual exceedance probabilities (large mean return periods) of the induced storm
86 surges (see Methods).

87

88 **Tampa**

89 Tampa, located on the central west Florida coast, is highly susceptible to storm surges. Although
90 many fewer storms have made landfall in this area than in regions farther north and west on the
91 Gulf Coast or further south on the Florida Coast, Tampa Bay is surrounded by shallow water and
92 low-lying lands; a 6-m rise of water can inundate much of the Bay's surroundings²⁹. Two
93 significant historical events have affected Tampa. The Tampa Bay hurricane of 1848 produced
94 the highest storm tide ever experienced in the Bay, about 4.6 m, destroying many of the few
95 human works and habitations then in the area. The Tampa Bay hurricane of 1921 produced an
96 estimated storm tide of 3-3.5 m, inducing severe damage (10 million in 1921 USD).

97 To investigate the current TC threat for Tampa, we simulate 7800 Tampa Bay synthetic
98 TC surge events in the observed climate of 1980-2005 as estimated from the NCEP/NCAR
99 reanalysis³⁰. To study how the threat will evolve from the current to future climates, we apply

100 each of 6 climate models to simulate 2100 surge events for the climate of 1980-2005 (control)
101 and 3100 surge events for each of the three climates--2006-2036 (early 21st century), 2037-2067
102 (middle), and 2068-2098 (late)--under the IPCC AR5 RCP8.5 emission scenario. The 6 climate
103 models, selected as in ref 24 from CMIP5 (Coupled Model Intercomparison Project Phase 5), are
104 CCMS (CCMS4; NCAR), GFDL (GFDL-CM3; NOAA), HADGEM (HADGEM2-ES; UK Met
105 Office Hadley Center), MPI (MPI-ESM-MR; Max Planck Institution), MIROC (MIROC5;
106 CCSR/NIES/FRCGC, Japan), and MRI (MRI-CGCM3; Meteorological Research Institute,
107 Japan).

108 The large synthetic surge database includes many extreme events affecting Tampa. As a
109 comparison, the 1921 Tampa surge event is also simulated (Fig. 1a). The 1921 Tampa hurricane
110 had a track similar to that of the 1848 Tampa hurricane³¹, traveling northwestward over the Gulf
111 of Mexico and making landfall north of Tampa Bay. The “worst” synthetic case (among 7800
112 events) in the reanalysis climate of 1980-2005 has a similar track (Fig. 1b). However, this grey
113 swan TC is more intense (upper Cat 3, compared to the lower Cat-2 1921 storm), inducing a
114 higher surge at Tampa of 5.9 m (compared to 4.0 m simulated for the 1921 storm). We have also
115 identified grey swan TCs affecting Tampa that have very different tracks, especially those
116 moving northward parallel to the west Florida coast before making landfall. For example, Fig.
117 1(c) shows an extremely intense storm (104 m/s; “worst” case generated under the late 21st
118 century climate projected by HADGEM) that moves northward parallel to the coast and turns
119 sharply towards Tampa Bay, inducing a storm surge of 11.1 m in Tampa. In such cases, the
120 storm surges are likely amplified by coastally trapped Kevin Waves. These waves form when the
121 storm travels along the west Florida coast and propagate northward along the Florida shelf,
122 enhancing the coastal surges, especially when the storm moves parallel to the shelf and at

123 comparable speed to the wave phase speed³². This geophysical feature makes Tampa Bay even
124 more susceptible to storm surge.

125 These grey swan TCs have very low probabilities, which can be quantified only within
126 the full spectrum of events. Fig. 2 shows the estimated storm surge level for Tampa as a function
127 of (mean) return period for the reanalysis climate of 1980-2005. The grey swan surge of 5.9 m
128 (Fig. 1b) has a return period of over 10,000 years in the 1980-2005 climate. In comparison, the
129 1000-year surge is about 4.6 m and the 100-yr surge is about 3.2 m. The surge level of the 1921
130 storm (approximately 3.3-3.8 m, as it likely happened at low tide) has an estimated return period
131 of 100-300 years in the 1980-2005 climate. We note here a potentially large uncertainty in the
132 analysis. In the simulations, we take the storm outer radius R_o to be its statistical mean³³ to
133 generate the radius of the maximum wind R_m (see Methods). As shown previously²⁶, neglecting
134 the statistical variation of storm size may greatly underestimate the surge risk, as the
135 distributions of the size metrics (R_o and R_m) may be positively skewed³³. Indeed, a sensitivity
136 analysis for Tampa shows that the estimated surge return periods would be significantly reduced
137 if a lognormal distribution of R_o ³³ (with the same mean) was applied; for example, the return
138 period of the 1921 storm surge could be reduced to as little as 60 years (not shown). However,
139 the result is very sensitive to the specific distribution of R_o , which itself is largely uncertain due
140 to data limitations and lack of fundamental knowledge of what controls the TC size in nature^{34,35}.

141

142 The more severe grey swan surges of above 8 m up to 11 m (Fig 1c) have extremely low
143 or negligible probabilities in the 1980-2005 climate, but they are projected to happen as 5,000-
144 150,000-yr events in the late 21st century. As shown in Fig. 3, the 6 climate models project that
145 the return period of the storm surges for Tampa will significantly decrease over the 21st century,

146 especially for the extremes (grey swans). This increase in storm surge threat is mainly due to the
147 increase in storm frequency and intensity. The magnitude of the surge, especially for the
148 extremes, is projected to increase by all 6 models, and the CCSM, HADGEM, and MPI models
149 project relatively larger increases (see Supplemental Fig. S1). The overall frequency of the
150 Tampa Bay storms is also projected to increase moderately (<25%) according to the CCSM,
151 HADGEM, and MRI models; greatly (<75%) according to MIROC and MPI; or extremely
152 (240%) according to GFDL (noted in Fig. 3). As a result, the CCSM and HADGEM models
153 project the largest increase in the frequency of the grey swans and little change in the normal
154 events while GFDL projects a relatively uniform increase in the frequency of all events, and the
155 other three models project relatively large (small) increases in the frequency of extremes (normal
156 events). Hence, large uncertainties exist among the climate models in the probable increase of
157 grey swans over the century. For example, a ten-thousand-year event in the late 20th century will
158 become a 1.5-7, 1.1-3.1, and 0.7-2.5 thousand-year event in the early, middle, and late 21st
159 century, respectively, depending on the climate models; and a one-thousand-year event in the
160 late 20th century will become a 2.7-13, 1.1-5.3, and 0.6-4.5 hundred-year event in the early,
161 middle, and late 21st century, respectively. (Supplementary Fig. S2 (S3) illustrates, for various
162 levels of events, how the return periods (annual exceedance probabilities) decreases (increases)
163 over the 21st century, projected by each of the 6 climate models.) Here the effect of neglecting
164 the variability of storm size may be relatively small for the projections of the change of the
165 probability. However, this analysis neglects the possible increase of the magnitude of storm size
166 in a warmer climate. Although such an increase in storm size, as suggested by potential intensity
167 theory³⁶, would further increase the surge risk¹³, the effect of climate change on storm size has
168 yet to be investigated observationally and numerically.

169

170 **Cairns**

171 The TC threat to Cairns, in the far north of Queensland, may not be well recognized. The city is
172 located about 300 km south of Bathurst Bay, which was hit in 1899 by Cyclone Mahina (the
173 most intense TC in the Southern Hemisphere, inducing what may have been the highest surge
174 inundation (13 m) in the historical record³⁷). According to the Australian Bureau of Meteorology,
175 at least 53 cyclones have affected Cairns since it was founded in 1876, and several high-intensity
176 storms (e.g., Cyclones Larry in 2006 and Yasi in 2011) were near-misses. Recent events include
177 Cyclones Justin in 1997, Rona in 1999, and Steve in 2000, all making landfall north of Cairns;
178 although these storms (< Cat 2) generated storm surges in Cairns of less than 1 m, they induced
179 major flooding (due also to tide and waves) and significant damage (\$100-190 million) in the
180 area. (Simulations of these historical cyclones, in comparison with observations, are shown in
181 Supplementary Fig. S4.)

182 To study the TC threat for Cairns, we simulate 2400 synthetic Cairns TC surge events in
183 the NCEP/NCAR reanalysis climate of 1980-2010. The “worst” surge for Cairns is about 5.7 m,
184 induced by an intense storm (80 m/s) traveling perpendicularly to the coast and landfalling just
185 north of Cairns (Fig. 4a). This grey swan TC is much stronger than Cyclones Justin, Rona, and
186 Steve and makes landfall much closer to Cairns. It resembles a hypothetical Cyclone Yasi that is
187 moderately intensified (by about 10 m/s) and shifted northward by about 160 km.

188 As shown by the estimated surge return curve in Fig. 4b, the grey swan surge of 5.7 m
189 has a return period of over 10,000 years in the 1980-2010 climate. As a reference, the 1000-year
190 surge is about 3.5 m, and the 100-yr surge is about 1.6 m. These results are significantly higher

191 than previous estimates based on synthetic storm databases generated by statistically extending
192 the historical storm records. For example, one such study³⁸ estimated that the 1000-yr storm
193 surge level for Cairns is about 2.3 m (storm tide of 2.9 m) and the 100-yr surge level is about 1.3
194 m (storm tide of 2.0 m); another³⁹ estimated the 10,000-yr storm tide to be 2.6 m, the 1,000-yr
195 storm tide to be 2.2 m, and the 100-yr storm tide to be 1.8 m. The lower estimates in these
196 previous analyses, especially for the most extreme events, were deduced by extrapolating the
197 storm record from several decades to tens of thousands of years. Analyses based on geological
198 evidence of paleo coastal inundations also yielded much higher estimates of such extremes for
199 the north Queensland coast than these historical-storm-based estimates⁴⁰; our results are more
200 consistent with the geological evidence (Nott, personal communication).

201

202 **The Persian Gulf**

203 The Persian Gulf is a Mediterranean Sea of the Indian Ocean, connected to the Arabian Sea
204 through the Strait of Hormuz and Gulf of Oman. The Persian Gulf is comprised of hot, shallow,
205 and highly saline water, which can support the development of intense TCs and storm surges.
206 However, no TC has been observed in the Persian Gulf, and TC development in the Arabian Sea
207 is limited by the region's typically low humidity and high wind shear⁴¹. Cyclone Gonu (2007),
208 the strongest historical TC in the Arabian Sea (Cat 3; 78 fatalities and 4.4 billion in damage),
209 came close to entering the Persian Gulf, making landfall at the mouth of the Gulf on the
210 easternmost tip of Oman and then in southern Iran. It is scientifically interesting and socially
211 important to ask if such a strong TC can travel into the Persian Gulf.

212 To answer this question, we assess the TC threat for three major cities bordering the
213 Persian Gulf: Dubai, Abu Dhabi, and Doha. For each of these cities, we simulate 3100 synthetic
214 TC surge events in the NCEP/NCAR reanalysis climate of 1980-2010. Since the maximum width
215 of the Persian Gulf is only about 340 km, it may be poorly resolved by the NCAR/NCEP
216 reanalysis resolution of 2.5 degrees (about 250 km); thus we also apply a higher-resolution
217 reanalysis dataset, the NASA' Modern-Era Retrospective Analysis⁴² (MERRA; with resolution
218 of 0.67 degrees x 0.5 degrees), to simulate TC surge events in Dubai. The obtained surge levels
219 and probabilities, however, are very similar for the two datasets. We here present the result for
220 Dubai from the MERRA reanalysis (while the results for Dubai, Abu Dhabi, and Doha from the
221 NCEP/NCAR reanalysis are shown in the Supplement). Some of the synthetic storms originate in
222 the Arabian Sea and move into the Persian Gulf, but the majority originates, surprisingly, within
223 the Gulf. Moreover, the most extreme surges are all induced by intense storms that originate
224 within the Gulf.

225 Fig. 5a shows the "worst" surge (among 3100 events in the climate of 1980-2010) for
226 Dubai. This grey swan TC originates in the northwest region of the Persian Gulf, moves
227 southeastwards in the Gulf, and makes landfall north of Dubai with extremely high intensity (115
228 m/s), generating a storm surge of 7.4 m in Dubai. The intensity of this grey swan TC is far
229 beyond the highest observed TC intensity worldwide (Typhoon Haiyan of 87 m/s). This
230 extremely high wind intensity is owing to very large potential intensities (PIs), made possible by
231 high sea surface temperature (SST; with summertime peak values in the range of 32-35°C⁴³) and
232 the deep dry adiabatic temperature profiles characteristic of desert regions. Indeed, the PI
233 calculated using the Dammam (Saudi Arabia) atmospheric sounding and an SST of 32-35°C is
234 between 109 m/s and 132 m/s. (The daily PI calculated using this sounding and the Hadley

235 Center observed SST, shown in Supplementary Fig. S5, confirms this result). Furthermore,
236 surface cooling from deep-water upwelling is nearly impossible in this shallow¹, highly saline,
237 and mixed body of water, and when, occasionally, the wind shear is small, the storm can fully
238 achieve its potential intensity. (We note, however, that the estimated pressure intensity has not
239 been similarly evaluated, which will be done in the future, but the storm surge is less sensitive to
240 the pressure than to the wind intensity.)

241 Fig. 5b shows the second highest synthetic surge generated for Dubai. This grey swan TC
242 originates in the southeast region of the Persian Gulf, moves directly towards the coast, and
243 makes landfall almost perpendicular to the coast and just north of Dubai, generating a storm
244 surge of 5.7 m in Dubai. The storm intensity is moderate (65 m/s). It is not necessary for the
245 storm to be extremely intense in order to generate extreme surges; some near “perfect”
246 combination of track, intensity, and size can induce devastating surge inundation in Dubai, given
247 its unusual shallow-water surroundings.

248 Nevertheless, given the prohibiting atmospheric environment in the region, these extreme
249 grey swan TCs have very low probabilities, with return periods on the order of 30,000-200,000
250 years (Fig. 5c). Also, the surge level decreases rapidly with decreasing return period. The 10⁴-
251 year surge for Dubai is about 4 m and the 10³-yr surge is about 1.9 m. The surges for return
252 periods less than 100 years are very small. Similar and even higher surge levels for Abu Dhabi
253 and Doha are also estimated using the NCAR/NCEP reanalysis (see Supplementary Figs. S6 and
254 S7).

¹ The mean depth of the Persian Gulf is 36 m, with a maximum depth of 90 m.

255 We note that these analyses are based on the climate of 1980-2010, during which the
256 Arabian Sea's synthetic TC activity increased, likely due to a decrease in the wind shear⁴⁴. Thus,
257 although TC development is limited in the Persian Gulf, a large TC threat exists and may be very
258 sensitive to changes of the atmospheric circulation in the region. Moreover, the SST in the
259 Persian Gulf had an upward significant trend during the period of 1950-2010, with an abrupt
260 increase in the 1990-2010 era⁴³. Further warming of the ocean may further increase the chance of
261 the Persian Gulf region being struck by an extreme storm.

262

263 **Final Remarks**

264 Assessments of the risks associated with natural hazards such as tropical cyclones have been
265 limited by the comparatively short length of historical records. This limitation is being overcome
266 by the new field of paleotempestology, which identifies TC events in the geological record, and
267 by bringing knowledge of storm physics to bear on the problem. Here we have used a physically-
268 based climatological-hydrodynamic method to assess the likelihood of highly destructive events
269 for three regions. Uncertainty in storm size induces uncertainty in the estimated probabilities;
270 accounting for the variation of storm size from storm to storm and in different climates, when
271 more reliable information on which becomes available, may yield significantly higher estimated
272 TC threats. In addition to the storm surge that we focus on here, coastal inundation is also
273 affected by the astronomical tide, waves, sea level rise, and future shoreline changes⁴⁵, all of
274 which will amplify the impact of grey swan tropical cyclones.

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Author contributions K. E. performed numerical simulations of the storms. N. L. carried out storm surge simulations and statistical analysis. N.L. and K.E. co-wrote the paper.

Additional information The authors declare no competing financial interests. Methods and Supplementary Information accompany this paper on www.nature.com/naturegeoscience.

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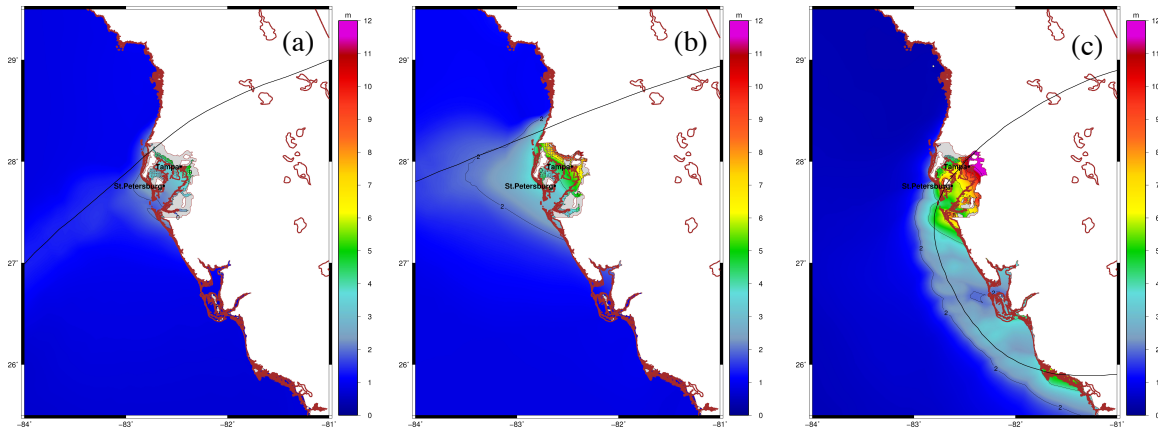


Figure 1. Two grey swan TCs (b and c) for Tampa compared to the 1921 Tampa Hurricane (a). The shaded contours represent the simulated surge height (m; above MSL); the maximum surge at Tampa (82.45W, 27.94N) is 4.0 m, 5.9 m, and 11.1 m for (a)-(c), respectively. The black curve shows the storm track. The storm characteristics when the storm moves closest to Tampa Bay mouth (82.72W, 27.58N) are (a). storm symmetrical maximum wind speed $V_m = 43.1$ m/s, minimum sea-level pressure $P_c = 967.8$ mb, radius of maximum wind $R_m = 35.0$ km, distance to the Bay mouth $ds = 37.7$ km, translation speed $U_t = 4.6$ m/s, and translation direction $\theta_t = 51.8$ deg; (b). $V_m = 54.7$ m/s, $P_c = 953.4$ mb, $R_m = 39.7$ km, $ds = 75.0$ km, $U_t = 5.6$ m/s, and $\theta_t = 67.6$ deg; and (c). $V_m = 104.3$ m/s, $P_c = 829.6$ mb, $R_m = 17.0$ km, $ds = 5.1$ km, $U_t = 2.0$ m/s, and $\theta_t = 20.0$ deg.

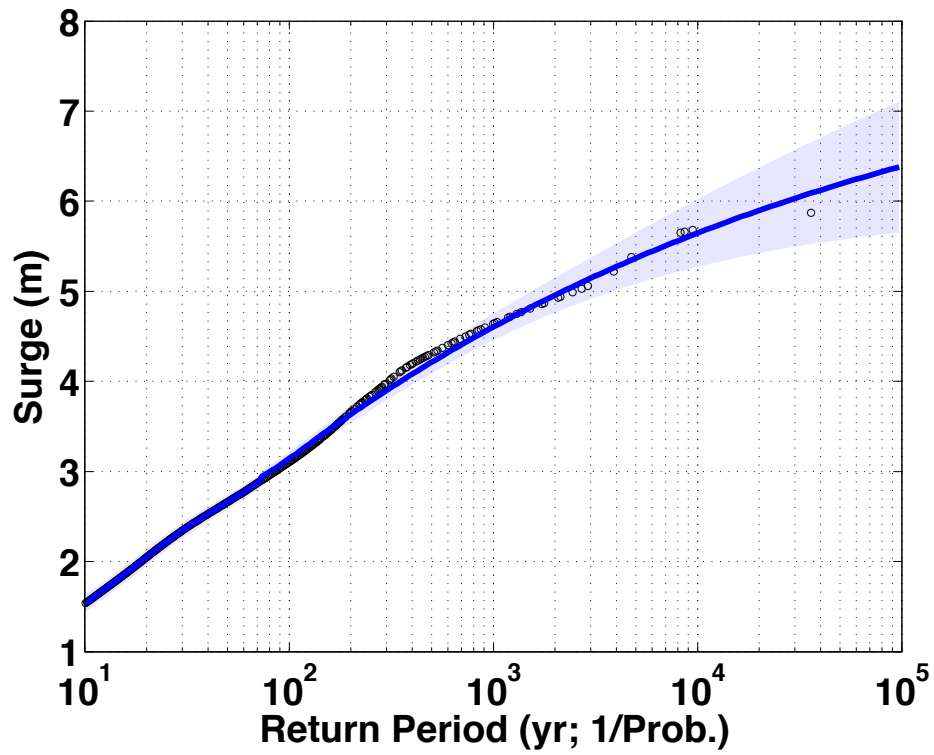


Figure 2. Estimated storm surge level as a function of the return period for Tampa (82.45W, 27.94N) for the NCEP/NCAR reanalysis climate of 1980-2005, based on 7800 synthetic events. The associated annual frequency of the synthetic events is 0.36. Black dots show the simulated data, and the shade shows the 90% statistical confidence interval.

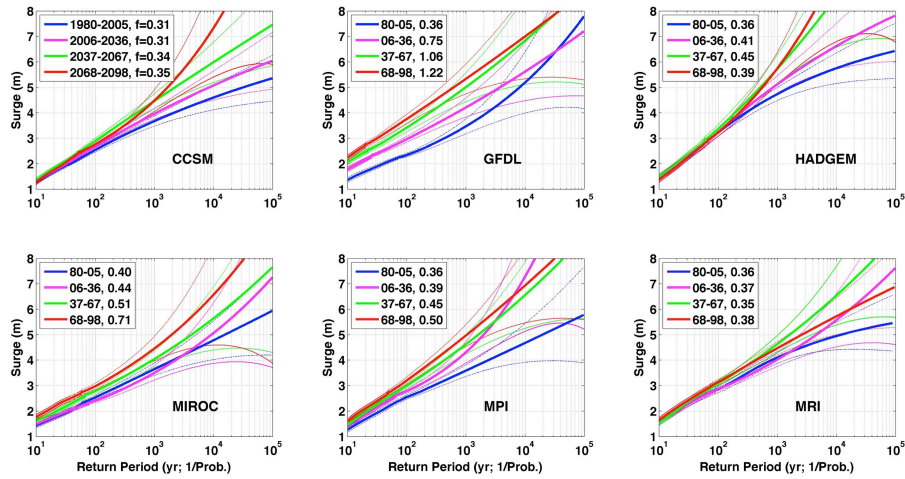


Figure 3. Estimated storm surge level as a function of the return period for Tampa (82.45W, 27.94N) in the climate of 1980-2005 (blue), 2006-2036 (pink), 2037-2067 (green), and 2068-2098 (red), projected using each of 6 the climate models for the IPCC AR5 RCP8.5 emission scenario. The annual frequency (f) is noted for each case. The thin dash curves show the 90% statistical confidence interval. (The data points and goodness of fit for the upper tail are shown in Supplementary Fig. S1.)

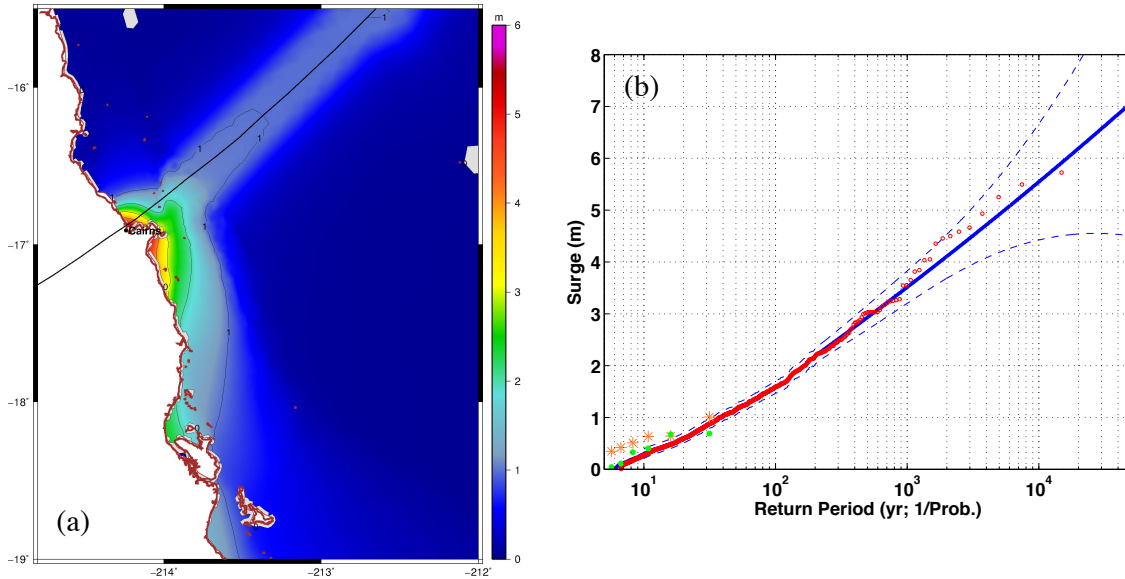


Figure 4. Storm surge risk analysis for Cairns, based on 2400 synthetic events in the NCEP/NCAR reanalysis climate of 1980-2010. The associated annual frequency for the synthetic events is 0.16. (a). The “worst” surge event for Cairns (145.76E, 16.91S). The shaded contours show the simulated surge height (m; above MSL). The black curve shows the storm track. The storm characteristics when the storm moves closest to Cairns are $V_m = 79.3$ m/s, $P_c = 901.1$ mb, $R_m = 22.3$ km, $ds = 9.9$ km, $U_t = 6.2$ m/s, and $\theta_t = 234.4$ deg. (b). Estimated storm surge level as a function of the mean return period for Cairns. The red dots show the synthetic data, and the dash curves show the 90% statistical confidence interval. Orange dots show the tidal-gauge-observed Cairns storm surges (6 in total) between 1980-2010; green dots show the simulated surges for these 6 historical TCs (the annual frequency of the historical storms is 0.19).

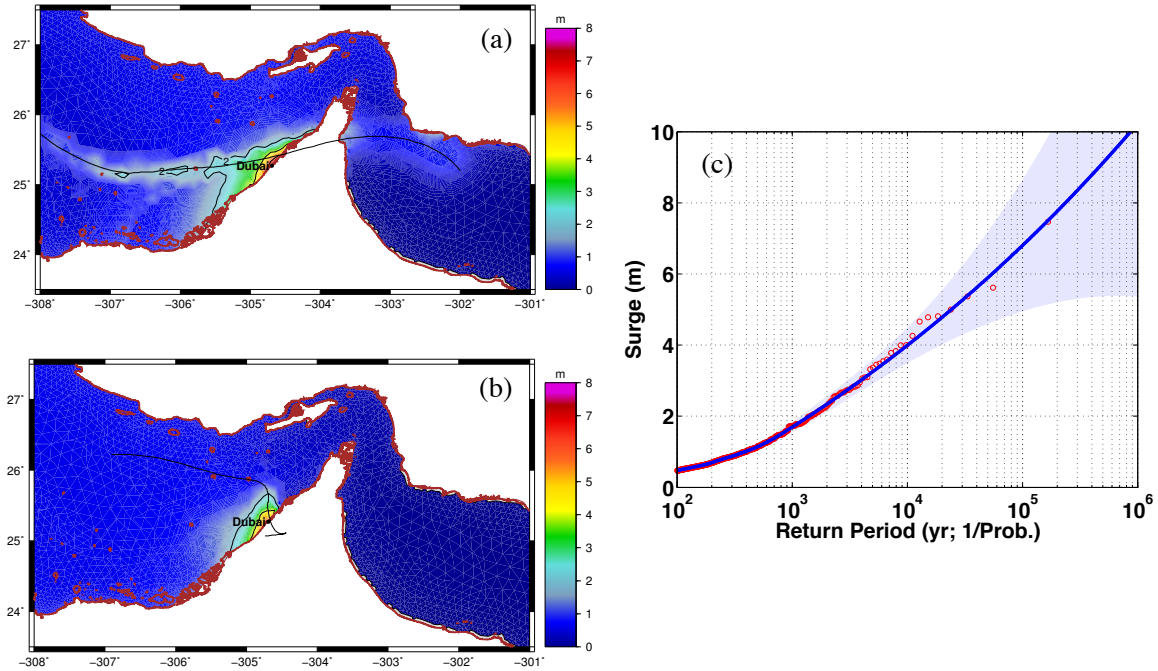


Figure 5. Storm surge risk analysis for Dubai, based on 3100 synthetic events in the MERRA reanalysis climate of 1980-2010. The associated annual frequency for the synthetic events is 0.037. (a). The “worst” surge (7.5 m) event for Dubai (55.31E, 25.27N). The shaded contours show the simulated surge height (m; above MSL). The black curve shows the storm track. The storm characteristics when the storm moves closest to Dubai are $V_m = 114.6$ m/s, $P_c = 784.2$ mb, $R_m = 13.8$ km, $ds = 18.4$ km, $U_t = 3.0$ m/s, and $\theta_t = 77.0$ deg. (b). The second “worst” surge (5.6 m) event for Dubai, with $V_m = 65.4$ m/s, $P_c = 927.3$ mb, $R_m = 21.3$ km, $ds = 7.8$ km, $U_t = 0.7$ m/s, and $\theta_t = 159.5$ deg. (c). Estimated storm surge level as a function of the return period for Dubai. The dots show the synthetic data, and the shade shows the 90% statistical confidence interval.

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Methods

Grey Swan Tropical Cyclones

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10 **Methods**

11 *Storm generation*

12 The climatological-hydrodynamic method includes three components: storm generation, storm
13 surge simulation, and statistical analysis. We use a statistical-deterministic TC model¹⁹ to
14 generate enough synthetic TCs in an ocean basin under a given climate to obtain a desired
15 number of TCs that make landfall in a particular coastal area of interest. Weak proto-storms are
16 seeded uniformly over the basin within a large-scale environment provided by a reanalysis or
17 climate model data set. Once initialized, the storms move in accordance with the large-scale
18 environmental wind. Along each storm track, the Coupled Hurricane Intensity Prediction
19 System⁴⁶ (CHIPS), a dynamic model, is used to simulate the storm intensity according to
20 environmental conditions such as potential intensity, wind shear, humidity, and the thermal
21 stratification of the ocean. These environmental conditions are modeled statistically based on the
22 reanalysis or climate model data set. The CHIPS model also predicts the storm radius of
23 maximum wind (R_m), given an externally supplied storm outer radius (R_o). We apply the
24 observed basin mean of R_o based on the historical record (e.g., 400 km for North Atlantic
25 storms³³) and assume it is constant over the lifecycle of a storm³³. Then we estimate R_m (varying
26 from storm to storm and over the lifecycle of a storm) from CHIPS.

27 We design specific criteria (a filter) for each study area to select local storms from basin-
28 wide events. Various storm tracks can induce significant surges in Tampa Bay, including those
29 that make landfall within or near the Bay as well as those that travel close offshore and parallel
30 to the coast. To capture all these storms, we create a two-line-segment filter encompassing the
31 Bay and surrounding coastal region. One line segment links a point on the coast (82.81W,

32 29.17N), about 180 km north of the Bay’s mouth, to a point over the ocean (83.8W, 27.58N)
33 about 100 km west of the Bay’s mouth. The other line segment links the ocean point (83.8W,
34 27.58N) to a coastal point (82.407W, 27.0N) about 70 km south of the Bay’s mouth. We select
35 all storms that cross either of these two line segments with intensity greater than 21 m/s; we call
36 these storms “Tampa Bay storms.” Simpler, circular filters are created for the other study areas.
37 We create a circle centered in Cairns (145.76E, 16.91S) with a radius of 100 km to select all
38 “Cairns storms” that move into this circle with intensity great than 21 m/s. Similarly, we create
39 100-km-radius circular filters centered at Dubai (55.31E, 25.27N), Abu Dhabi (54.37E, 24.47N),
40 and Doha (51.53E, 25.28N).

41 Given the storm characteristics of selected storms in a study area, we estimate the surface
42 wind and pressure fields using parametric methods fit to the explicitly modeled maximum wind
43 speed, radius of maximum winds, and minimum surface pressure. In particular, the surface wind
44 (10-min wind at 10 m) is estimated by fitting the wind velocity at the gradient height to an
45 analytical hurricane wind profile⁴⁷, translating the gradient wind to the surface level with a
46 velocity reduction factor (0.85) and an empirical formula for inflow angles, and adding a fraction
47 (0.55 at 20 degrees cyclonically) of the storm translation velocity to account for the asymmetry
48 of the wind field induced by the surface background wind⁴⁸. The surface pressure is estimated
49 also from a simple parametric model⁴⁹.

50

51 *Surge simulation*

52 With the storm surface wind and pressure fields as input, we apply the Advanced Circulation
53 (ADCIRC) model²⁵ to simulate the storm surge. ADCIRC is a finite element hydrodynamic

54 model that has been validated and applied to simulate storm surges and make forecasts for
55 various coastal regions^{50,51}. It allows the use of an unstructured grid with very fine resolution near
56 the coast and much coarser resolution in the deep ocean. The ADCIRC mesh we developed for
57 Tampa covers the entire Gulf of Mexico. The mesh has a peak resolution of about 100 m along
58 the west Florida coast near Tampa and extends on land up to the 10-m height contour in the
59 Tampa Bay area. The meshes developed for other study regions are relatively coarser (given
60 coarser bathymetric data). To capture the effect of storms approaching from various directions,
61 the mesh for Cairns has as its lower boundary the Australian coastline of Queensland, the
62 Northern Territory, and part of Western Australia. The mesh extends over the Indian and South
63 Pacific Oceans (from 114.0E to 176.0E) and is bounded above by Indonesia and Indonesian New
64 Guinea. The resolution is about 1 km on the Queensland coast around Cairns. The mesh
65 developed for Dubai covers the entire Persian Gulf and extends over the Arabian Sea (down to
66 16.0N). The resolution is about 2 km near Dubai. The same mesh is used for Abu Dhabi and
67 Doha; the resolution around these two locations is about 3-4 km.

68 To evaluate our surge modeling configuration and ADCIRC meshes, we simulated
69 historical events for Tampa and Cairns (the Persian Gulf has no historical storms), with the storm
70 characteristics obtained from the Best Track databases^{52,53}. The simulated storm surge in Tampa
71 for the 1921 hurricane is about 4.0 m (see Fig. 1a in the main article), which is comparable to
72 that observed in this region (~3.3-3.8 m, considering the storm tide was estimated to be 3.0-3.5
73 m and happening likely at low tide), given the large uncertainties in both the observed surge
74 level and storm characteristics (especially the size) for this early storm. (Note that in this case,
75 because an observation of R_m is available only at landfall and there is no information about R_o ,
76 we estimated R_o from the landfall R_m using an empirical relationship²⁶ between them and the

77 wind intensity and then kept the estimated R_o constant to estimate R_m for the time periods before
78 landfall using the empirical relationship.) For Cairns, we simulated storm surges for all 6
79 historical Cairns storms between 1980-2010 (selected using the same filter as for the synthetic
80 storms) plus Cyclone Yasi in 2011. Simulations are close to the observations for the most
81 significant events, including Cyclones Justin (1997), Rona (1999), and Yasi (see Supplementary
82 Fig. S4), but the simulation underestimates the surge for Cyclone Steve (2000). Not all simulated
83 historical surges match well with the observations individually, mainly due to the uncertainty in
84 storm size (since an empirical estimate²⁶ of the R_m using the basin mean R_o was applied due to the
85 lack of observations). However, the simulations compare relatively well with all observations
86 statistically (see Fig. 4 in the main article).

87

88 *Statistical analysis*

89 Statistical analysis is performed on the synthetic surge datasets. For a specific location and a
90 given climate scenario, we assume the arrival of storms to be a stationary Poisson process, with
91 arrival rate as the storm annual frequency. For each storm arrival, the probability density
92 function (PDF) of its induced storm surge is characterized by a long tail. We apply a Peaks-
93 Over-Threshold (POT) method to model this tail with a Generalized Pareto Distribution (GPD),
94 using the maximum likelihood method, and the rest of the distribution with non-parametric
95 density estimation. The estimated storm annual frequency and surge PDF are then combined to
96 calculate the (mean) return period (the reciprocal of the annual exceedance probability) for
97 various surge levels¹³, with the associated statistical confidence interval calculated using the
98 Delta method⁵⁴.

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Supplementary Information

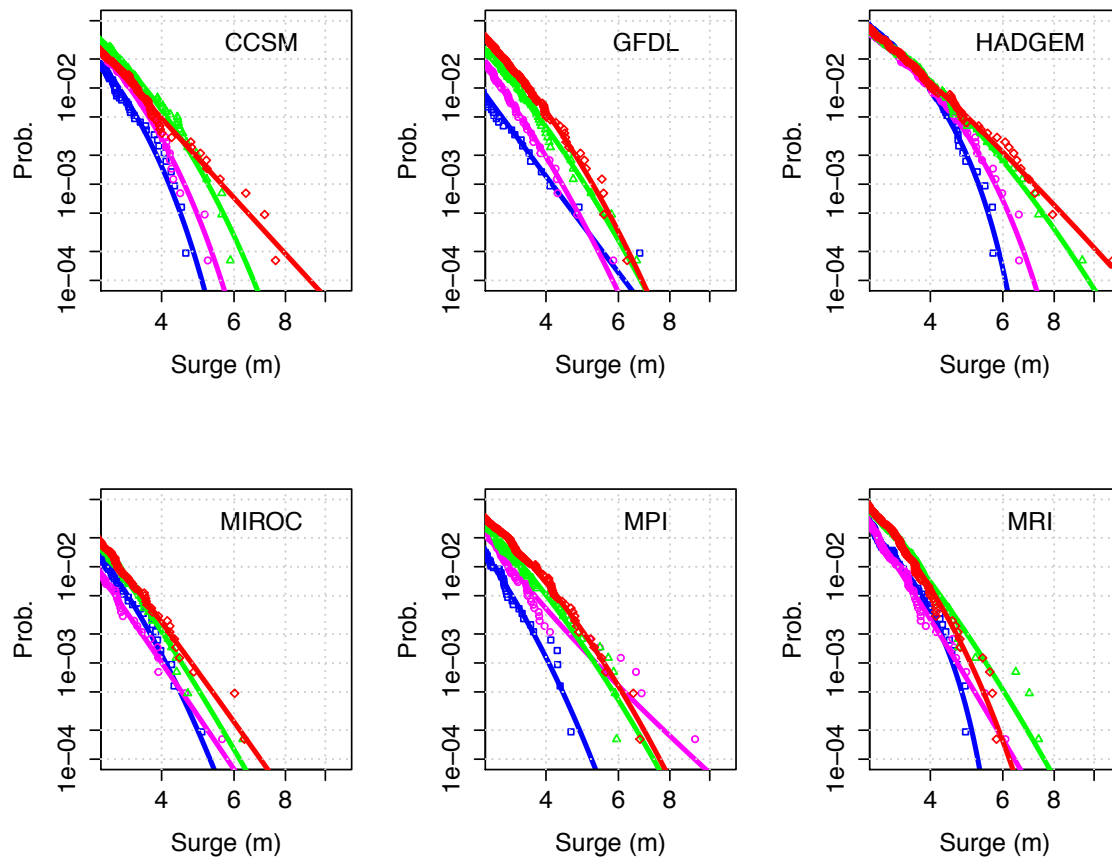
Grey Swan Tropical Cyclones

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Technology, Cambridge, MA 02139-4307, USA

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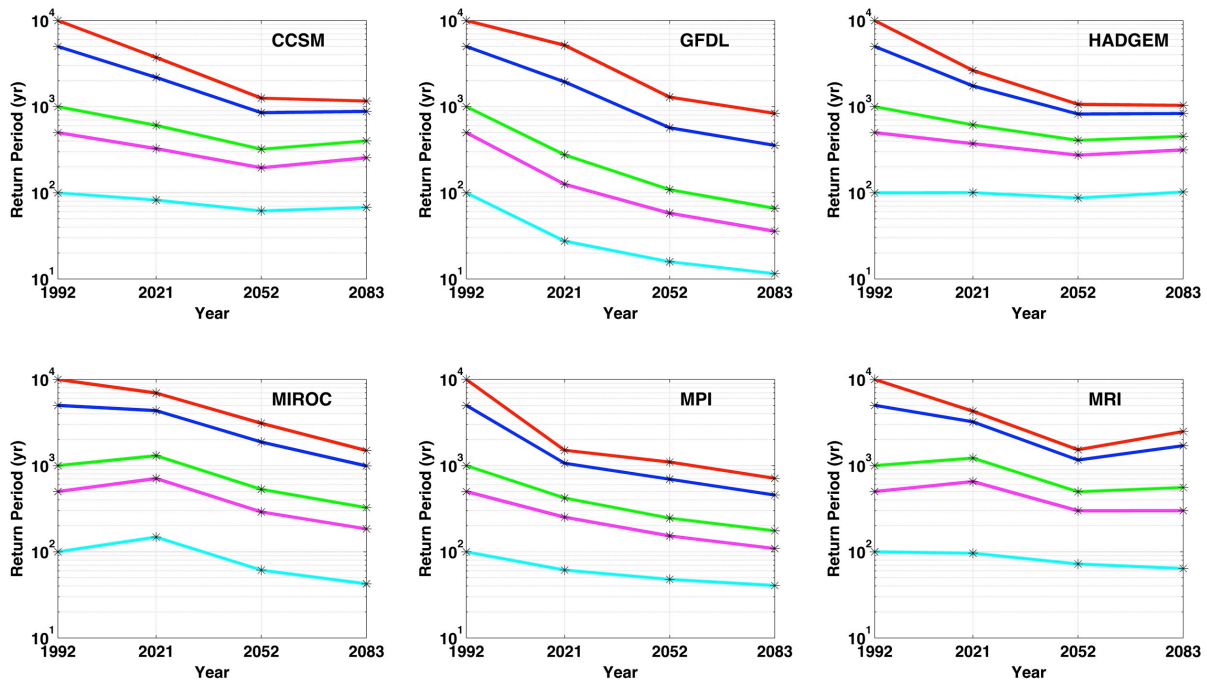
12 Figure S1. Generalized Pareto distribution (GPD) fit (curves) of the upper tail of the distribution

13 (dots) of storm surge for Tampa, in the climate of 1980-2005 (blue), 2006-2036 (pink), 2037-

14 2067 (green), and 2068-2098 (red), projected using each of the 6 climate models for the IPCC

15 AR5 RCP8.5 emission scenario.

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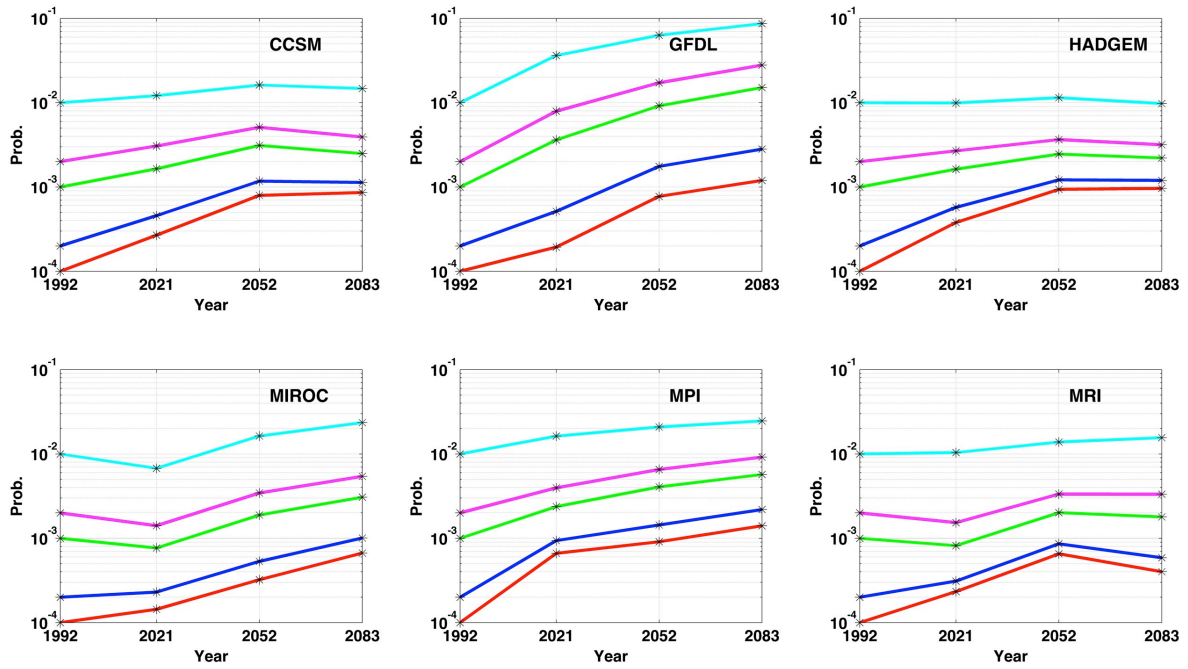
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18 Figure S2. The change of the return period of a 10,000-year (red), 5,000-year (blue), 1,000-year
 19 (green), 500-year (pink), and 100-year (cyan) event from the late 20th century to the late 21st
 20 century, projected for Tampa, using each of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

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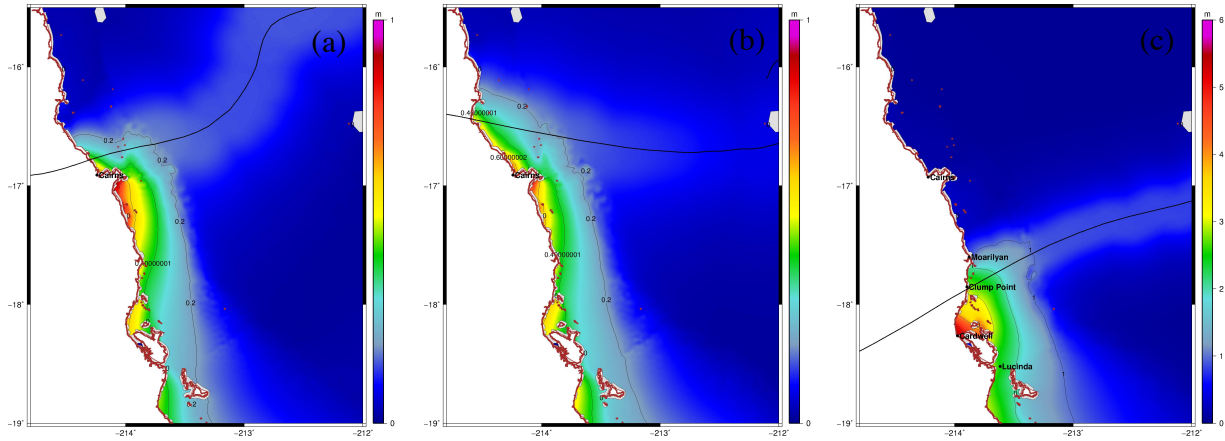
30 Figure S3. Same as Fig. S2, but presented as the change of annual exceedance probability (the
 31 reciprocal of the mean return period).

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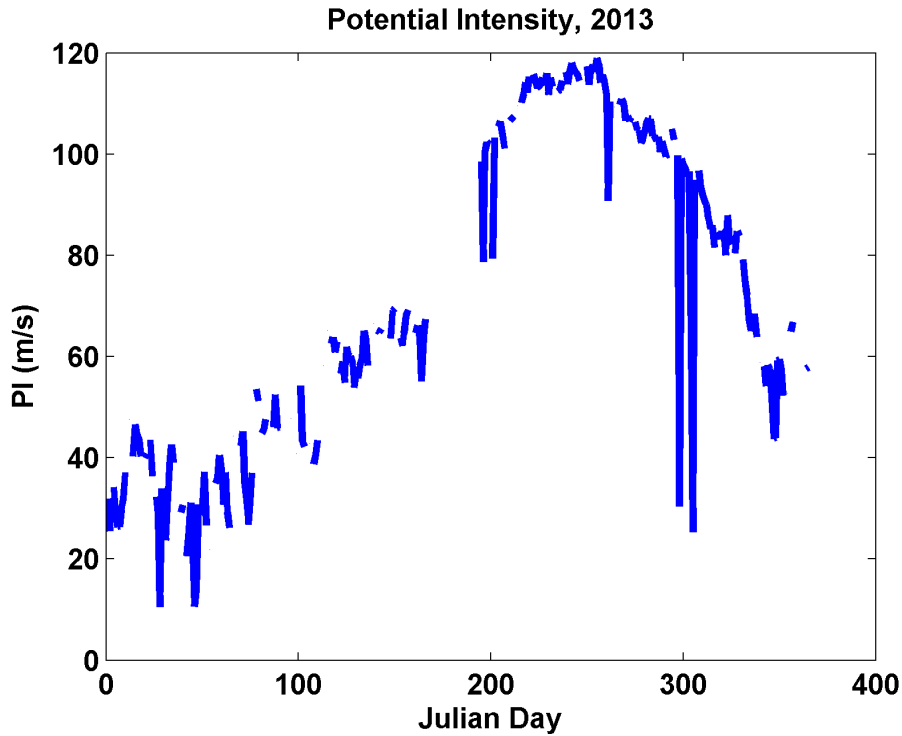
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38 Figure S4. Simulated surges for three historical storms in the Cairns region. (a). Cyclone Justin
 39 of 1997. The simulated surge at Cairns is 0.69 m (the observation is 0.63 m). (b). Cyclone Rona
 40 of 1999. The simulated surge at Cairns is 0.67 (the observation is 0.63 m). (c). Cyclone Yasi of
 41 2011. The simulated surges at Moarilyan, Clump Point, Cardwell, and Lucinda are 1.03 m, 2.88
 42 m, 5.45 m, and 2.48 m, respectively (the observations are 1.30, 2.97, 5.33, and N/A due to tidal
 43 gauge failure). The shaded contours show the simulated surge height (m; above MSL). The black
 44 curve shows the storm track. (The observed storm surge is estimated as the difference between
 45 the observed maximum water level, obtained from the State of Queensland, Department of
 46 Science, Information Technology, Innovation and the Arts, and the predicted astronomical tide,
 47 obtained from the Australian National Tidal Center.)

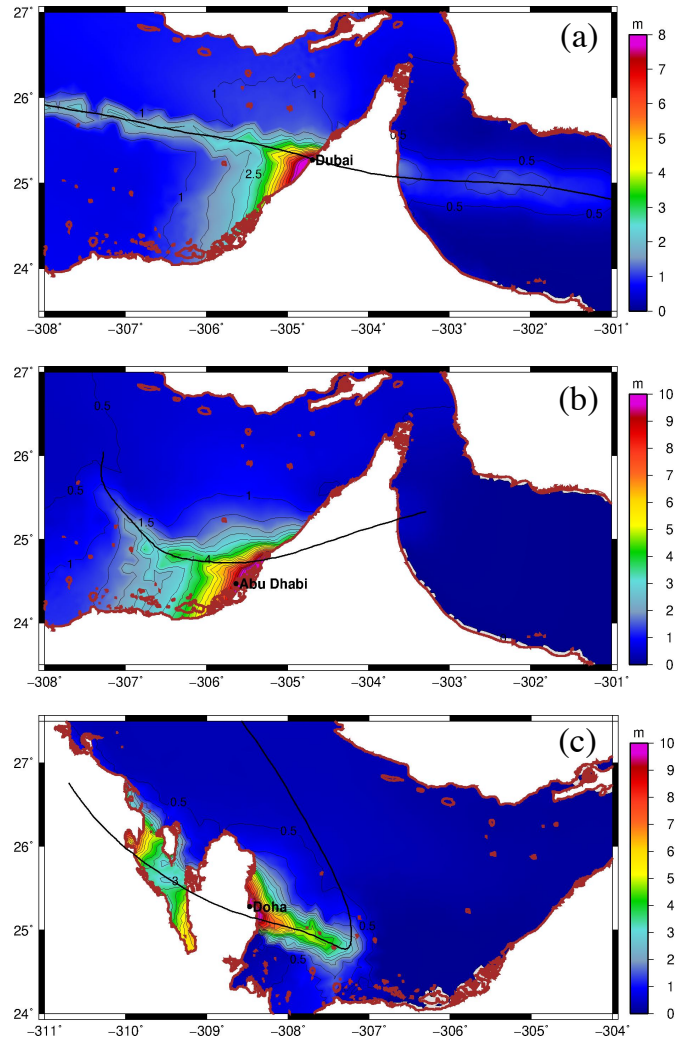


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49 Figure S5. Daily potential intensity (PI) in the Persian Gulf during the year 2013. Data applied in
50 the calculation includes the atmospheric sounding at Dammam, Saudi Arabia, for 12 GMT each
51 day (data obtained from the University of Wyoming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

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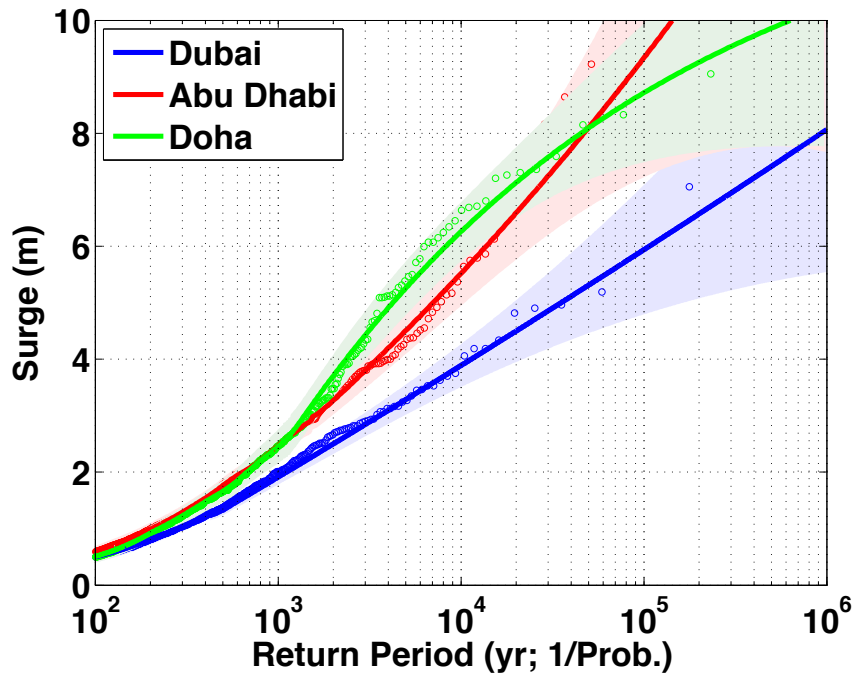
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58 Figure S6. Three grey swan TC surge events for three major cities in the Persian Gulf, based on
 59 the NCEP/NCAR reanalysis climate of 1980-2010. (a). The worst surge event (among 3100
 60 events), inducing a maximum surge of 7.1 m for Dubai. (b). The worst surge event (among 3100
 61 events), inducing a maximum surge of 9.5 m for Abu Dhabi. (c). The worst surge event (among
 62 3100 events), inducing a maximum surge of 9.1 m for Doha. (The higher surges in Abu Dhabi
 63 and Doha compared to Dubai are mainly induced by their different local geophysical features;
 64 the lower resolutions in the numerical mesh may have also led to overestimates; see Methods.)



65

66 Figure S7. Estimated storm surge level as a function of return period for Dubai (blue), Abu
 67 Dhabi (red), and Doha (green), each based on 3100 synthetic events in the NCEP/NCAR
 68 reanalysis climate of 1980-2010. The associated annual frequencies of the synthetic events are
 69 0.032, 0.024, and 0.025 for Dubai, Abu Dhabi, and Doha, respectively. The dots show the
 70 synthetic data, and the shading shows the 90% statistical confidence interval. (The return level
 71 curve for Dubai is very similar to that obtained based on the MERRA reanalysis, as shown in Fig.
 72 5c in the main article.)