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16 **Assessing the medium-term risk to reef damage and rubble**
17 **generation for the Great Barrier Reef**

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25 **Abstract**

26 Coral reef systems live in multi-hazard environments and are exposed to a wide range of
27 disturbance events that operate at different spatial and temporal scales. We identify seven
28 drivers derived from hazards that have and can result in reef damage in the Great Barrier Reef
29 (GBR): waves, winds, bottom current velocity, coral bleaching, crown-of-thorns seastar
30 outbreaks, ship groundings, and tsunamis. We map these drivers individually, apply damage
31 thresholds where applicable, and combine the normalized drivers into an additive vulnerability
32 index for the GBR. The Index can be applied at a range of scales from reef groups to the entire
33 reef system and we show that the GBR has a moderate risk profile to damage. Risk to reef
34 damage broadly increases towards the central region with lowest risk at the northern and
35 southern ends of the GBR. Specific hotspots of high risk to damage are identified including the
36 Cairns region and Swains Reef area. The Cape York and Mary Burnett Natural Resource
37 Management zones represent regions with the lowest vulnerability scores and, therefore, are
38 important to consider as potential refugia and nurseries for restocking reefs damaged in other
39 parts of the GBR. Our approach takes a comprehensive and holistic view of all the disturbance
40 drivers that the GBR experiences and will continue to experience in the coming decades at
41 different frequencies and intensities. Given that substantial effort and resources are now being
42 directed globally to active restoration of coral reefs, such efforts can be undone if management
43 activities do not take a holistic approach to disturbance drivers.

44 **1 Introduction**

45 Coral reefs face unprecedented impacts from a variety of sources leading to high coral mortality
46 rates and reef damage. Drivers of coral mortality such as crown-of-thorns seastar (CoTS)
47 outbreaks and mass coral bleaching events resulting from atmospheric and marine heatwave
48 conditions can be classified as pre-conditioning drivers that result in more standing dead coral
49 susceptible to erosion [1,2] and impacts from material legacies [3,4]. Direct, physical drivers of

50 reef damage include waves and strong currents from storms and tropical cyclones (also
51 referred to as hurricanes and typhoons, hereafter cyclones) [5,6], tsunamis [7,8], ship
52 groundings [9,10], anchoring, and destructive fishing practices such as blast fishing [11–13]. The
53 combined effects of these drivers lead to varying levels of exposure to reefs across the world
54 [14–18]. A direct consequence of these pre-conditioning and direct drivers of reef damage is the
55 generation of coral rubble – the physical breakage of coral skeletons and reef framework
56 [19,20].

57 Coral rubble is a natural component of reefs and forms part of the natural carbonate sediment
58 cycle and formation of reefs [19–24]. Last in the chain of successional erosion from live coral,
59 dead coral, to coral rubble, rubble forms an important habitat on reefs [25,26]. Coral rubble can
60 harbor the greatest metazoan diversity on reefs [26–28] but can also house pest species such as
61 CoTS [29]. The paradox of coral rubble is that these diverse rubble habitats rely on sufficient live
62 coral to continually generate new rubble that over time breaks down to sand and mud [26]. Over
63 geologic timescales, initial biological binding of rubble subsequently becomes a permanent
64 rigid binding and lithification contributing to reef accretion [21,26,30–32]. However, large
65 volumes or extents of coral rubble on reefs generated by disturbances such as tropical cyclones
66 or hurricanes [5,6,18,33] and blast fishing [11,34] can quickly become problematic for reef
67 recovery and emblematic of reef damage.

68 Coral reefs are increasingly impacted by both a diversity of drivers of reef damage from
69 population growth [35] to climate change [36–38] and a higher frequency of disturbances such
70 as bleaching events and less frequent but more intense cyclones [6,39]. These repeated
71 impacts shorten the natural recovery time of reefs which can lead to an increase in coral rubble.
72 Unstabilized rubble patches can act as “killing fields” for new coral recruits by smothering and
73 abrading small corals [10,11,13,32,40–44]. These factors can cause reefs to transition from
74 coral- to rubble-dominated states [7,11–13,45,46]. While many reef monitoring programs

75 include coral rubble as a benthic substrate category in reef assessments, the extent and
76 temporal dynamics of rubble are rarely included in reporting activities which limit our
77 understanding of rubble at scale [33]. Despite this knowledge gap, there is growing interest in
78 the active restoration and stabilization of rubble areas generated from reef damage [33,47–49].

79 We summarize the global drivers that contribute to pre-conditioning, coral mortality events and
80 direct generation of coral rubble as a proxy for reef damage in Table 1. The largest rubble
81 generation events are typically the result of acute disturbances such as cyclones causing
82 damaging waves and strong subsurface currents and tsunamis [5–7,50–57]. Storms and
83 cyclones play an important role in the development of reef framework with evidence of storm
84 ridges deposited in the geologic record [23,58,59]. The impact of tsunamis on coral reefs is
85 variable from extreme with coral mortality and large piles of rubble generated to surprisingly little
86 damage despite being in the direct path [7,8,56,57,60,61]. The largest historical event to affect
87 the Australian coastline was the 17 July 2006 Indonesian tsunami that had a run-up height of
88 7.90 m in Western Australia [62]. Other rubble generation drivers are mainly direct human
89 impacts on the reef such as ship groundings [9,63,64] that can be in conjunction with anchor
90 damage but on its own, anchor damage can be highly destructive locally [65–67]. Blast fishing is
91 highly destructive to reefs and observed to generate large fields of rubble quickly; this is a
92 particular problem for Southeast Asian reefs [13]. Other direct human impacts such as channel
93 dredging and coral mining [68,69] and trampling [70–72] contribute to rubble generation at
94 smaller spatial scales.

95 **Table 1. Pre-conditioning and direct generation drivers of reef damage.**

Global drivers of reef damage	Pre-conditioning or Direct Generation	Spatial Extent	Frequency	Reference(s)
Great Barrier Reef Drivers				
<i>Bioerosion</i>	Direct Generation	Local	Fundamental reef process, little known about specific role in rubble generation.	[73–75]
Coral Bleaching	Pre-conditioning	Local to Global	Mass bleaching events have occurred in 1998, 2002, 2016, 2017, 2020, 2022, and 2024.	[76]
<i>Coral mining or harvesting</i>	Direct Generation	Local to Regional	Primarily on Southeast Asian, Indian Ocean, and Pacific reefs.	[68,69,77–79]
Crown-of-thorns Seastars (CoTS) Outbreaks	Pre-conditioning	Regional	CoTS outbreaks have initiated in 1962, 1979, 1992, and 2011 typically starting in the northern GBR and cascading south over the span of a decade.	[80–82]
Cyclones: wind, waves, bottom current velocity	Direct Generation	Local to Regional	Occurrence of cyclones since 1984: 1984, 1985, 1986, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2004, 2005, 2006, 2008, 2009, 2010, 2011, 2013, 2014, 2015, 2017, 2018, 2019, 2021, 2022, 2023. 2024. See S1 Appendix for additional details.	[6,17,83–85]
Ship grounding risk including anchor damage	Direct Generation	Local	Years with at least 1 ship grounding on the GBR: 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2006, 2007, 2009, 2010, 2011, 2018, 2021	[10,84,86]
<i>Terrestrial run-off, flooding and freshwater plumes</i>	Pre-conditioning	Local to Regional	Major flooding events since 1984: 1991, 2010, 2011, 2013. 2019, 2024. High flow events reach mid-shelf reefs every 12.5 years.	[87–93]
<i>Trampling</i>	Direct Generation	Local	Daily on high tourism reefs.	[70,94,95]
Tsunamis	Direct Generation	Regional	Tsunami history in Queensland: 1868, 1877, 1960, 1971, 1977, 2004, 2006, 2007, 2010, 2011, 2022, 2023	[7,8,56,60,61,96,97]
Other drivers				
<i>Blast fishing</i>	Direct Generation	Local	Significant driver of rubble on Southeast Asian coral reefs.	[11–13]
Coral Disease	Pre-conditioning	Local to Regional	Significant driver of coral mortality in the Caribbean.	[98]
<i>Volcanic eruptions</i>	Direct Generation	Local to Regional	No direct impacts or active volcanism within the GBR. Potential damage from volcanic pumice rafts generated in the Pacific.	[99–103]

96 *Note: Drivers relevant for the reef damage vulnerability analysis of the Great Barrier Reef (GBR) are distinguished from those not included (italicized) in the GBR vulnerability*
97 *index.*

98 In addition to direct rubble generation, drivers such as bioerosion, coral bleaching, CoTS
99 outbreaks, freshwater plumes, and land-based pollution may lead to significant coral mortality
100 weakening standing corals that can later be broken by physical processes. Coral bleaching and
101 CoTS outbreaks can cause mass coral mortality in discrete events [104–106]. Impacts from land
102 such as freshwater plumes from high rainfall, sedimentation, and eutrophication can be either
103 chronic or acute. Poor land management can lead to deterioration of water quality over decades
104 and centuries with a subsequent decrease in coral cover [107]. Conversely, high rainfall events
105 and flooding can lead to conditions that promote low oxygen events (hypoxia) or kill corals
106 outright [87–89]. In addition to direct rubble generation, drivers such as bioerosion, coral
107 bleaching, CoTS outbreaks, freshwater plumes, and land-based pollution may lead to
108 significant coral mortality weakening standing corals that can later be broken by physical
109 processes. Coral bleaching and CoTS outbreaks can cause mass coral mortality in discrete
110 events [104–106].

111 Ultimately, it is the combination of direct generation events and pre-conditioning coral mortality
112 that causes reef damage, generating rubble at different spatial and temporal scales which
113 determines the vulnerability of a reef or reef system to future rubble generation. A key challenge
114 for reef management and restoration is understanding: 1) the range of damage drivers that
115 operate in a reef system, 2) what parts of the reef system will experience damage, 3) the extent,
116 intensity and frequency of damage drivers; and, 4) the cumulative impact of different drivers to
117 identify areas of confluence and therefore reefs most at risk from damage. This knowledge
118 helps inform the current state and future scale of potential reef damage. Protective and active
119 restoration efforts can be prioritized by identifying those reefs with the greatest cumulative
120 threat. Here, we apply the concept of vulnerability to reef damage and the generation of coral
121 rubble for a reef system. Vulnerability is generally defined as the “degree to which a system is
122 susceptible to, and is unable to cope with adverse effects based on its exposure, sensitivity, and
123 adaptive capacity components” which sits within the more general concept of risk [108,109].

124 Vulnerability indices have been used in a variety of contexts such as climate change, natural
125 hazards, and socio-ecological systems. The scale and use of such tools is broad from a Climate
126 Vulnerability Index for World Heritage Properties [110] to a Heat Vulnerability Index for
127 population health [111]. In a coral reef ecosystem context, indices have been constructed to
128 quantify coral reef resilience [14,112,113], community disturbance [114], and fisheries
129 [115,116]. Indices focusing on condition and resilience of the benthos focus on coral metrics
130 such as cover and community composition [14,112,113,117]. Indices are a useful synthesis of
131 relevant metrics and processes across space and time that can communicate ecosystem
132 condition and trends to the public, managers, and politicians [118]. With climate change and
133 the uncertainties and risks of different impacts changing [39,119], it is imperative that reef
134 managers prioritize areas most vulnerable to damage. In addition, rubble generation metrics
135 could be integrated with work around connectivity [120] and coral resilience [14] to give
136 managers a holistic picture of stressors of a reef system.

137 We focus our vulnerability analysis on the exposure component to reef damage in the Great
138 Barrier Reef (GBR) in Australia from 1985 to 2024. The GBR is the largest reef system in the world
139 covering 26,519 km² [121]. Effective management of large systems such as the GBR requires
140 prioritization of limited resources for the biggest conservation impact [122]. Given its size and
141 latitudinal extent (10.7°S to 24.5°S), the GBR exists in a multi-hazard environment, exposed to
142 cyclones [e.g., 41], CoTS outbreaks [80,123] and mass coral bleaching [124,125]. However, the
143 location and prevalence of these natural hazards vary along the extent of the GBR as well as
144 from inshore to offshore. The GBR faces a rapidly developing coastline of eastern Queensland
145 that is experiencing fast population growth ranging from 0.3%/yr in Rockhampton to 1.8%/yr in
146 Livingstone from 2012 to 2022, [126] including urban and coastal infrastructure development.
147 Several export terminals for natural resources are located inshore of the GBR and are
148 connected by major shipping channels that dissect the GBR increasing the risk of ship
149 groundings across the region [86]. Tourism expenditure on the GBR generates AU\$3.3 billion to

150 the Australian economy [127] with 2.4 million tourists visiting in 2019 [128] but also increases
151 risks to reef damage from trampling, anchoring and ship groundings [129].

152 **2 Methods**

153 We investigate the vulnerability of the GBR to reef damage by integrating several different
154 historical datasets of hydrodynamic conditions (wave height and bed velocities), shipping, CoTS
155 outbreaks, bleaching events, cyclone winds, and tsunami risk to develop *maps and a*
156 *vulnerability index* at a range of scales: individual reefs, management zones, and the entire GBR.

157 We considered two pre-conditioning drivers causing coral mortality, bleaching and CoTS
158 outbreaks, and five direct damage drivers, waves, bottom velocity of wave-generated currents,
159 shipping, cyclones, and tsunamis to define the rubble vulnerability index. Despite being
160 important for overall reef health [71], we excluded land-based pollution and freshwater plumes
161 [92] because reliable and comparable data only exists from 2010 to 2023 (e.g.,
162 www.ereefs.org.au). We note that data exist on bioerosion and trampling on specific reefs within
163 the GBR but are lacking in longer term, spatially explicit datasets to be included here and can
164 locally cause an increased vulnerability above what is measured in this study. The drivers have
165 disparate spatial and temporal scales at which they operate. For example, while the temporal
166 span of the data available varies between datasets, the main limiting factor is the spatial
167 resolution. Thus, we synthesized each driver separately to summarize at a consistent spatial
168 resolution of $0.05^\circ \times 0.05^\circ$ using interpolation.

169 **2.1 Coral Bleaching - Degree Heating Weeks**

170 Bleaching has become one of the primary drivers of coral decline globally and the GBR [130].
171 The GBR has experienced moderate bleaching events (<30% corals affected) since 1980 with
172 severe events (>30% corals affected) starting in 1998 and occurring with increasing frequency
173 and severity [37]. Coral bleaching stress is proxied by degree heating weeks (DHWs) based on

174 satellite sea surface temperature (SST) where 1 DHW is equal to 1°C above the climatological
 175 maximum monthly mean for 1 week [131,132]. To define bleaching occurrence and extent in the
 176 GBR, global, monthly DHW data (April 1985 – December 2024) at 0.05°x0.05° spatial resolution
 177 were downloaded from the US National Oceanographic and Atmospheric Administration Coral
 178 Reef Watch platform [133] and cropped to the Great Barrier Reef Marine Park (GBRMP)
 179 boundary [134]. The data was filtered for DHWs >8°C-weeks to estimate exposure to bleaching
 180 alert level 2 associated with coral mortality of heat-sensitive corals (Table 2). The annual
 181 maximum per pixel was extracted and averaged in decadal bins: 1985-1994, 1995-2004, 2005-
 182 2014, and 2015-2024. These decadal averages were averaged for the final DHW summarization
 183 for the index.

184 **Table 2. The US National Oceanic and Atmospheric Administration Coral Reef Watch degree heating**
 185 **week bleaching alert levels.**

Degree Heating Week Range [DHW]	NOAA Coral Reef Watch Bleaching Alert Level	Potential Bleaching and Mortality
0 < DHW < 4	0 – bleaching warning	Risk of possible bleaching
4 ≤ DHW < 8	1 – bleaching alert 1	Risk of reef-wide bleaching
8 ≤ DHW < 12	2 – bleaching alert 2	Risk of reef-wide bleaching and mortality of heat-sensitive corals
12 ≤ DHW < 16	3 – bleaching alert 3	Risk of multi-species mortality
16 ≤ DHW < 20	4 – bleaching alert 4	Risk of severe, multi-species mortality (>50% of corals)

186 Note: The new bleaching alert 5 level is not included as this level is not reached on the Great Barrier Reef.
 187 See https://coralreefwatch.noaa.gov/product/5km/index_5km_baa-max-7d.php.

188 **2.2 Crown-of-Thorns Seastars (CoTS)**

189 Four severe outbreaks of CoTS are known for the GBR since 1962 with each resulting in mass
 190 coral mortality [81,82,135,136]. The outbreaks can span over a decade slowly cascading down
 191 the GBR [137]. CoTS data were obtained from the Australian Institute of Marine Science Long-
 192 term Monitoring Program manta tow surveys across the GBRMP. The surveys count CoTS on 2
 193 minute, 200 m long tows roughly 200 m from the reef edge [138] starting in 1983. The period of
 194 1985-2024 was summarized for the index by splitting the time into the 3 periods in line with the
 195 CoTS outbreaks: 1985-1991, 1992-2009, and 2010-2024 [137]. The maximum annual CoTS
 196 density per reef were averaged for each outbreak period. These outbreak period averages were

197 interpolated across the GBRMP. The 3 resulting interpolations were averaged for the final CoTS
198 summary layer for the index.

199 **2.3 Waves**

200 Waves are important environmental contributors for reef growth [139] but also a major cause of
201 coral damage and rubble generation during extreme events [140,141]. Waves of 4-m height,
202 “very rough” seas in the Douglas sea scale (S1 Appendix) [141], can damage the reefs by moving
203 large reef rock fragments, up to 63 m³, and generate and transport rubble [142].

204 We use the significant wave height obtained from the Centre for Australian Weather and Climate
205 Research (CAWCR) Wave Hindcast aggregated collection [143] to represent the characteristic
206 wave height of the impinging waves. The CAWCR has a spatial resolution of 4 arcmin (~7.4-km
207 at the equator but downscaled to a 0.05° x 0.05° grid via a linear interpolation) in the GBR with
208 hourly output. The exposure to damaging waves in the GBR is given by the number of hours
209 under “rough seas” conditions from 1985-2024.

210 **2.4 Bottom current velocity**

211 Waves generate currents close to the seabed which may break coral and transport rubble. The
212 intensity of these currents can be estimated by the peak orbital velocity near the bottom (U_b).
213 Castro-Sanguino et al. [5] showed that U_b of wind-induced waves is a better predictor of coral
214 cover loss than only cyclone wave height following Cyclone Ita. Bottom velocity thresholds for
215 rubble sliding and flipping are 0.09-0.20 m s⁻¹ and 0.12-0.35 m s⁻¹, respectively [19], although it
216 vary depending on the rubble size and shape [19]. The maximum or peak orbital velocity U_b was
217 estimated at 1.25 m s⁻¹ for Cyclone Ita, but cyclone-derived bottom velocities can be as high as
218 3 m s⁻¹ [144]. Thus, U_b can be forceful enough to mobilize rubble, especially under storm
219 conditions, and potentially the mobilized rubble may collide and break living coral causing
220 subsequent damage to the reef.

221 The peak orbital velocity U_b is dependent on the significant wave height, peak wave period, and
222 depth, and is calculated following [145] (S2 Appendix). The significant wave height and peak
223 wave period were sourced from the CAWCR, and the depth sourced by the Project 3DGBR:
224 gbr100 High-resolution Bathymetry for the Great Barrier Reef and Coral Sea [146], which is
225 upscaled to the CAWCR grid. Once U_b is calculated in the CAWCR grid, it is then interpolated to
226 a $0.05^\circ \times 0.05^\circ$ grid in the GBRMP. The exposure to U_b that may flip rubble is the accumulated
227 time for which $U_b > 0.25 \text{ m s}^{-1}$ from 1985-2024.

228 **2.5 Cyclone contributions to damaging waves and strong bottom** 229 **velocities**

230 Frequently, “rough seas” impacting the GBR originate from storms that occur close to or far
231 from the reef. Cyclones occurring close to reefs can be one of the most severe mechanical
232 disturbances of coral reefs [51]. Their impacts accounted for 48% of coral cover loss on the GBR
233 from 1985-2012 [15]. Cyclones impact reefs and coastal areas through destructive winds, high
234 seas, strong subsea or bottom currents, storm surge and intense rainfall. The propagation of
235 cyclone waves depends on the cyclone wind intensity, and bathymetry [147]. Consequently,
236 cyclone waves induce subsea currents which are dependent on these variables as well. Given
237 the importance of cyclones to rubble generation, we explore their contributions to the exposure
238 of “rough seas” and U_b across the GBR; that is, the fraction of the exposure time to each driver
239 attributable to cyclones.

240 We used the Australian Tropical Cyclone Database [148] from 1985-2024 for determining
241 cyclone location and wind intensity. Here, we considered waves, and associated bottom
242 velocities attributed to cyclones are those within a 1,000-km radius from the storm center. We
243 only considered Category 1 or greater cyclones on the Australian cyclone intensity scale. Wave
244 heights are sourced from the CAWCR, as in Section 2.3. The 1,000-km radius covers wave-

245 related impacts that can reach up to 800-km from their track [17], as fetch is not a limiting factor
246 for cyclone waves [96].

247 **2.6 Cyclone winds**

248 Cyclone winds can be destructive to islands, cays and coastal areas including terrestrial and
249 coastal plants, animals, and built structures [84,85,150]. In addition, the occurrence or
250 exposure of reefs to cyclone winds is a proxy of recovery time between cyclone events. The
251 extreme cyclone winds act over extensive regions of shallow water and its forcing is more
252 relevant for waves produced in shallower water [151]. For this study, the cyclonic wind exposure
253 is the accumulated time, in hours for which the wind intensity is that of a tropical cyclone
254 Category 1 in the Australian scale ($> 17 \text{ m s}^{-1}$, gale force winds) and is calculated every $0.05^\circ \times$
255 0.05° in the GBRMP from 1985-2024. The cyclone extension of the gale force winds is estimated
256 by a model considering the 2003-2024 seasons to account for areas likely experiencing cyclone
257 winds (S1 Appendix).

258 **2.7 Shipping risk**

259 Shipping comprises 90% of international trade with 8.4 billion tonnes of cargo transported by
260 sea each year, which is expected to triple by 2060 [152]. Ships can strike reefs generating rubble
261 and are a proxy of the human footprint in the GBRMP. The most recent incidents of ships striking
262 reefs were in 2010 off Gladstone and 2000 off Cairns [153,154]. Ship track data were obtained
263 from the Australian Maritime Safety Authority [155] and hourly geospatial vessel positioning
264 from satellite Automatic Identification Systems required on commercial vessels. This dataset
265 excludes small recreational vessels. The hazard associated with ships is dependent on the
266 distance from the ship to individual reefs. A statistical approach of the ship hazard is adopted to
267 estimate their area of influence based on their distance from each reef. The exposure of reefs to
268 ship hazards is the expected value of the number of times a reef is within the ship's area of

269 influence. The vulnerability of shipping activities to each reef is calculated at a $0.05^\circ \times 0.05^\circ$ grid
270 across the GBRMP (S3 Appendix).

271 **2.8 Tsunamis**

272 Tsunamis are a low probability event compared to other natural hazards such as cyclones but
273 potentially high-risk events for the GBR. There have been 10 tsunamis impacting Queensland in
274 the last 100 years with minimal reports of damage to the GBR [62,96]. The largest tsunami wave
275 captured in Queensland was 0.82 m on the Gold Coast, ~500 km south of the GBR, from the
276 Hunga Tonga-Hunga Ha’pai eruption in 2022 [96]. On greater timescales, the Cairns region has
277 experience an estimated two large tsunamis >11 m in the last millennium with evidence of large
278 boulders tossed onto the outer reefs by waves [57]. The 2024 Tsunami Guide for Queensland
279 [96] estimates that the state could be vulnerable to a “well-directed” tsunami with 10 m
280 maximum water-levels with a 10,000-yr Average Occurrence Interval. Tsunamis impacting the
281 east coast of Australia principally originate in the subduction zones extending from New
282 Zealand to Papua New Guinea, but tsunamis can also originate locally as a result of submarine
283 landslides along the continental shelf edge [156].

284 The Geoscience Australia Probabilistic Tsunami Hazard Assessment (PTHA18) [157,158]
285 estimates the frequency of tsunamis in Australian waters through simulation of hundreds of
286 thousands of tsunami scenarios from key earthquake sources in the Pacific and Indian Oceans
287 affecting Australia. PTHA18 provides the tsunami maximum water-level, or maximum stage,
288 attained at a particular location with respect to the mean sea level that is exceeded once from
289 10 to 10,000 years on average. We used the 1 in 100-year exceedance-rate to calculate the risk
290 of tsunamis in the GBRMP to balance a realistic timescale and water levels that could cause
291 damage to the reef, 0.11 to 2.86 m for 1 in 100-year exceedance-rate. In the PTHA18, the
292 maximum-stage values are evaluated at specific points called “hazard points”. The
293 corresponding 1 in 100-year exceedance-rate tsunami maximum-stage at each GBRMP grid

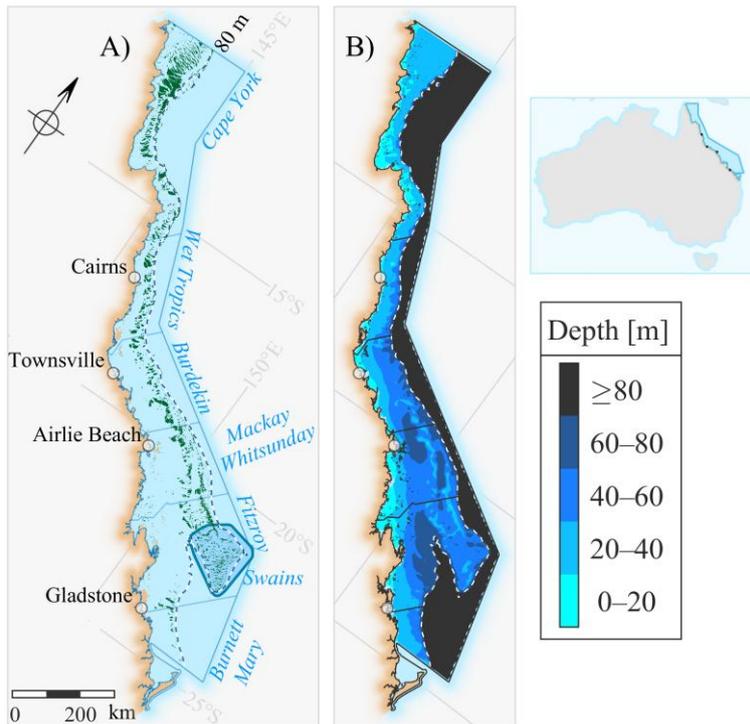
294 point is obtained from nearest neighbor interpolation including bathymetry at hazard points as a
295 covariate using the Geoscience Australia high-resolution depth model [159].

296 **2.9 Vulnerability Index**

297 The seven drivers have disparate spatial and temporal scales at which they operate. To
298 overcome these disparities, the exposure of the GRBMP to each driver is expressed as a value
299 representative of the highest risk experienced given the available data. The values of each driver
300 are rescaled to a range of 0 to 1 representing the minimum and 99.9th percentile value of each
301 driver, respectively, that is:

$$302 \quad I_n = \frac{V_n - V_{\min,n}}{V_{99.9,n} - V_{\min,n}} \quad \text{eqn. 1}$$

303 Where I_n is the rescaled value corresponding to each n (CoTs, Shipping, etc.) driver, V_n is the
304 respective value; the subindices *maximum* and *minimum* indicate the 99.9th percentile and
305 minimum values over the GRBMP grid. The exception is DHWs where 0 was retained as the
306 minimum as some areas of the Reef never accumulated >8°C-weeks. The drivers were summed
307 and the total divided by 7 to retain the 0-1 scale for the final index [160]. A vulnerability score of
308 0 (1) would represent the minimum ($\geq 99.9^{\text{th}}$ percentile) value for all drivers. The Index was then
309 cropped and masked with the GBR reef features layer (*gisaimsr* R package) [161] to limit index
310 values to reef areas. We describe spatial risk using the Natural Resource Management (NRM)
311 zones of the GRBMP (Fig 1). Low, moderate, high levels of vulnerability were classified based on
312 the 25th and 75th percentiles of vulnerability. The index was validated calculating the proportion
313 of coral/algae, rock, rubble, and sand from the 10 x 10 m resolution GBR10 Benthic Habitat map
314 [162] in each low/moderate/high vulnerability polygon and averaged per vulnerability status
315 group. With higher vulnerability to reef damage, we would expect to see less coral/algae and
316 more rubble.



317

Fig 1. Geography of the Great Barrier Reef Marine Park. (A) Extent of the GBRMP with reef polygons, Natural Resource Management (NRM) zones, principal coastal towns and Swain Reef Group. (B) GBRMP bathymetry. Edge of the continental shelf represented by the 80-m isobath (dashed line). Markers every 200 km. Map projection: Oblique Mercator rotated by -55° , origin (147°E , 18°S)

318

3 Results

319

3.1 Coral Bleaching – Degree Heating Weeks

320

The 40-year estimations of Coral Reef Watch Alert 2 or greater coral bleaching stress causing

321

mortality ($\text{DHW} > 8^\circ\text{C-weeks}$) as predicted by SST on the GBR shows that DHWs have increased

322

over the 4 decades across all the NRM zones (Fig 2A-D). Nearly a fifth, 17.25%, of the Marine

323

Park has never accumulated $> 8^\circ\text{C-weeks}$ in the last 40 years mostly in the central region.

324

Almost half of the Burdekin (48%) and 27% of the Mackay Whitsunday NRMs have not recorded

325

accumulated $\text{DHW} > 8^\circ\text{C-weeks}$ (S4 Appendix). All 6 Regions had similar Alert 2 DHW exposure

326

in the last decade from 2015-2024 with mean DHW ranging from $9.03 - 10.07^\circ\text{C-weeks}$ (Fig 2D).

327

The region of highest accumulated DHW was the eastern edge of the Cape York NRM (Fig 2E).

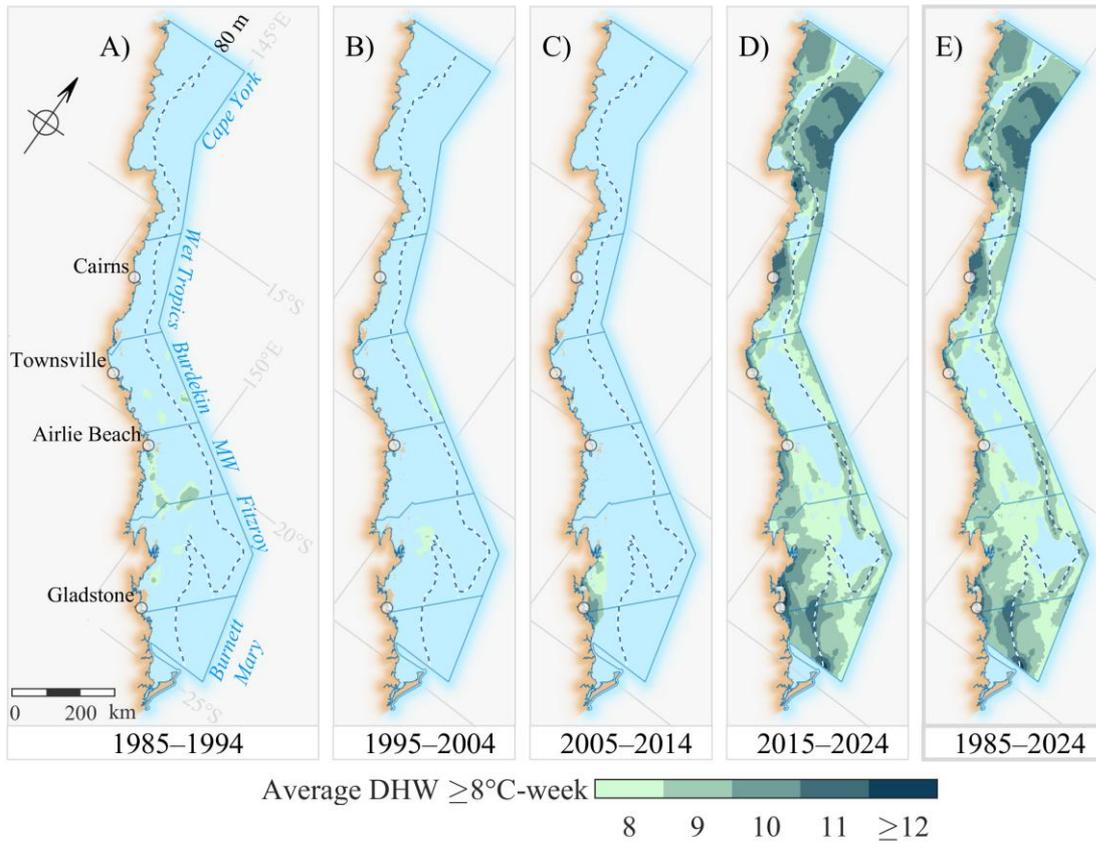
328

However, this high accumulation in the Cape York NRM is in deeper waters off the continental

329

shelf (Fig 2B) lacking shallow reefs. The Burnett Mary NRM had substantial exposure to DHW

330 >8°C-weeks as well as the Cape York, Cairns, Townsville, and Airlie Beach inshore areas (Fig
 331 2D,E; S4 Appendix).



332

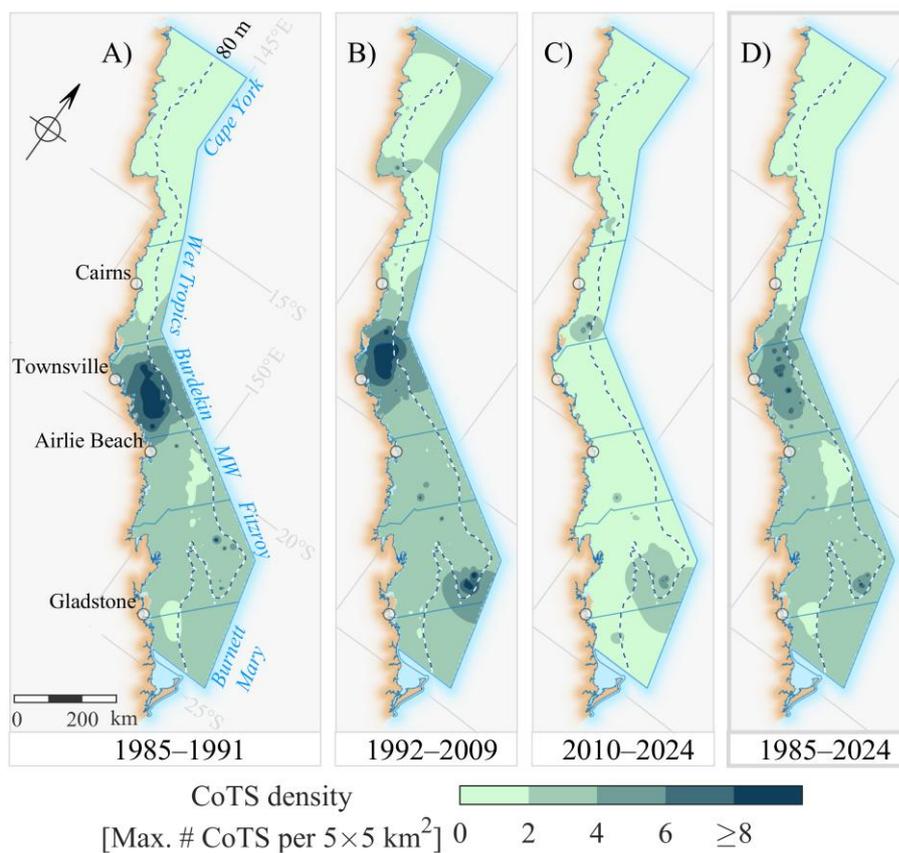
333 **Fig 2. Degree Heating Week accumulation from 1985-2024 in the Great Barrier Reef.** US National
 334 Oceanic and Atmospheric Administration Coral Reef Watch 5 km resolution, monthly data from 1985 to
 335 2024 filtered for degree heating weeks (DHW) $\geq 8^\circ\text{C}$ -weeks. Average of the maximum annual DHW $\geq 8^\circ\text{C}$ -
 336 weeks (A) from 1985 to 1994, (B) 1995 to 2004 (C), 2005 to 2014, and (D) 2015 to 2024. (E) Decadal
 337 average of the whole period (E). In (A), the NRM Mackay Whitsunday is abbreviated as MW.

338 3.2 Crown-of-Thorns Seastars

339 CoTS are native to the GBR and an adult CoTS can consume and therefore kill 150-250 cm² of
 340 live coral a day to pre-condition the reef for rubble generation [163,164]. The Australian Institute
 341 of Marine Science Long-term Monitoring Program conducted 176,247 manta tows counting
 342 CoTS from 1985-2024 with densities ranging from 0-358 CoTS tow⁻¹. All observations of CoTS
 343 >200 tow⁻¹ were recorded in 2000 or earlier and 95.3% of tows recorded 0 CoTS tow⁻¹ [138]. Over
 344 the 3 CoTS outbreak periods, average CoTS densities of the maximum CoTS count per reef
 345 dropped substantially from 4.32 CoTS in 1985-1991, to 3.51 CoTS from 1992-2009, and 1.57

346 CoTS from 2010-2024. The number of Severe CoTS outbreaks where CoTS densities >1
 347 calculated by the averaging CoTS density per reef over each period decreased from 6.92% to
 348 4.90% to 3.85% from 1985-1991 to 1992-2009 to 2010-2024, respectively.

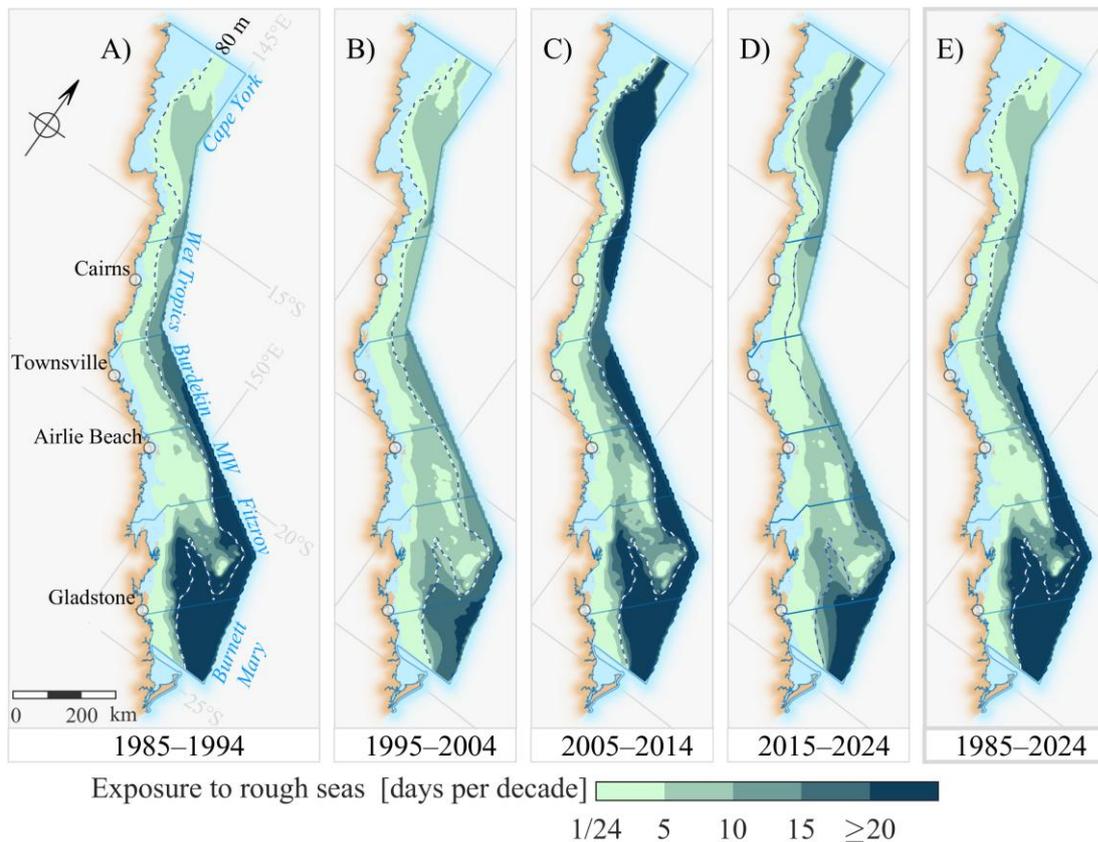
349 The average of the final interpolated CoTS layer across the GBRMP was 2.35 CoTS density (Fig 3).
 350 Between the 3 outbreak periods, interpolated spatial distributions of CoTS hotspots were
 351 variable. From 1985-1991, the Burdekin NRM had the highest densities of CoTS with an average
 352 of 5.86 CoTS (Fig 3A). During 1992-2010, the Burdekin Region (5.05 CoTS) and Swains Group in
 353 the southern Fitzroy NRM (3.39 CoTS) had the highest average CoTS values (Fig 3B). In the
 354 current outbreak period from 2011-2024, the southern Wet Tropics (1.56 CoTS) and Fitzroy
 355 NRMs (1.93 CoTS) had the largest CoTS hotspots. (Fig 3C).



357 **Fig 3. Maximum CoTS density from 1985-2024.** Crown-of-Thorns Seastars (CoTS) density from the
 358 Australian Institute of Marine Science manta tow surveys from 1984-2024. Interpolated CoTS densities
 359 from max count per reef average densities across outbreak period (A) 1985-1991, (B) 1992-2009, (C) 2010-
 360 2024, and (D) average of the CoTS interpolations for all three outbreak periods. MW—Mackay Whitsunday.

361 **3.3 Waves and Rough Seas**

362 Rough and higher seas can move reef boulders and dislodge reefs colonies. The exposure to
363 “rough seas” has spatial and decadal variability (Fig 4A-D). Exposure is higher offshore than
364 inshore, decreasing abruptly along the edge of continental shelf and reflecting the strong
365 capacity of the reefs along the edge to attenuate impinging waves [165]. Decadal variability of
366 the shelf is significant, indicating a strong decadal variability in the wave climate. Decades of
367 high exposure (1985-1994 and 2005-2004, active decades) have been followed by decades of
368 low exposure (1995-2004 and 2015-2024, calm decades). Calm decades are therefore likely to
369 be more favorable for coral growth and growth of faster growing branching corals like *Acropora*
370 which are a major contributor to coral rubble reefs along the edge of the shelf than active
371 decades. In general, the reefs most exposed to rough seas are those along the edge of the
372 continental shelf and, in active decades, the Swains Group in the Fitzroy NRM.



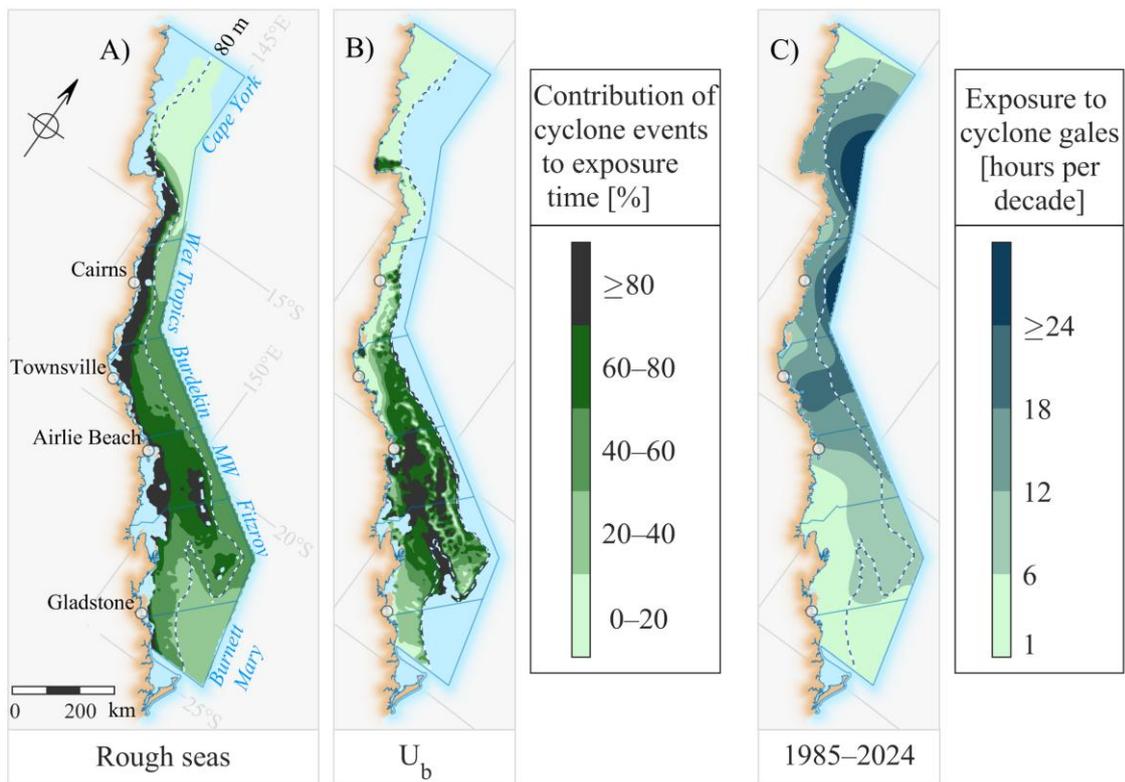
373

374 **Fig 4. Exposure to “rough seas.”** Accumulated exposure to “rough seas” (A) from 1985 to 1994, (B) from
 375 1995 to 2004, (C) from 2005 to 2014, and (D) from 2015 to 2024. (E) average decadal exposure to rough
 376 seas from 1985-2024. Note: top left corner of each map is out of the CAWCR domain and exposure is not
 377 calculated there. MW—Mackay Whitsunday.

378 Across the continental shelf and regardless of whether a decade is active or not, the average
 379 decadal exposure time is at a minimum in the Cape York NRM (<5 days) and largest in the Fitzroy
 380 NRM (>20 days, Fig 4E). The minimum exposure time in Cape York NRM reflects the high density
 381 of the reef matrix, the shallow shelf (~20-m), and at lower latitudes north of the main regions for
 382 cyclone formation. In contrast, the largest exposure time in the Fitzroy NRM is aided by the more
 383 fragmented and smaller reefs there, e.g., the Swain Group, and the absence of reefs offshore
 384 Gladstone together with a deep shelf (Fig 1). Additionally, the enhancement of the trade winds
 385 may at times develop “rough seas” in this unprotected area. Although this potential pathway for
 386 rough seas may be rather rare as these winds are frequently under 10 m s^{-1} it should not be ruled
 387 out [166,167].

388 **3.3.1 Contributions of cyclones to “rough seas”**

389 It is well known the damage to reefs from “rough seas” caused by cyclones passing nearby
 390 (waves within 1000-km from the cyclone center) [6,10,168]; however, “rough seas” can also be
 391 generated by distant storms and propagate beyond fetch. Fig 5A shows the fraction of the
 392 exposure time to “rough seas” attributed to passing cyclones. In this regard, cyclones are the
 393 primary source of “rough seas,” accounting for 60–100% of the exposure time over the
 394 continental shelf from southern Cape York to the Mackay Whitsunday NRM (Fig 5A). In the
 395 Fitzroy and Burnett Mary NRMs, and offshore Burdekin, their influence is reduced to 40-60% of
 396 the exposure time, except in the Swain Group, where it is 60-80%. This shows that cyclones are
 397 the dominant contributor to damaging “rough seas” on most reef areas.

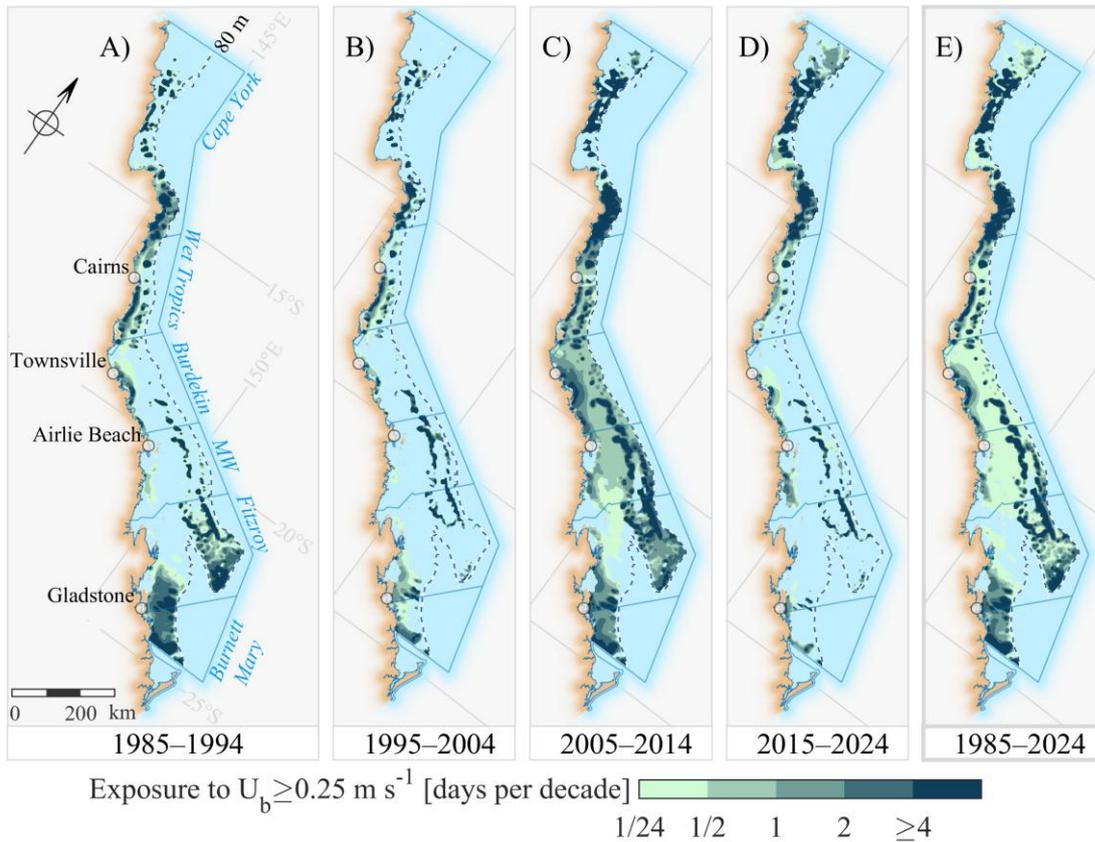


398 **Fig 5. Contributions of cyclones to “rough seas,” rubble mobilizing currents ($U_b \geq 0.25 \text{ ms}^{-1}$) and**
 399 **exposure to cyclonic gale winds.** Fraction of exposure time attributed to (A) cyclone waves and (B)
 400 associated $U_b \geq 0.25 \text{ ms}^{-1}$ for the period of 1985-2025. (C) Average decadal exposure time from 1985-
 401 2024. MW—Mackay Whitsunday.
 402

403 **3.4 Rubble mobilizing currents**

404 Peak orbital bottom velocity is higher for waves with larger heights and longer periods over
405 shallower waters (S2 Appendix). The maps of decadal exposure to rubble mobilizing currents
406 ($U_b \geq 0.25 \text{ m s}^{-1}$) are dominated by patches of large exposure times (>4 days) around reefs,
407 resulting from waves propagating on the shallow waters surrounding the reefs (Fig 6E).
408 Nevertheless, there is some spatial variability, for example, most of the reefs in the Burdekin
409 NRM have short exposure times.

410 The decadal exposure time to rubble mobilizing currents shares the same decadal variability as
411 exposure to rough seas (Fig 6A-D), with the decade of 2005-2014 having anomalously high
412 exposure times for the majority of the GBRMP decades (Fig 6C). Largest exposure times
413 occurred south of Townsville in the Fitzroy and Burnett Mary NRMs, and in the Swains Group. In
414 contrast, north of Townsville, this decadal variability is less significant, and instead there may
415 be a weak trend of increasing exposure time over the decades in the northernmost part of the in
416 the northmost part of the Cape York NRM. This contrast between north and south of Townsville
417 suggests different wave regimes operating in the GBRMP.



418

419 **Fig 6. Exposure to rubble-mobilizing currents ($U_b \geq 0.25 \text{ m s}^{-1}$).** Accumulated exposure to rubble
 420 mobilizing currents (A) from 1985 to 1994, (B) from 1995 to 2004, (C) from 2005 to 2014, and (D) from
 421 2015 to 2024. (E) Average decadal exposure from 1985-2024. MW—Mackay Whitsunday.

422 3.4.1 Contributions of cyclones to rubble mobilizing currents

423 Cyclones are only responsible for up to 20% of the exposure time to rubble mobilizing currents
 424 over the continental shelf from the Cape York NRM to the Burdekin NRM (Fig 6B). In the Mackay
 425 Whitsunday MW and Fitzroy NRMs, cyclones are responsible for most the exposure time, except
 426 notably in the Swains Group. The opposite spatial patterns for cyclonic contributions to “rough
 427 seas” and rubble mobilizing currents indicates that cyclone-induced “rough seas” do not reach
 428 rubble mobilizing threshold of 0.25 m s^{-1} because of the short period nature of these waves.

429 3.5 Cyclone gale force winds

430 Exposure to cyclone winds shows a north to south pattern, higher in the north and decreasing
 431 southward with shorter exposure times inshore than offshore (Fig 5C). The decrease in exposure

432 to cyclone winds shoreward reflects the general weakening of cyclones as they approach land.
 433 Reefs located from the Cape York to Burdekin NRMs are the most exposed to the effects of
 434 cyclonic winds, suggesting that these reefs are at higher risk of derived effects of wind damage.
 435 Regardless of *the* exposure to rough seas, rubble mobilizing currents, *and gales attributable to*
 436 *cyclones* (Fig 5), the damage to individual reefs from individual cyclones varies depending on a
 437 combination of the distance of the reef to the cyclone, cyclone intensity and track, bathymetry,
 438 depth of the reef and potentially land topography which modulates the near surface cyclone
 439 winds. An example of this is this variability in damage to reefs along the track of Severe Tropical
 440 Cyclone Debbie in 2017. Inshore reefs of the Whitsunday Islands such as those at Hayman
 441 Island were devastated while those further offshore were spared [169]. Nevertheless, and
 442 despite the importance of small-scale mechanisms damaging reefs due to cyclones, the
 443 present maps provide a broad perspective of the cyclone’s footprint.

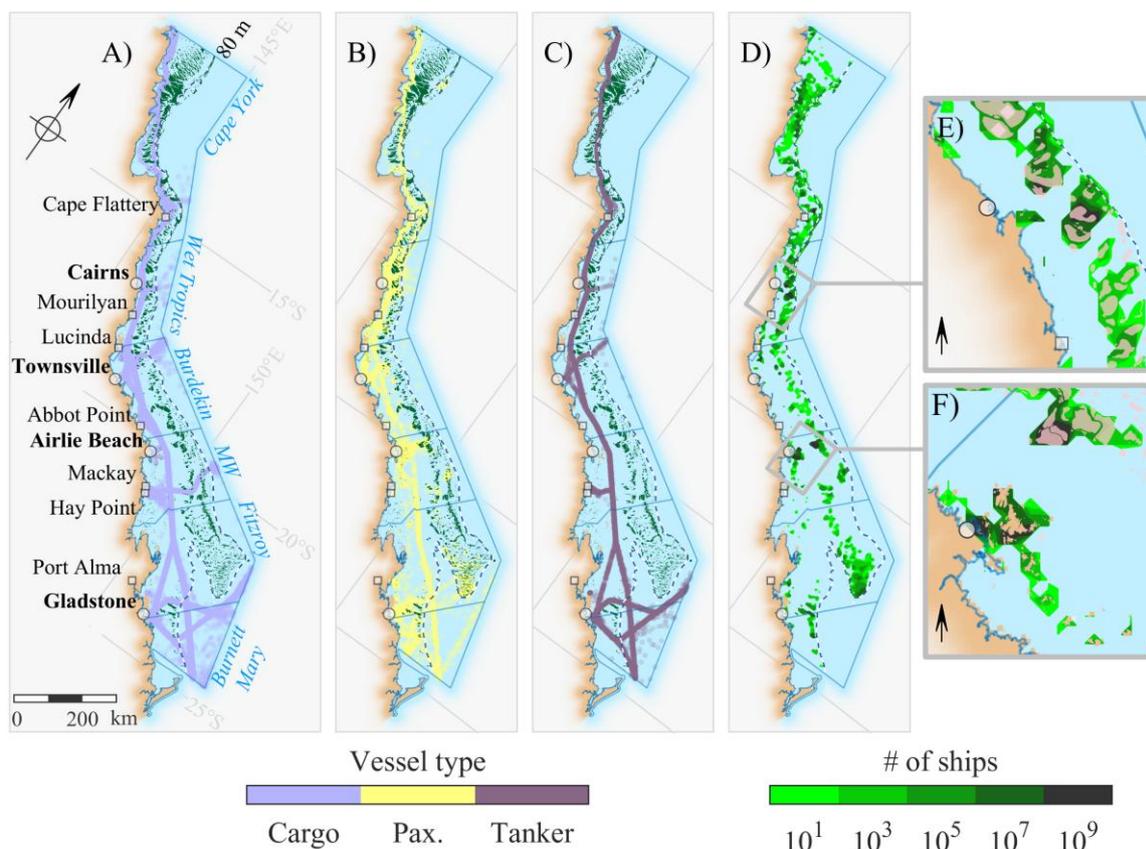
444 **3.6 Shipping risk**

445 Between 2019-2021, there were 2,051,157 ship observations in the GBRMP based on 4,836
 446 unique vessels exceeding 10 m length. The 3 vessel types captured include cargo ships,
 447 passenger ships and tankers. The overall ship traffic remained constant despite disruption from
 448 the COVID-19 pandemic and was dominated by cargo ships (87-92%), which are the largest
 449 ships with the average length of 219-223 m (Table 3).

450 **Table 3. Commercial vessel traffic in the Great Barrier Marine Park.**

Type	Year	Observations	% of Year Total	Unique Craft	Ave. Craft Length [m]
Cargo ship	2019	664,531	92%	2,135	223
Cargo ship	2020	541,632	90%	2,073	219
Cargo ship	2021	593,914	87%	2,182	222
Passenger ship	2019	28,427	4%	62	135
Passenger ship	2020	28,245	5%	86	75
Passenger ship	2021	51,137	8%	78	22
Tanker	2019	27,942	4%	206	198
Tanker	2020	34,558	6%	228	197
Tanker	2021	33,806	5%	218	207

451 Traffic reported by year (2019-2021) and vessel type (cargo, passenger, and tanker) within the Great
 452 Barrier Reef Marine Park downloaded from the Australian Maritime Safety Authority. Geolocated ship
 453 position is collected hourly using the Automatic Identification Systems required on commercial vessels.
 454 46,965 observations did not have timestamp data.
 455 Different vessel types follow different routes within the GBRMP. Cargo ships and tankers have 3
 456 main channels where they transit inshore to major ports along the coast and travel up and down
 457 inshore of the GBR (Fig 7A,C). Passenger ships have much more distributed tracks linked to
 458 tourism within the park. Tankers are the least common and concentrated in the Burnett Mary
 459 NRM (Fig 7B). The highest risk of ship strike is from cargo ships as they make up most of the
 460 commercial shipping traffic (Table 3). The Mackay Whitsunday NRM has the most ship traffic
 461 and associated risk of ship strike (Fig 7D,F). The Cape York and Wet Tropics NRMs (Fig 7E,F)
 462 have elevated risk from shipping impacts due to reefs designated as tourist destinations,
 463 whereas in the Gladstone area in the Burnett Mary and Fitzroy NRMs, vessel traffic is due to
 464 cargo ships and tankers.



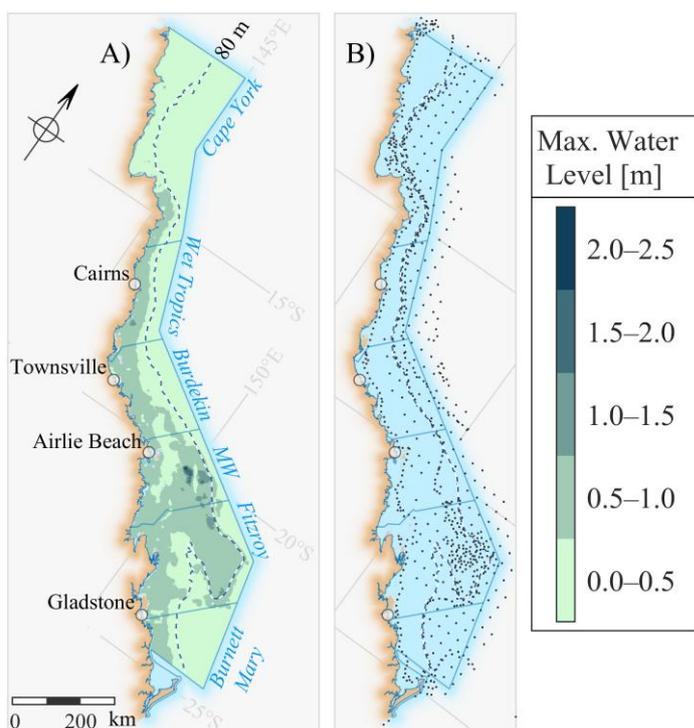
465

466 **Fig 7. Ship traffic of commercial vessels in the Great Barrier Reef Marine Park from 2019-2021.** (A)
 467 Cargo ship, (B) Passenger ship (Pax.), (C) and tanker ship positions based on the Automated Integrated

468 Systems from the Australian Maritime Safety Authority. The industrial ports (squares) in the Marine Park
 469 and major towns (circles) are shown. Blue areas in the Marine Park reflect areas of no large vessel traffic.
 470 (D) Accumulated reef exposure to ships calculated by taking the \log_2 of the sum of the individual ships
 471 area of influence within the limits of a coral reef (see eqn. S5). (E) Inset of reef exposure to ships in the
 472 Cairns region, (F) and inset of reef exposure to ship in the Airlie Beach region. MW–Mackay Whitsunday.

473 3.7 Tsunamis

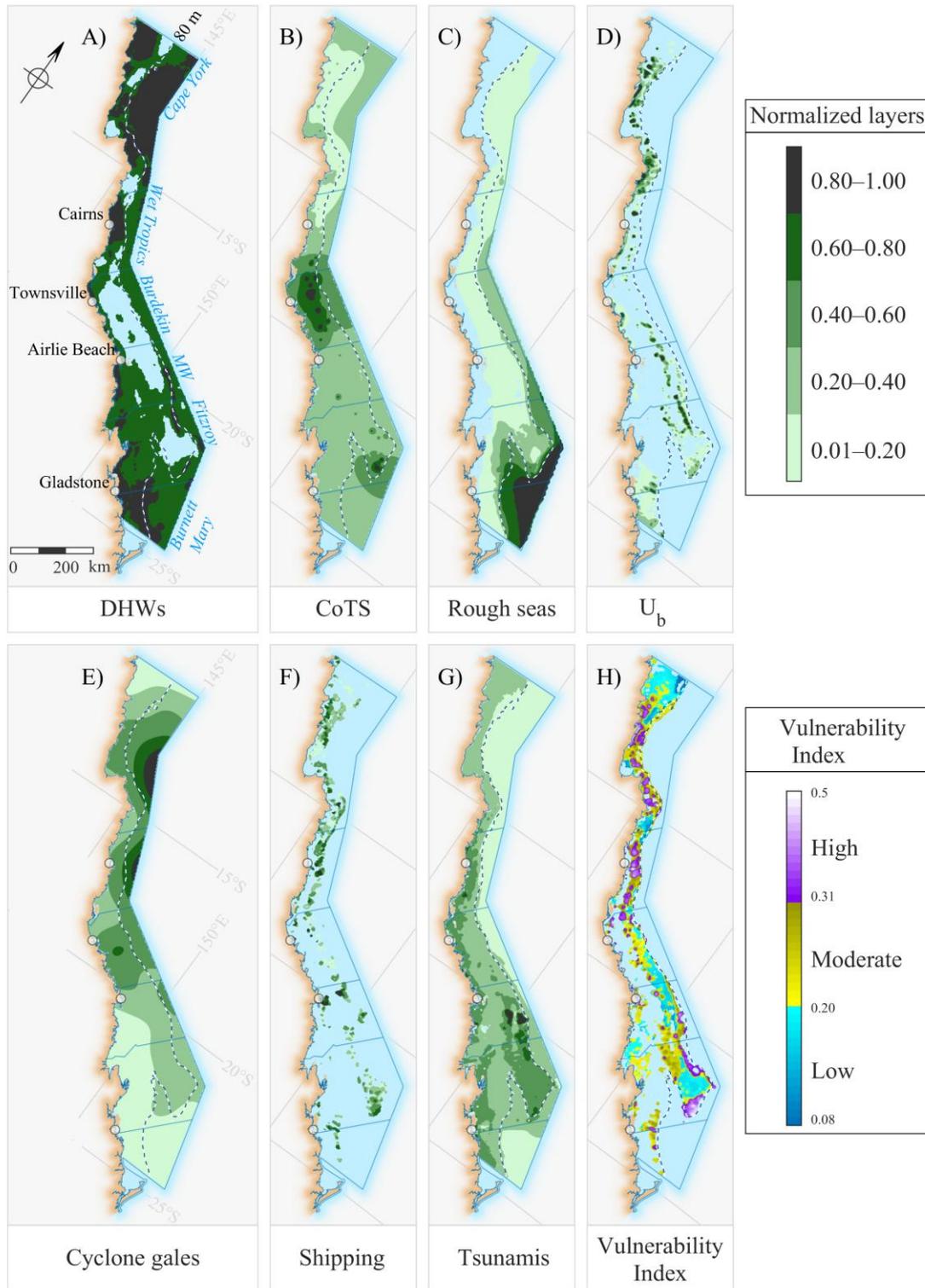
474 Tsunami risk is greatest for the central and southern GBR in the Mackay Whitsunday and Fitzroy
 475 NRMs with the highest 1 in 100-year exceedance rate of 1.67 m on the outer reef. This means
 476 that the maximum water-level would be 1.67 m above mean sea level in a 1 in 100-year tsunami.
 477 The maximum values of 1.67 m indicate that the GBR is not prone to hazardous tsunamis with a
 478 1% probability annually and consistent with the timescales in previous observations [57].
 479 Inshore reefs have a moderate level of tsunami risk as the bathymetry shallows landwards.
 480 Overall, tsunami risk decreases northwards, with minimal risk in the Cape York NRM (Fig 8).



481
 482 **Fig 8. Tsunamis risk in the Great Barrier Reef Marine Park (GBRMP).** A) Tsunami 1 in 100-year maximum
 483 water level of the GBRMP based on the Geoscience Australia Probabilistic Tsunami Hazard Assessment
 484 2018. (B) Hazard points. The 80 m isobath shown for reference (dashed line). MW–Mackay Whitsunday.

485 **3.8 Reef Vulnerability Index**

486 The Index developed considers the 7 drivers to quantify vulnerability to reef damage for the GBR
487 (Fig 9). There are 3,750, 0.05° x 0.05° reef pixels – this was constrained by the shipping dataset
488 where the calculated risk of ship strike was per reef. The Reef Vulnerability Index ranges from
489 0.07-0.51 with the median value of 0.25 and average of 0.26 (± 0.07 SD; Fig 9). This Index range
490 indicates that no reef had a combination of all minimum or maximum values of the 7 drivers
491 incorporated into the Index. The Index average per NRM zone was comparable, ranging from
492 0.24 in Mackay Whitsunday to 0.30 in the Wet Tropics.



493 **Fig 9. The seven, normalized drivers of reef damage in the Great Barrier Reef Marine Park.**
 494 Normalization goes from 0 to 1 where 0 (1) represents the minimum (99.9th percentile) value. (A) DHW–
 495 degree heating weeks, (B) CoTS–crown-of-thorns seastars, (C) Rough seas, (D) wave-derived bottom
 496 velocity, (E) cyclone gales, (F) shipping risk, (G) tsunami and (H) Vulnerability Index only in reef pixels;
 497 grouped into low (< 0.20), moderate (0.20-0.31) and high vulnerability (> 0.31) scores based on 25th and
 498 75th percentiles. 80 m isobath (dashed line). MW–Mackay Whitsunday.

500 The high vulnerability areas were spread across the GBR and had different drivers responsible

501 for the high scores (S4 Appendix). The driver that contributed most to the highest, top 25%

502 vulnerable pixels was DHWs or coral bleaching stress with an average 0.76 across all the high
 503 vulnerability pixels. Shipping had the highest relative contribution with a 0.20 difference
 504 between the high and moderate vulnerability areas (Table 4). Validation with the GBR10 benthic
 505 habitat map showed that coral/algae classification decreased from low to moderate
 506 vulnerability from 15 ($\pm 17\%$) to 11 ($\pm 15\%$) with similar coral/algae for high vulnerability areas (11
 507 $\pm 13\%$). Rubble is the lowest cover class and was constant between low-high vulnerability areas
 508 (Table 4). An interactive version of the re-scaled drivers and final index is available at
 509 https://seacatkim.github.io/test_rubble_index/.

510 **Table 4 Average re-scaled values of each driver summarized by the high (>75th percentile), moderate,**
 511 **and low (< 25th percentile) vulnerability.**

Vulnerability	Crown-of-Thorns Seastars	Gale Force Winds	Wave Height	Shipping	Tsunamis	Bed Velocity	Degree Heating Weeks	
High	0.28	0.36	0.14	0.29	0.39	0.27	0.76	
Moderate	0.25	0.30	0.11	0.09	0.33	0.10	0.61	
Low	0.23	0.27	0.13	0.04	0.33	0.07	0.18	
	Coral/Algae		Rock		Rubble		Sand	
	Average	SD	Average	SD	Average	SD	Average	SD
High	0.11	0.13	0.15	0.21	0.03	0.05	0.19	0.24
Moderate	0.11	0.15	0.17	0.25	0.02	0.06	0.11	0.17
Low	0.15	0.17	0.22	0.26	0.03	0.04	0.11	0.16

512 The proportion of Coral/Algae, Rock, Rubble, and Sand from the Great Barrier Reef 10 Benthic Habitat
 513 map at 10 x 10 m resolution was calculated and summarized for High/Moderate/Low vulnerability areas.

514 4 Discussion

515 The Vulnerability Index together with the decadal exposure maps provides insight into the
 516 exposure of seven drivers causing damage to the GBR. Vulnerability Index together with the
 517 decadal exposure maps provides insight into the exposure of seven drivers causing damage to
 518 the GBR. There are numerous efforts to understand pre-conditioning coral mortality (i.e., coral
 519 bleaching, CoTS) and direct disturbances (i.e., waves, bottom currents, cyclones, shipping,
 520 tsunamis) that impacts the GBR either as individual drivers [6,51,83,170,171] or compounded
 521 drivers [14,15,18]. Much of this work is in the context of understanding hard coral resilience, the
 522 capacity to absorb or withstand and recover from disturbances, on the reef with a focus on

523 three main disturbances, coral bleaching, cyclones, and CoTS outbreaks with hydrodynamics
524 often considered independently. The Index indicated coral bleaching stress quantified as DHWs
525 was the greatest contributor to reef damage with bottom velocity and shipping having a
526 relatively high contribution to high vulnerability areas (Table 4) highlighting the need to
527 understand reef damage drivers beyond these three main disturbances. For example, reefs in
528 the Wet Tropics NRM are highly vulnerable arising from the confluence of high exposure to DWH
529 $>8^{\circ}\text{C}$ -week, ships (mostly passenger boats), and relatively high exposure to cyclones. In Fitzroy
530 NRM, high vulnerability is due to relatively high exposure of DWH $>8^{\circ}\text{C}$ -week, CoTS outbreaks,
531 bottom velocity, and potential tsunamis (Fig 9).

532 **4.1 Coral bleaching**

533 DHWs and CoTS are the two drivers with clear decadal trends. The dramatic increased exposure
534 to mortality inducing heat stress (DWH $>8^{\circ}\text{C}$ -week) over the 2015-2024 decade across the GBR
535 reveals an emerging and unprecedented risk for the entire GBRMP. This follows numerous
536 reports of bleaching events across the globe in recent years due to climate change [172,173].
537 However, there are regions in the far north, central, and southern GBR that have not experienced
538 any DHWs $>8^{\circ}\text{C}$ -weeks in the last 40 years (Fig 2E).

539 How these spatial temporal variations in SST and other physical and meteorological variables
540 play into potential climate refugia on the GBR is an area of much interest. According to the last
541 40 years of DWH data, potential refugia are spread across the extent of the GBR from Cape York
542 through to Fitzroy NRMs along the continental shelf and with a few inshore areas. An analysis of
543 2 km resolution SST for Australian Regional Seas revealed 2 refugia along the northern and
544 southern ends of the GBR continental shelf driven by a combination of local oceanographic and
545 meteorological processes during the summer and mechanisms providing regular upwelling
546 [174]. The upwelling along the continental shelf in the Far North and Wet Tropics NRMs is mainly
547 due to tidal mixing with narrow channels between dense reef structures that facilitates onshore

548 and upwards flow of cool water [175]. The lack of high DHW accumulation in the Swains Group
549 is similarly influenced upwelling from tidal mixing in addition to the East Australian Current
550 [176] and “tidal pumping” [177]. Our analysis indicated a few inshore areas in the Far North,
551 Wet Tropics, and Burdekin NRMs had never accumulated DHWs >8°C-weeks which is in
552 agreement with a similar analysis using DHWs [178]. However, when comparing climate model
553 predictions of climate refugia on the GBR, agreement in the inshore areas is 0 nearly across the
554 coast and highest agreement is in the southern GBR/Swains Group [174,178]. Despite multiple
555 analyses highlighting the southern GBR as a climate refugia [174,178,179], in the fourth global
556 coral bleaching event from 2018-2024 the southern GBR has experienced catastrophic
557 bleaching [180]. Satellite-based SST and bleaching metrics have limitations in their accuracy of
558 predicting in situ bleaching [181]. Bleaching also depends on atmospheric drivers [182,183]
559 including cloud cover which may decrease due to climate change [184] and hydrodynamics
560 conditions that modulate heat stress. These factors should be considered in future studies.

561 **4.2 Crown-of-Thorns Seastars**

562 The long-term record reveals that reef damage from CoTS outbreaks is localized and affects
563 reefs in two NRMs. Despite these persistent hotspots of outbreaks, CoTS outbreaks have not
564 expanded to all reefs and the Far North Queensland reefs in the Cape York NRM have had little
565 exposure to CoTS outbreaks. Outbreaks have been recorded in the Far North and modelling
566 suggests they are much less frequent every 50-80 years in the northern GBR, although the
567 remote nature of the region makes consistent surveying a challenge [137]. As one of the few reef
568 impacts that is directly manageable [82,135,136,185], the CoTS Control Program has been a
569 priority since the third outbreak starting in 2002. The Program has had positive outcomes with
570 net increases in coral cover on outbreaking reefs where more culling occurred compared to
571 reefs with lower culling effort [81] which our analysis corroborated. The overall spatial
572 distribution is reflected in the distribution of the 3rd and 4th outbreaks on the GBR starting in

573 2002 and 2011, respectively, with Established and Severe Outbreaks in the Burdekin, Fitzroy,
574 and Burnett Mary NRM zones [81] (Fig 3C). Given the efficacy of the CoTS Control Program, it is
575 not surprising the relative contribution of the CoTS overall vulnerability is low and contributes
576 equally between the low to high vulnerability area (Table 4). Thus, CoTS are not a pressing driver
577 for reef damage.

578 **4.3 Rough seas and rubble-mobilizing currents**

579 Our results show that impinging “rough seas” are strongly dampened (dissipation by bottom
580 friction, or wave braking) along the continental shelf’s edge, consistent with [165,186], and
581 protecting the inner and mid reefs from “rough seas.” In the Mackay Whitsundays and Fitzroy
582 NRMs, the outer reefs dampen much of the offshore “rough seas” as indicated by the sharp
583 gradient in the exposure time along them. In contrast, both the outer and inner reefs have
584 relatively high exposure to rubble-mobilizing currents indicating calmer seas can produce
585 rubble-mobilizing currents e.g., Cape York and Wet Tropics NRMs. In general, for any specific
586 depth, higher and longer period waves will result in higher U_b values, and smaller waves require
587 longer periods to reach higher U_b values (S2 Appendix). These shorter waves with relatively large
588 periods may result from the aftermath of wave breaking, for example, infragravity waves
589 generated during wave breaking in the outer reefs [187–189]. Furthermore, it is known that
590 infragravity waves are not well dampened by reefs or shallow depths, reaching the inner reefs
591 and the shoreline [190], and may develop rubble-mobilizing currents. Therefore, in terms of
592 rubble mobilization, not only “rough seas” may produce rubble-mobilizing currents but also
593 waves resulting from their breaking in the outer reefs propagating to the inner reefs.

594 Neither the decadal exposure to “rough seas” and rubble-mobilizing currents show significant
595 trends in the last 40 years but there is decadal variability. The variability consists of an active
596 decade of high exposure (1985–1994 and 2005–2014) followed by an inactive one (1995–2004
597 and 2015–2024), and is more noticeable in the southern GBRMP, from Mackay Whitsunday to

598 Burnett Mary NRMs. Notably cyclones passing by the southern GBRMP follow this decadal
599 variability (2 cyclones in 1985–1994, 2 in 2005–2014 but only one in 1985–1994 and one in 2015–
600 2024, S2 Appendix), but they are responsible for 40–60% of the exposure time in the inner shelf
601 and 20–40% out of the shelf suggesting that other factors drive the exposure to “rough seas”.
602 These factors may be non-tropical systems operating in southeast Australia, such as East Coast
603 Lows, distant cyclones undergoing extratropical transition or other extratropical systems. East
604 Coast Lows are low-pressure systems that occur several times each year more active off the
605 southeastern coast of Australia [191]. They can reach gale force winds and develop “rough
606 seas”, and their weather may sporadically span up to southeast Queensland [191,192] and
607 potentially to the southern GBRMP. Notably, East Coast Low activity and cyclone impacts in the
608 southern GBRMP share the same decadal variation of the exposure to “rough seas,” i.e., 1985–
609 1994 and potentially 2005–2014 correspond to periods of enhanced activity (Fig 4C,D). In turn,
610 the decadal variation of the cyclonic activity appears to be modulated by the Interdecadal
611 Pacific Oscillation [191,193], implying that the decadal variability of “rough seas” exposure in
612 the southern GBRMP may be driven by the Interdecadal Pacific Oscillation (Fig 4C,D).

613 **4.4 Cyclones producing rough seas and rubble-mobilizing currents**

614 Exposure to cyclones gales is high in the north (Cape York to Burdekin NRMs) and low in the
615 south GBRMP (Mackay Whitsunday to Burnett Mary NRMs), show decadal variability in the
616 number of cyclone events in the 1985–2024 period (S1 Appendix). This means that at the
617 GBRMP scale there are no clustering effects, but there may be at scales of 300 km [194],
618 suggesting that clustering effects are dependent on the spatial scale. Cyclones contribute the
619 most to the exposure time to “rough seas” in the northern GBRMP and in the outer reefs in the
620 Mackay Whitsunday and Fitzroy NRMs, consistent with [141]. In terms of rubble-mobilizing
621 currents, cyclones contribute most to the exposure time in broad areas in the Mackay
622 Whitsundays and Fitzroy NRMs, especially in the outer reefs. However, there are broad areas

623 where cyclones are not the primary sources of neither “rough seas” (south GBRMP and offshore
624 the Burdekin NRM; Fig 5A) nor rubble-mobilizing currents (northern GBRMP and the Swain
625 Group in Fitzroy; Fig 5B).

626 In summary, despite most of the literature has focused on reef damage by cyclones [5,6,14,18]
627 we have shown that other sources of “rough seas” and rubble-mobilizing currents operate in the
628 GBRMP and should be considered in future studies. For example, infragravity waves may be the
629 primary source of rubble-mobilizing currents in northern GBRMP. In parts of the southern
630 GBRMP, East Coast Lows or other extratropical systems may be responsible for “rough seas.”
631 These other sources should be considered for determining rubble mobilization and reef damage
632 by “rough seas.”

633 **4.5 Uncertain drivers - tsunamis, shipping**

634 Assessment of ship and tsunami hazards remains a challenge because of the infrequent nature
635 of both ship strikes to the reef and tsunamis. We presented a simple way to estimate the
636 shipping hazard by taking the expected number of times ships spend near each individual reef
637 and high-risk areas were in agreement with recent incidents of ship strikes. For example, ship
638 traffic to ports such as Cape Flattery, Mourilyan, and Gladstone are high risk areas (**Fig 7A,D**)
639 and the last major ship grounding on the GBR was off Gladstone on Douglas Shoal in 2010. This
640 incident resulted in 115,000 m² of severe damage to the shoal with moderate damage to the
641 remaining 400,000 m² [195]. High tourism and boating activity supported by large marinas such
642 as in the Whitsunday and Cairns regions are other high-risk areas is also highlighted in the
643 presented maps (**Fig 7B,D**). Although commercial ship traffic represents the largest risk of ship
644 strike to the reef, smaller scale ship strikes from recreational boating are likely more common
645 but difficult to quantify risk and the resulting damage as their movements are not readily
646 available.

647 There is evidence in the geologic record of at least two tsunami events occurred in the last
648 millennium producing >11 m tsunami waves capable of crossing the GBR and causing damage
649 [57], but overall there are poor records of tsunamis in the GBR. The increased maximum water-
650 level occurring only in a restricted area in the Mackay Whitsundays NRM, may be due to some
651 shoaling as the tsunami propagates over the shelf. The PTHA18 recognizes the high uncertainty
652 associated with the maximum water-levels despite recent advances [158]. Modelled tsunamis
653 become less accurate closer to the coast as coastal bathymetry is more poorly represented
654 [157]. The maximum water-level measures temporary water-level as an indicator of tsunami
655 magnitude but does not accurately measure the number of waves, wave heights, wave damage,
656 or receding water levels prior to advancing waves. One remotely operated vehicle survey five
657 weeks post-tsunami concluded that the rapid tsunami drawdown and sudden release of
658 sediment and debris was responsible for most of the coral reef damage caused [61]. Thus,
659 maximum-water level may not be the best predictor of tsunami damage to reefs. Tsunamis are
660 difficult to predict and unlikely; however, they can cause significant reef damage if one were to
661 occur. They remain a broad and general assessment of the GBR.

662 **4.6 Management Implications**

663 Maps of variations in drivers of reef damage can be used to help manage reefs for climate
664 change [196]. The reef damage vulnerability index developed here considers the most up-to-
665 date data to diagnose the exposure level to each of the main drivers of damage across the
666 GBRMP. The analysis of decadal variations of the drivers assists to inform the expected
667 vulnerability of the GBR in the coming years. CoTS density is decreasing, but DHW is increasing.
668 There are no expected trends in the exposure to “rough seas, rubble mobilizing currents and
669 gale winds. By evaluating each driver separately and collectively across the whole GBRMP, this
670 vulnerability mapping is a useful tool for managers to monitor and prioritize management
671 actions in both the short and medium-term. The spatially explicit index improves situational

672 awareness within management zones and allows managers to identify the main risks of reef
673 damage in certain reef areas and determine what are manageable risks (Fig 9). In combination
674 with local site knowledge from tourism and Indigenous groups, the Index can provide guidance
675 on key areas to monitor for signs of reef damage. This is especially important as the resolution
676 of the index at present ($0.05^\circ \times 0.05^\circ$) is too coarse for fine-scale management actions such as
677 identifying specific sections of reefs for restoration.

678 Our analysis, based on historical datasets, identifies the level of exposure to different drivers
679 that cause damage to coral reefs and potentially lead to coral rubble generation. It helps identify
680 areas that can be targeted by specific interventions such as outplanting of enhanced thermally
681 tolerant corals and cooling and shading methodologies to reduce bleaching risk [47]. The
682 vulnerability mapping also has long-term significance because increased and more frequent
683 reef damage leading to increased rubble generation and coverage of reefs reduces substrate
684 availability for active restoration.

685 This study complements recent work, providing improved guidance for implementing
686 restoration and adaptation techniques. For example, Leung and Mumby [48] analyzed the
687 bathymetry profiles of the forereefs in the GBR to determine the potential for rubble
688 accumulation. They estimated that about 20% of the GBR reefs have bathymetric profiles
689 favorable for trapping rubble. The Pompey Reefs and the Capricorn and Bunker group in the
690 Fitzroy NRM were found to be particularly susceptible to trapping more rubble. Our Index
691 classifies the Pompey reefs as highly vulnerability as they are exposed to the warm waters of the
692 East Australian Current and can experience “very rough” seas due to cyclones. The connection
693 then between reef damage, rubble generation and long-term accumulation in ecologically
694 important reef zones is significant for the recovery and long-term resilience of reefs.

695 While vulnerability and resilience are related, they have important distinctions. Ecological
696 resilience typically focuses on mechanistic processes that allow systems to withstand and

697 recover through time from disturbances [197] while vulnerability is the susceptibility of a system
698 to adverse effects. Vulnerability was designed as an operational approach from its conception
699 [109,197] and typically focuses on spatial dimensions of prospective threats or hazards and
700 resilience on retrospective disturbances and stressors [197].

701 An important outcome of some recent studies assessing resilience across the GBR is identifying
702 reef areas that show high-resilience to disturbance events as informed by coral cover [e.g.,
703 17,21,113,187] or may act as ‘refugia’ where the effects of a disturbance event can be
704 minimized [e.g., 121,127]. Part of the southern GBR and particularly the Swains Group area has
705 been identified as an area of greater resilience [14,174]. It could be that regions while highly
706 vulnerable also harbor ecological resilience to recover. This is unlikely as increasing frequency
707 of disturbances impacting the GBR has been shown to decrease the reefs ability to recover
708 [198]. Alternatively, the discrepancy between high vulnerability and high resilience could arise
709 because different disturbances or drivers of reef damage are being considered. While the
710 Swains Group area shows more resiliency to bleaching because of bathymetric and current
711 interactions that promote upwelling and mixing of cooler waters [174], it is an area that shows
712 higher vulnerability to damage from CoTS outbreaks (Fig 3), cyclonic effects (Fig 5) and tsunamis
713 (Fig 8). In summary, to assess the long-term health and resilience of reefs and whether they can
714 be relied on as refugia, it is critical to undertake vulnerability assessments beyond the well-
715 studied disturbances such as cyclones, bleaching, and CoTS to all potential disturbance events
716 that can impact those reefs.

717 Managing reefs in a multi-hazard environment systematically is challenging. Our
718 comprehensive and holistic approach of synthesizing all the disturbance drivers that a reef
719 system experiences (Table 1) can be applied to any reef. Indices of vulnerability can be defined
720 at any scale, from individual reefs to management zones to the entire reef ecosystem. A
721 vulnerability index analysis can also be undertaken using future projections under climate

722 change scenarios that can include projections of key drivers of reef damage such as coral
723 bleaching and cyclones.

724 A potential end-state of reefs following damaging events is to become a rubble-dominated reef
725 characterized by persistent rubble fields and reduced reef structural complexity that inhibits
726 reef recovery [e.g., 6,22,24]. A key gap is the lack of data quantifying coral rubble through time.
727 Coral rubble data captured benthic monitoring [33] and citizen science programs [200] should
728 be leveraged to better understand rubble dynamics at scale through time but would likely
729 require additional training of machine learning pipelines which are now standard. Disturbances
730 such as ship groundings and cyclones have resulted in increases in coral rubble locally [6,10]
731 but there is no empirical evidence for coral rubble increasing at scale across the GBR.

732 Substantial effort and resources are now being directed globally to active restoration practices
733 with the aim of returning impacted reefs to pre-disturbance states [47,201]. Such efforts can be
734 undone if rubble volume and extent increase because of disturbances that reduce the amount
735 of viable substrate for restoration and the available time between disturbances. In conclusion,
736 vulnerability analysis of reef damage as we have undertaken here for the GBR provides a
737 valuable tool to understand where damage is likely to occur, by what mechanisms, in what
738 likelihood and the range of drivers that can cause reef damage. Such tools should be embedded
739 into decision-making processes around coral reef management.

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 1366

1367 7 Supporting Information

1368 **S1 Appendix. S1 Figure. Cyclones whose radius of gale force wind reached the Great Barrier Reef.**
 1369 Colors indicate cyclone category along each track.

1370
 1371 **S2 Appendix. S2 Fig. U_b for significant wave height and peak wave period for a 20-m depth.** U_b for
 1372 significant wave height (horizontal axis) and peak wave period (vertical axis) at a depth of 20 meters.

1373
 1374 **S4 Appendix. S3 Fig. Distribution of the crown-of-thorns seastar (CoTS) densities per reef.** Data from
 1375 the Australian Institute of Marine Science Long Term Monitoring Program mean CoTS per manta tow data
 1376 per reef per outbreak period: 1983-1984, 1985-1991, 1992-2009, and 2010-2024. The data before 1985
 1377 was not included in the analysis. Lines represent thresholds for Severe Outbreak (> 1).

1378
 1379 **S4 Appendix. S4 Fig. Distribution of reef damage vulnerability index values.** Pink line indicate 25th
 1380 percentile, 0.21, and blue line is the 75th percentile, 0.31, used as thresholds for low/moderate and
 1381 moderate/high vulnerability.

1382
 1383 **S4 Appendix. S5 Fig. High vulnerability areas for each driver.** High vulnerability (> 0.31) areas as
 1384 polygons from the final vulnerability index plotted on each of the individual 7 scaled (0-1) drivers

1385 combined into the final index. (A) Cyclone waves, (B) Cyclone wind, (C) CoTS – crown-of-thorns seastars,
1386 (D) Shipping, (E) DHW – degree heating weeks, (F) Tsunamis, and (G) Cyclone bed velocity.

1387

1388 **S1 Appendix. S1 Table. Tropical cyclones impacting the Great Barrier Reef Marine Park.** The tropical
1389 cyclone season in which a cyclone occurred and the El Niño Southern Oscillation (ENSO) phase.

1390 *Crossed over the GBR as a category 3 cyclone.

1391 ‡ Did not cross the GBR but their gale force winds extended to the GBR.

1392 † Crossed the GBR with intensity lower than that of a category 1 cyclone. Seasons go from Nov of the year
1393 prior to the

1394

1395 **S1 Appendix. S2 Table. Douglas sea scale adapted from the World Meteorological Organization.**

1396

1397 **S1 Appendix. S3 Table. Parameters of the lognormal distribution for the R_{17} —gale-force wind average**
1398 **radii values.** The logarithm value 120 (km) corresponds to the median value of R_{17} values.

1399

1400 **S4 Appendix. S4 Table. Metadata of drivers used in the vulnerability index.** Source, spatial resolution,
1401 time period, and units of drivers of reef damage constituting each layer of the Great Barrier Reef
1402 Vulnerability Index developed in this study.

1403

1404 **S4 Appendix. S5 Table. Areas within the NRM that have experienced DHW) ≥ 8 .**

1405

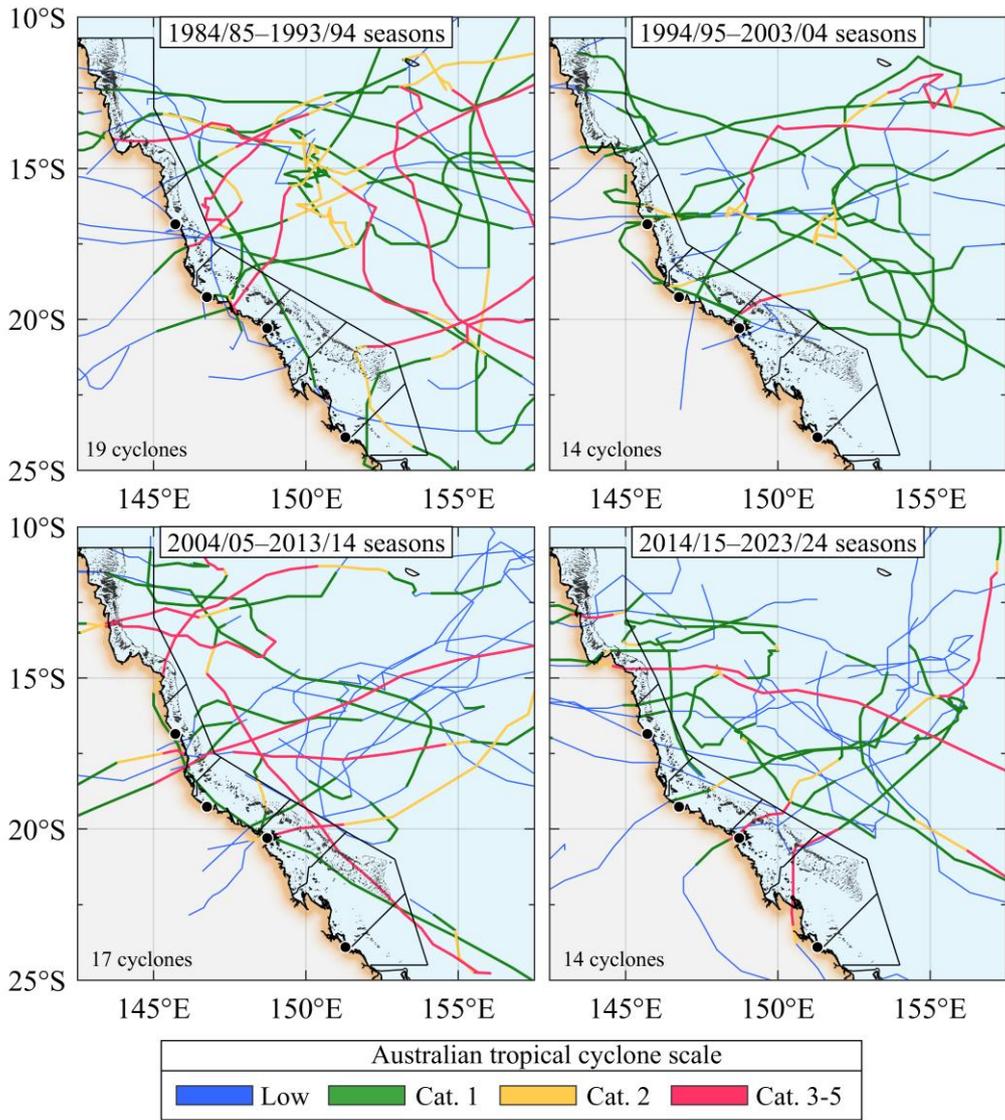
1406 **8 S1 Appendix. Constraining Cyclone Winds and Cyclones**
 1407 **that impacted the GBR**

1408 **S1 Table. Tropical cyclones impacting the Great Barrier Reef Marine Park.**

Name	Season	ENSO Phase	Name	Season	ENSO Phase
Jim	1984	Neutral	Tessi*	2000	Niña
Kathy	1984	Neutral	Abigail	2001	Neutral
Lance	1984	Neutral	Erica†	2004	Neutral
Odette	1985	Niña	Fritz	2004	Neutral
Unnamed†	1985	Niña	Grace†	2004	Neutral
Pierre	1985	Niña	Ingrid*	2005	Neutral
Tanya	1985	Neutral	Jim†	2006	Niña
Vernon	1986	Neutral	Kate	2006	Neutral
Winifred*	1986	Neutral	Larry*	2006	Neutral
Manu	1986	Neutral	Monica*	2006	Neutral
Charlie*	1988	Neutral	Guba	2008	Niña
Delilah†	1989	Niña	Ellie	2009	Niña
Aivu*	1989	Niña	Hamish*	2009	Neutral
Meena	1989	Neutral	Olga	2010	Niño
Felicity	1990	Neutral	Ului*	2010	Niño
Nancy†	1990	Neutral	Tasha	2011	Niña
Ivor*	1990	Neutral	Anthony	2011	Niña
Joy	1991	Neutral	Yasi*	2011	Niña
Daphne†	1991	Neutral	Tim†	2013	Neutral
Kelvin	1991	Neutral	Dylan	2014	Neutral
Mark	1992	Niño	Edna	2014	Neutral
Unnamed†	1992	Niño	Hadi†	2014	Neutral
Fran	1992	Niño	Ita*	2014	Neutral
Nina†	1993	Neutral	Marcia*	2015	Neutral
Oliver†	1993	Neutral	Nathan*	2015	Neutral
Roger†	1993	Neutral	Debbie*	2017	Neutral
Rewa*	1994	Neutral	Iris†	2018	Niña
Unnamed†	1995	Neutral	Owen	2019	Niño
Celeste*	1996	Niña	Penny	2019	Niño
Dennis	1996	Neutral	Trevor	2019	Neutral
Ethel	1996	Neutral	Ann†	2019	Neutral
Gillian†	1997	Neutral	Kimi	2021	Niña
Ita	1997	Neutral	Lucas†	2021	Niña
Justin	1997	Neutral	Seth	2022	Niña
Katrina	1998	Niño	Tiffany	2022	Niña
Nathan	1998	Niño	Gabrielle†	2023	Niño
Rona*	1999	Niña	Jasper	2024	Niña
Steve	2000	Niña	Kirrily	2024	Niña
Vaughan†	2000	Niña			

1409 The tropical cyclone season in which a cyclone occurred and the El Niño Southern Oscillation (ENSO)
 1410 phase.

1411 *Crossed over the GBR as a category 3 cyclone.
 1412 ‡ Did not cross the GBR but their gale force winds extended to the GBR.
 1413 † Crossed the GBR with intensity lower than that of a category 1 cyclone. Seasons go from Nov of the year
 1414 prior to the year to April of the season year; for example, the season 2024 goes from November 2023 to
 1415 April 2024.
 1416



1417

1418 **S1 Figure. Cyclones whose radius of gale force wind reached the Great Barrier Reef.** Colors indicate
 1419 cyclone category along each track.
 1420

1421 **S2 Table. Douglas sea scale adapted from the World Meteorological Organization.**

Degree	Wave Height	Description
	(m)	
0	0	Calm (glassy)
1	0-0.10	Calm (rippled)
2	0.1-0.50	Smooth
3	0.50-1.25	Slight
4	1.25-2.50	Moderate
5	2.50-4.00	Rough
6	4.00-6.00	Very rough
7	6.00-9.00	High
8	9.00-14.00	Very high
9	>14.00	Phenomenal

1422

1423

1424 **8.1 Constraining Cyclone Winds**

1425 A location is impacted by damaging tropical cyclones (TCs) wind when is within the radius of
 1426 gale-force wind (17m/s, R_{17}). This wind threshold corresponds to a category 1 TC
 1427 ([http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-](http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/understanding/categories/#tropical-severity-and-categories)
 1428 [centre/understanding/categories/#tropical-severity-and-categories](http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/understanding/categories/#tropical-severity-and-categories)). Here, instead of
 1429 considering the radius at each individual time to determine if a location is impacted or not, R_{17} is
 1430 proxied as a probability density function (pdf) applicable for all tropical cyclones impacting the
 1431 GBR. This follows a two-step process:

1432 First, the available records of R_{17} for the seasons 2003 to 2024 from the BoM best-track data
 1433 (BoM, 2024) are collated and fitted to a lognormal distribution (Table S3). Second, we estimate
 1434 the likelihood for a TC event occurring at a location at distance “d” from the TC position by the
 1435 survival function $S(d)$ of the R_{17} distribution, this is:

1436
$$S(d) = 1 - cdf(d) \tag{eqn. S1}$$

1437 where $cdf(d)$ is the cumulative density function of the R_{17} pdf. The survivor function in this case
 1438 simply indicates the probability for R_{17} extending to a distance “d”.

1440 **S3 Table. Parameters of the lognormal distribution for the R_{17} —gale-force wind average radii values.**

Metric	μ	σ
R_{17}	$4.78 = \log(120)$	0.525

1441 Note: The logarithm value 120 (km) corresponds to the median value of R_{17} values.

1442 Second, we constrain position uncertainty. The position uncertainty is highly dependent on TC
 1443 intensity (Torn and Snyder, 2012). In this study, the estimated position uncertainty is taken to be
 1444 the same for all cyclones impacting the GBR. This value is 50-km and corresponds to the 95th
 1445 percentile value of the BoM’s best-track position uncertainty for the 2002/03-2021/2022
 1446 seasons at the times when a TC is a severe TC (\geq cat. 3). The position uncertainty provides the

1447 radius for a disc centred at the recorded TC position such that the actual TC centre is uniformly
1448 distributed within this disc; this disc is equivalent to a kernel density estimator function for the
1449 TC centre.

1450 By combining both elements, the probability of being within the R_{17} radius and considering the
1451 position uncertainty, the probability for site X to be impacted by a TC is, with centre at \mathbf{x}' , is:

$$1452 \quad P(\mathbf{X}|\mathbf{x}' \mp \Delta\mathbf{x}) = \frac{1}{A} \int_{\Omega} \mathcal{S}(d(\mathbf{X}, x)) dA$$

1453 eqn. S2

1454 In equation S2, Ω is the uncertainty disc with radius 50-km, $d(\mathbf{X}, x)$ is the distance between the
1455 site at X and each point within the uncertainty envelope, $\mathcal{S}(d)$ is as in eqn. S1. A is the solid
1456 angle of Ω , and dA the area differential.

1457 Based on eqn. S2, and a sample of N TCs, the expected number of times a location \mathbf{X} experiences
1458 gale force or stronger winds is:

$$1459 \quad \bar{N}_{\mathbf{X}} = \sum_{i=1}^N \sum_{t=1}^{T_i} P(\mathbf{X}|\mathbf{x}'_t \mp \Delta\mathbf{x}_t) \quad \text{eqn. S3}$$

1460

1461 The subindex t in eqn. S3 corresponds to individual positions along each TC track (linearly
1462 interpolated every hour from six hours), T_i the individual positions along the track, and P is the
1463 Probability as in eqn. S2. Equation S3 states that the expected number of times a location is
1464 impacted by a cyclone is given by the sum of individual probabilities for each cyclone along its
1465 track to impact said location.

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1472 9 S2 Appendix. Bottom current velocity calculations

1473 Here we have followed the approach of Callaghan et al. (2015) to derive the peak bottom
1474 current velocity (U_b). In summary, Callaghan et al. (2015) used relationships from linear theory
1475 (Airy, 1841) and assumed that the wave heights follow a Rayleigh distribution. The relation
1476 between U_b (bottom velocity), h_s (significant wave height), T_p (Peak wave period), and h (depth)
1477 is:

$$1478 \quad U_b \approx \frac{\pi H_{RMS}}{T_p \sinh(kh)}$$

1479 eqn. S6
1480 With H_{RMS} being

$$1481 \quad H_{RMS} \approx \frac{1}{1.4} h_s$$

1482 eqn. S7
1483 and k is the wavenumber satisfying the linear dispersion:

$$1484 \quad kh \tanh(kh) = \frac{4\pi^2}{g \times T_p^2} h$$

1485 eqn. S8
1486 In eqn. S8, $g=9.81 \text{ m s}^{-2}$ is the gravitational acceleration. Equation (S8) is solved iteratively for kh
1487 using a Newton-Raphson method and then used in (S8) to obtain U_b .

1488 The first guess for the Newton-Raphson iteration is $k_1 h = k_o h - k_o h \times \exp(-(k_o h)^{5/4})$ being

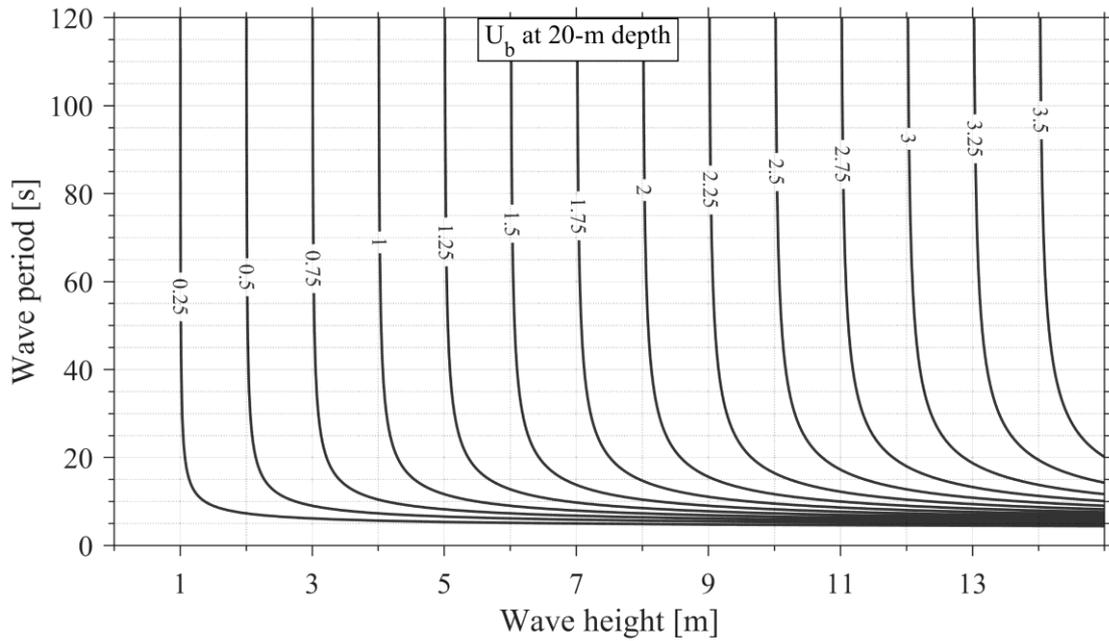
$$1489 \quad k_o h = \frac{4\pi}{g \times T_p^2} h$$

1490 Then iterate i from 1 to 5 initializing with the first guess in the next equation:

$$1491 \quad k_{i+1} h = k_i h - \frac{k_i h \times \tanh(k_i h) - k_o h}{\tanh(k_i h) + k_i h \times (1 - \tanh^2(k_i h))}$$

1492 The fifth iteration ($k_5 h$) has an error of about 10^{-8} .

1493



1494

1495 **S2 Fig. U_b for significant wave height and peak wave period for a 20-m depth.** U_b for significant wave
1496 height (horizontal axis) and peak wave period (vertical axis) at a depth of 20 meters.

1497 **9.1 References**

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1503

1504 **10 S3 Appendix. Shipping impacts calculations**

1505 Here it is assumed that the ship’s area of influence follows an exponential distribution
1506 depending on the distance d from the ship. Then, the probability of being within its area of
1507 influence is given by the survival function:

1508
$$S_s(d) = 1 - \text{cdf}(d) = e^{-d/\mu}$$

1509 eqn. S9
1510 where cdf is the cumulative density function for the exponential distribution, d is the distance
1511 between the ship and the reef and μ is the rate parameter of the exponential distribution, taken
1512 to be 0.5-kms. The exposure of a reef to shipping is calculated as the logarithm of the sum of
1513 each individual probability of ship impact. That is:

1514
$$\bar{N} = \log_{10}\left(\sum_{i=1}^B S_s(d_i)\right)$$

1515 eqn. S10
1516 where B is the number of ship positions reported in the period 2019-2021, d_i the distance
1517 between each ship position and each vertex of each reef polygon. Subsequently, the reef
1518 locations are placed in a 5x5km grid and the exposure map is presented in that grid. The
1519 exposure at each grid point is the sum of the exposures for each vertex in the grid point.

1520

1521

11 S4 Appendix. Reef Damage Driver and Index Figures.

1522

S4 Table. Metadata of drivers used in the vulnerability index.

Driving factor	Source	Resolution	Time period	Variable: units	Section
Coral Bleaching	United States National Oceanic and Atmospheric Administration Coral Reef Watch	0.05°x0.05°	April 1985- July 2024	Degree heating week: °C-week	2.1
Crown-of-thorns Seastars Outbreaks	Australian Institute of Marine Science	Manta tow surveys	1985-2024	average CoTS per manta tow	2.2
Significant wave height	Centre for Australian Weather and Climate Research Wave Hindcast	0.067°x0.067°	Jul 1985 to Jun 2024	Significant wave height: meters Exposure to rough seas: days	2.3
Bottom current velocity	Derived from significant wave height and bathymetry from Project 3DGBR: gbr100 High-resolution Bathymetry for the Great Barrier Reef and Coral Sea	0.067°x0.067°	Jul 1985 to Jun 2024	m/s Exposure to rubble mobilizing currents: days	2.4

Cyclone winds (gale-or stronger winds)	Bureau of Meteorology Australian Tropical Cyclone Database	0.05°x0.05°	Jul 1985 to Jun 2024	Exposure to cyclone winds: hours	2.6
Shipping	Australian Maritime Safety Authority	Meters	2019 to 2021	# of ships weighted by the inverse of their distance to each reef	2.7
Tsunamis	Geoscience Australia Probabilistic Tsunami Hazard Assessment	Individual points	Synthetic data	Maximum water level: meters	2.8

1523 Source, spatial resolution, time period, and units of drivers of reef damage constituting each layer of the

1524 Great Barrier Reef Vulnerability Index developed in this study.

1525

1526 **S5 Table. Areas within the NRM that have experienced DHW) ≥ 8 .**

Name	DHW<8 [pixels]	DHW ≥ 8 [pixels]	TOTAL [pixels]	DHW<8 [%]	DHW ≥ 8 [%]
Fitzroy	457	2527	2984	0.15	0.85
Mackay Whitsunday	447	1236	1683	0.27	0.73
Burnett Mary	4	1335	1339	0.00	1.00
Wet Tropics	123	936	1059	0.12	0.88
Burdekin	769	847	1616	0.48	0.52
Cape York	312	2868	3180	0.10	0.90

1527

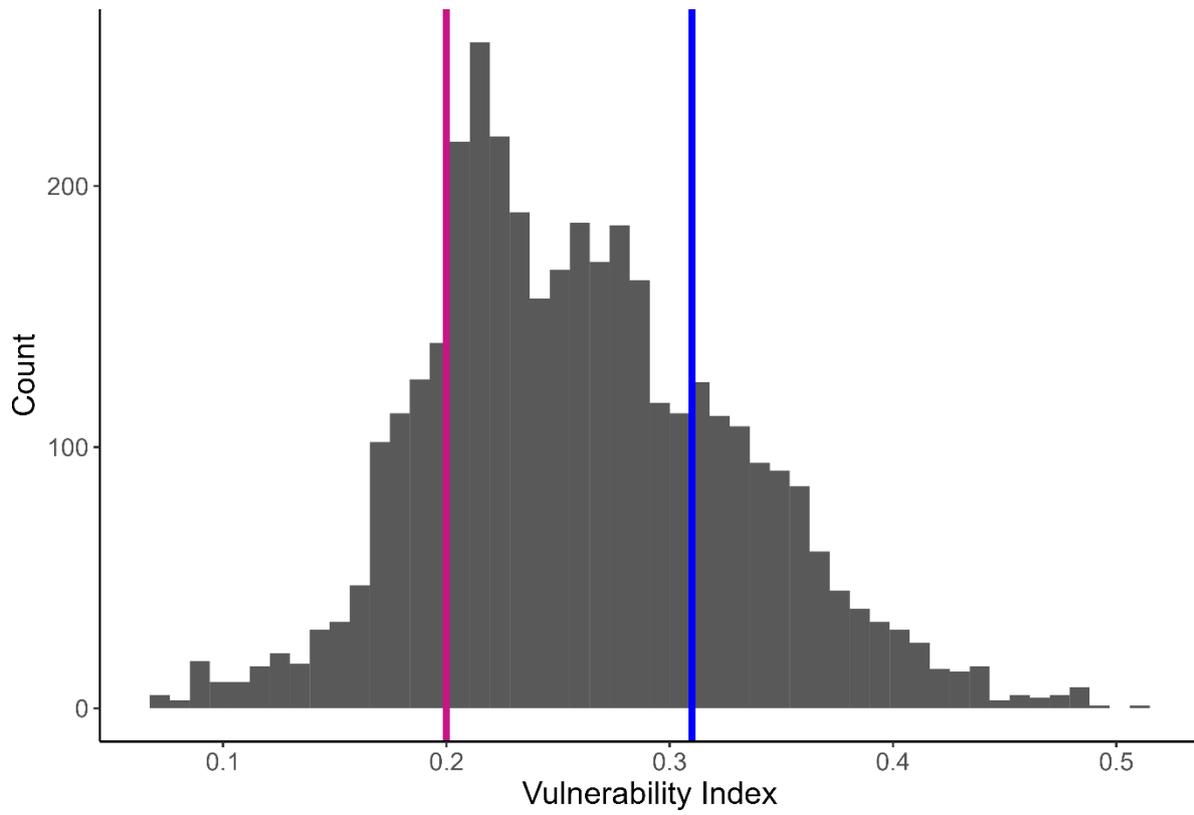
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1529

1530 **S3 Fig. Distribution of the crown-of-thorns seastar (CoTS) densities per reef.** Data from the Australian
 1531 Institute of Marine Science Long Term Monitoring Program mean CoTS per manta tow data per reef per
 1532 outbreak period: 1983-1984, 1985-1991, 1992-2009, and 2010-2024. The data before 1985 was not
 1533 included in the analysis. Lines represent thresholds for Severe Outbreak (> 1).

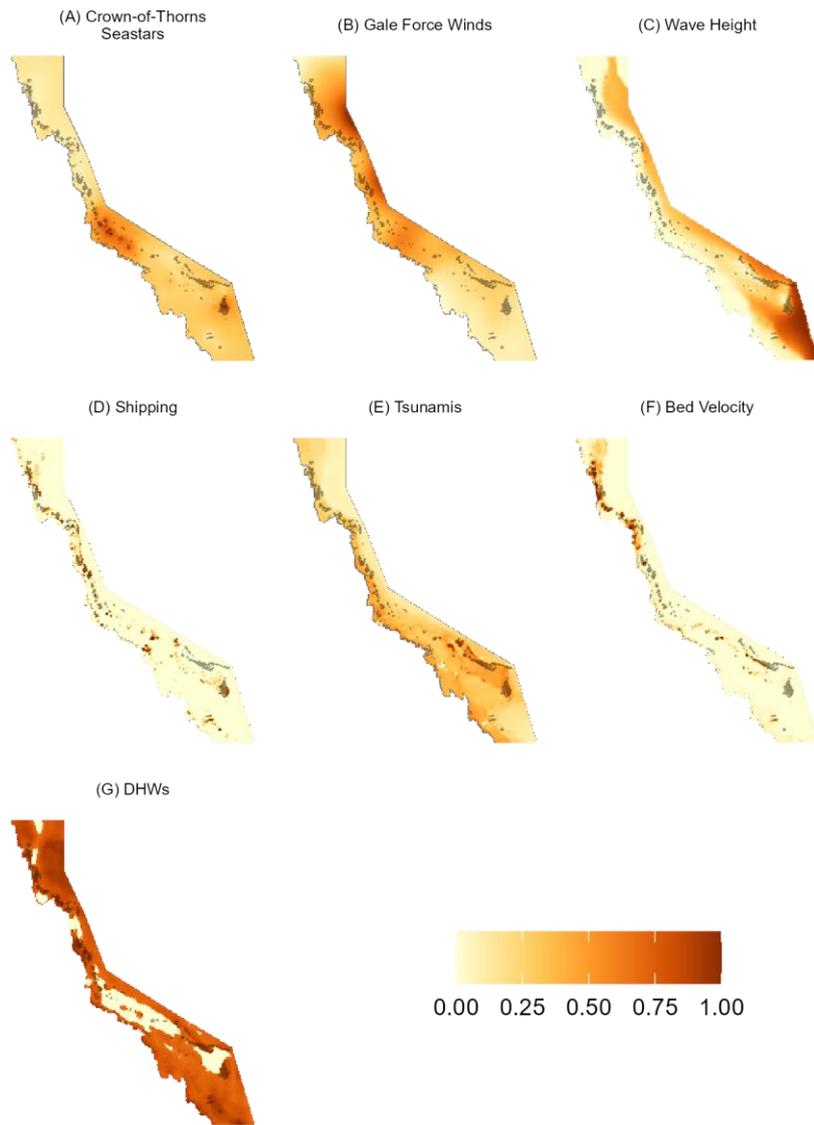
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1535

1536 **S4 Fig. Distribution of reef damage vulnerability index values.** Pink line indicate 25th percentile, 0.21,
1537 and blue line is the 75th percentile, 0.31, used as thresholds for low/moderate and moderate/high
1538 vulnerability.
1539

1540



1541

1542 **S5 Fig. High vulnerability areas for each driver.** High vulnerability (> 0.31) areas as polygons from the
 1543 final vulnerability index plotted on each of the individual 7 scaled (0-1) drivers combined into the final
 1544 index. (A) Cyclone waves, (B) Cyclone wind, (C) CoTS – crown-of-thorns seastars, (D) Shipping, (E) DHW –
 1545 degree heating weeks, (F) Tsunamis, and (G) Cyclone bed velocity.
 1546