

1 One Hundred and Fifty Years of Warming on Caribbean Coral Reefs

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9 **Abstract**

10 Anthropogenic climate change is rapidly altering the characteristics and dynamics of
11 biological communities. This is especially apparent in marine systems as the world's oceans
12 are warming at an unprecedented rate, causing dramatic changes to coastal marine
13 systems, especially on coral reefs of the Caribbean. We used three complementary ocean
14 temperature databases (HadISST, Pathfinder, and OISST) to quantify change in thermal
15 characteristics of Caribbean coral reefs over the last 150 years (1871–2020). These sea
16 surface temperature (SST) databases included combined *in situ* and satellite-derived SST
17 (HadISST, OISST), as well as satellite-only observations (Pathfinder) at multiple spatial
18 resolutions. We also compiled a Caribbean coral reef database identifying 5,326 unique
19 reefs across the region. We found that Caribbean reefs have warmed on average by 0.20 °C
20 per decade since 1987, the calculated year that rapid warming began on Caribbean reefs.
21 Further, geographic variation in warming rates ranged from 0.17 °C per decade on
22 Bahamian reefs to 0.26 °C per decade on reefs within the Southern and Eastern Caribbean
23 ecoregions. If this linear rate of warming continues, these already threatened ecosystems
24 would warm by an *additional* 1.6 °C on average by 2100. We also found that marine
25 heatwave (MHW) events are increasing in both frequency and duration across the
26 Caribbean. Caribbean coral reefs now experience on average 5 MHW events annually,
27 compared to 1 per year in the early 1980s. Combined, these changes have caused a
28 dramatic shift in the composition and function of Caribbean coral reef ecosystems. If reefs
29 continue to warm at this rate, we are likely to lose even the remnant Caribbean coral reef
30 communities of today in the coming decades.

31 **Introduction**

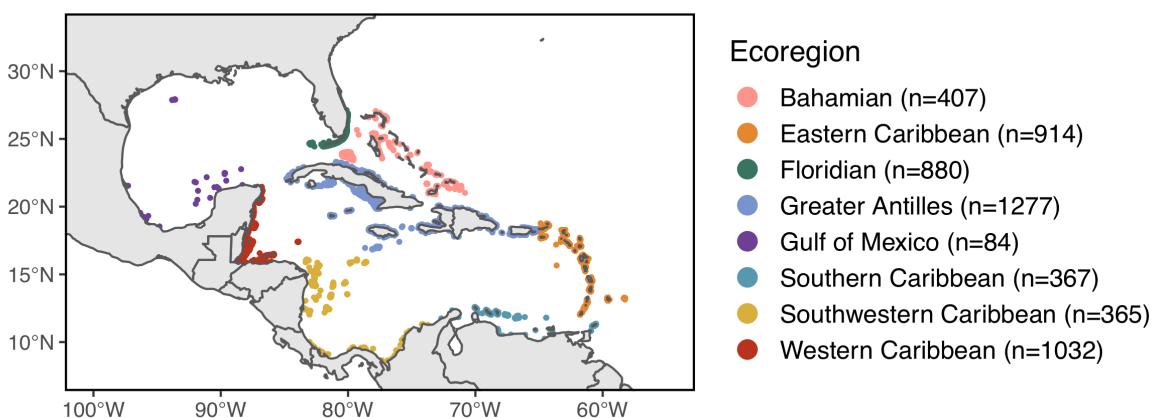
32 Greenhouse gas emissions are warming the planet, intensifying disturbances (e.g., fires and
33 cyclonic storms), and modifying countless other aspects of the environment. This is causing
34 extinctions, altering species composition, and degrading nearly every ecosystem on earth.
35 Although we tend to think of surface warming as a terrestrial phenomenon, the oceans have
36 stored about 93% of the additional retained heat since 1955 ^{1,2}. The impacts of warming on
37 marine communities are widespread, affecting a large range of taxa ³. Most marine species
38 are ectothermic, so their body temperature matches that of the surrounding seawater.
39 Therefore, warming increases their metabolism and subsequently their caloric demands,
40 growth rates, behaviors, etc ^{4,5}. This in turn has widespread effects on species interactions
41 and the structure of marine food webs ⁶. Ocean heating has also been linked to disease
42 outbreaks, the loss of foundation species that provide habitat structure (e.g., corals and
43 kelps), reductions in primary production, and many other changes ⁷. The recent National
44 Climate Assessment ⁸ described the well-documented effects of ocean warming as
45 “ecosystem disruption” and concluded it will “intensify as ocean warming, acidification,
46 deoxygenation, and other aspects of climate change increase.”

47 Warming episodes are driving unprecedented changes in coral reef ecosystem
48 function and biodiversity globally ^{9–11}. These changes on coral reefs are particularly evident
49 on Caribbean reefs that have already experienced dramatic ecological shifts over the past
50 several decades ^{12,13}. Increasing SST on coral reefs has been associated with many
51 negative ecological consequences, including coral bleaching ¹⁴, higher disease prevalence
52 ¹⁵, increased mortality ¹⁶, and overall reductions in metabolic processes across marine taxa
53 ^{17,18}. While ocean warming is a global phenomenon, differences in the rate of warming can
54 be highly localized ¹⁹, emphasizing the need to understand the thermal histories of the
55 ecosystems most vulnerable to projected ocean warming.

56 The purpose of this study was to quantify the long-term (150 year) spatiotemporal
57 trends in ocean temperature across the Greater Caribbean, and specifically on Caribbean
58 coral reefs. We compiled three open-access sea surface temperature (SST) datasets

59 (HadISST, Pathfinder SST, and OISST) for all mapped coral reef locations across the
60 Greater Caribbean (**Figure 1**). Numerous previous studies have documented the
61 anthropogenic heating of the ocean generally^{2,20}, and of coral reefs in particular^{19,21}. Our
62 study builds on this work by focusing on coral reefs of the Greater Caribbean, updating the
63 analysis through 2020, and by adding an assessment of coral reef marine heatwaves to the
64 standard focus on spatiotemporal trends temperature.

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66

67 **Figure 1. Caribbean coral reef site locations and ecoregion designation.** The colour of
68 each reef represents the designated ecoregion and n denotes the number of unique reef
69 locations within that ecoregion.

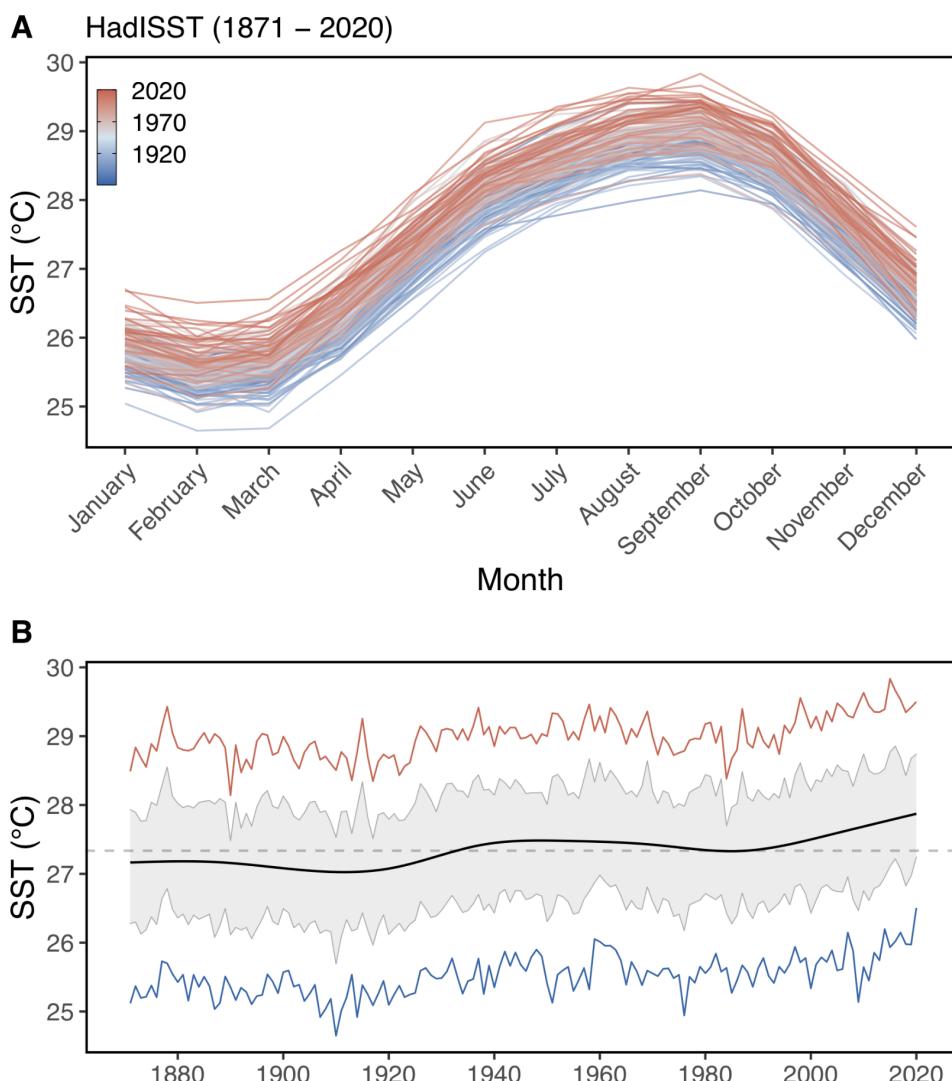
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71 **Results and Discussion**

72 Our results indicate that Caribbean coral reefs continue to warm and that warming over the
73 last 150 years was apparent every month (**Figure 2A**). In fact, recent spring temperatures
74 often meet or exceed annual highs (typically in September) observed in the late 19th
75 century. Caribbean reef surface temperatures were relatively stable in the mid 20th century
76 (due to volcanic activity²²), then warming increased around 1987 (**Figures 2B**;
77 **Supplementary Figure 1**). This timing is similar to long-term records of global ocean
78 surface temperature and ocean heat content²³ (**Figure 2B**). We found that the average

79 linear warming rate for the Caribbean reefs over the last 30 years (1987–2020; HadISST
80 database) was 0.16 °C per decade (**Figure 2; Table 1**). Based on satellite data alone
81 (**Supplementary Figures 2 and 3**; Pathfinder database), the average coral reef warming
82 rate during this period was 0.20 °C per decade (**Table 1**). At this rate, the mean temperature
83 on Caribbean reefs would be roughly 1.6 °C higher by 2100 assuming continued linear
84 warming — and that is in addition to already realized warming.

85



86

87 **Figure 2. Historic SST trend on Caribbean coral reefs (1871–2020).** Long-term SST
88 records (HadISST) on Caribbean coral reefs depicting **A**) mean monthly SST each year

89 (represented by line colour: blue to red) and **B**) GAM smoothed annual mean SST time
90 (black line), annual maximum (red line), and annual minimum (blue line) SST. The grey
91 dashed horizontal line denotes the overall mean SST for all sites over the entire period (27.3
92 °C) and the grey ribbon represents the 95% confidence interval around the annual mean
93 SST through time.

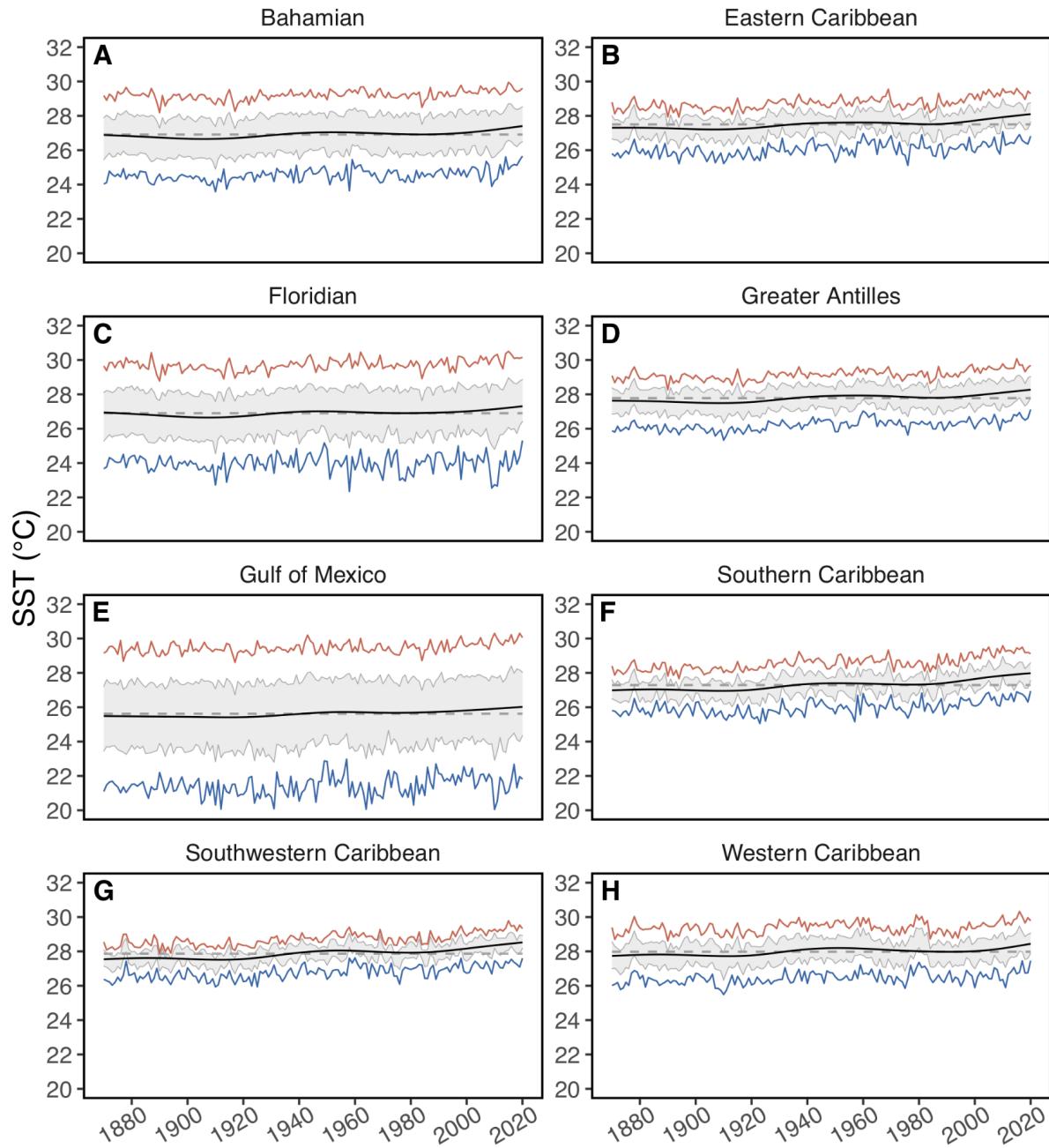
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95 The observed warming rates of Caribbean coral reefs in this and previous studies
96 report similar values, however, these rates are somewhat greater than estimates for the
97 global ocean surface (**Table 2**). Winter et al. ²¹ reported a warming rate of about 0.25 °C per
98 decade for the reef off La Parguera, southwestern Puerto Rico (1966–1995). Similarly,
99 Hoegh-Guldberg ²⁴ found the warming rate was 0.23 °C per decade (1981–1999) off the
100 south coast of Jamaica. Kuffner et al. ²⁵ described a remarkable temperature record
101 collected by lighthouse keepers for five coral reefs off the Florida Keys starting in 1878 that
102 also observed SST warming at 0.25 °C per decade between 1975 and 2006. It is reassuring
103 (if surprising) that studies of vastly different scales and based on disparate methods,
104 including *in situ* measurements (e.g., filling a bucket with seawater then measuring
105 temperature by hand with a thermometer) ²¹, remote sensing via satellite ¹⁹, and databases
106 based on both (this study) report similar warming rates. Moreover, Caribbean reef warming
107 rates are approaching the CMIP5 RCP 8.5 model prediction of about 0.3 °C per decade ²⁶.
108 This “business as usual” emissions model is now viewed by many climate scientists as
109 “unlikely”, especially for the end of this century. Yet, our results and previous work suggest
110 that Caribbean coral reefs are already warming far more quickly than scenarios considered
111 more likely (e.g., RCP 4.5).

112 We compared long-term coral reef temperature trends among eight previously-
113 defined ecoregions within the Caribbean ²⁷. Our results indicate that reefs within all
114 ecoregions have clearly warmed since 1871 (**Figures 3; Supplementary Figure 4**), albeit at
115 somewhat different rates. Our inflection point analysis determined that the initial year of rapid

116 warming also varied among ecoregions. For example, rapid warming was identified in the
117 Gulf of Mexico and Southern Caribbean starting in 1981, while rapid warming was not
118 detected until 1999 in the Western Caribbean (**Figures 3; Supplementary Figure 4;**
119 **Supplementary Table 2**). So, although the Western Caribbean began warming much later,
120 recently it has warmed at a substantially higher rate of 0.24 °C per decade. Since recent
121 rapid warming began in each region, warming rates ranged from about 0.17 °C per decade
122 on Bahamian reefs to 0.26 °C per decade on reefs in the Southern and Eastern Caribbean
123 (**Figure 3; Supplementary Table 2**). Overall, these warming rates translate to an increase
124 in annual coral reef temperatures between 0.53 and 0.99 °C over the last 30 years.

125 Subregional patterns of warming across the Caribbean calculated here are similar to
126 other SST parameters used for assessing thermal risk on coral reefs, such as degree
127 heating weeks (accumulation of temperature anomalies exceeding the monthly maximum
128 mean SST¹⁶; DHW). Ecoregions within the Caribbean with faster rates of warming (e.g.,
129 Southern and Eastern Caribbean [mean 0.26 °C per decade], **Supplementary Table 2**)
130 have also been reported to have some of the highest occurrences of weekly SST anomalies
131²⁸, maximum DHWs¹⁶, and coral bleaching or mortality risk events²⁹. The variability in
132 warming parameters across Caribbean ecoregions is likely a significant contributor to
133 differences in coral cover among these regions since the mid 1990s³⁰.



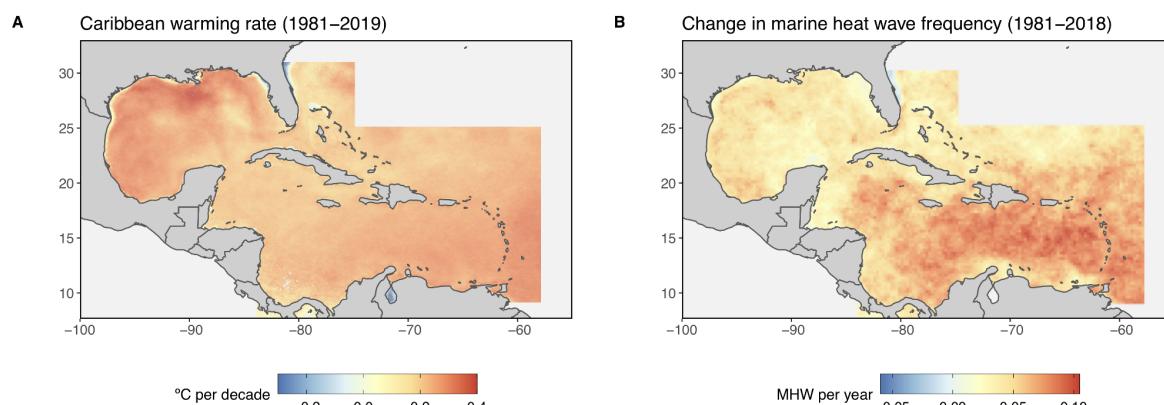
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135 **Figure 3. Historic SST trends on coral reefs within ecoregions (1871–2020).** Long-term
136 SST records (HadISST) on Caribbean coral reefs separated by ecoregion depicting GAM
137 smoothed annual mean SST time (black line), annual maximum (red line), and annual
138 minimum (blue line) SST. The grey dashed horizontal line denotes the mean SST over the
139 entire period and the grey ribbon represents the 95% confidence interval around the true
140 annual SST mean for each ecoregion.

141 While increasing SST on Caribbean coral reefs is clearly a major concern, warming is
142 not limited to reef locations. Sea surface temperatures are rising across the entire Caribbean
143 basin at a mean rate of 0.04 °C per decade since 1871 (HadISST data; **Supplementary**
144 **Figure 6**) and more rapidly since 1981 at 0.23 °C per decade (Pathfinder SST data; **Figure**
145 **4A; Supplementary Figure 6**). This recent rate of ocean warming (0.23 °C per decade from
146 1981–2019) is similar to those previously calculated for the Caribbean basin. For example,
147 Chollett et al. ¹⁹ reported a rate for the entire Caribbean and southeastern Gulf of Mexico of
148 0.27 °C per decade (1985–2009). It is clear that the Caribbean basin is experiencing rapid
149 warming (**Figure 2B, 3, 4A; Supplementary Figures 6, and 7**). Additionally, rapid increases
150 in ocean heat content across the region has been apparent ³¹, driving increases in other
151 severe events such as increased storm activity and marine heatwaves (MHWs).

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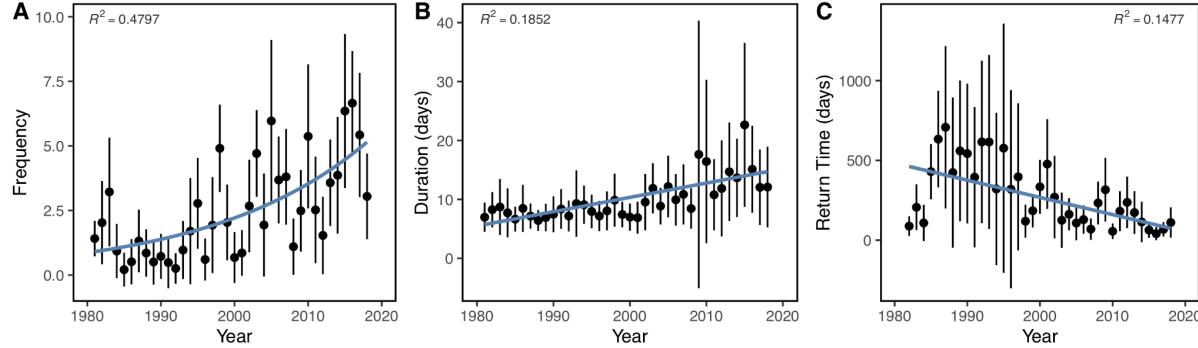


155 **Figure 4. Warming patterns throughout the Caribbean Sea.** Increasing warming events
156 across the Caribbean depicted through **A**) rate of SST change (°C per decade) from 1981 to
157 2019 (Pathfinder; mean slope 0.23 ± 0.07 °C per decade) and **B**) increasing marine
158 heatwave events (slope of counts per year). Grey ocean area was not included in these
159 analyses.

160

161 We complemented our analyses of increasing Caribbean SST with an assessment of
162 changes in marine heatwaves on Caribbean coral reefs. Marine heatwaves (MHW) are
163 discrete warming events characterized by rate of onset, duration of event (five days or
164 longer), and the intensity of warming ³². Over the past several decades, MHW have
165 increased in both frequency and duration globally ³³. Likewise, we found that heatwaves are
166 occurring more frequently across the entire Caribbean basin (**Figure 4B; Supplementary**
167 **Figure 5**) and on Caribbean coral reefs (**Figure 5A; Supplementary Tables 3 and 4**). The
168 average frequency of MHW events on Caribbean coral reefs has increased from about 1 per
169 year in the 1980s to almost 5 per year in the 2010s (**Figure 5A; Supplementary Table 4**),
170 with current events lasting on average about 14 days each (**Figure 5B; Supplementary**
171 **Table 4**). Additionally, the decadal mean return time (number of days elapsed since the last
172 MHW event) has steadily declined from 377 days in the 1980s to just 111 days in the 2010s
173 (**Figure 5C; Supplementary Table 4**), suggesting that Caribbean reef organisms and
174 communities have approximately one third the time to recover from such thermal events.

175



176
177 **Figure 5. MHW trends (1981–2018) across Caribbean coral reefs.** Temperature data are
178 based on OISST gridded data to determine **A**) marine heat wave (MHW) frequency (number
179 events per year) with Nagelkerke pseudo R^2 ; **B**) MHW duration (number days per event) with
180 linear model R^2 ; and **C**) return time (number days per event) since the previous MHW event
181 with linear model R^2 reported. Points denote annual mean values (\pm SD) and blue lines
182 represent linear (lm or glm) trends.

183

184 MHW trends are fairly consistent across Caribbean ecoregions (**Supplementary**
185 **Figure 8**), however, coral reefs within the Eastern Caribbean are experiencing the greatest
186 increase in MHW duration compared to the 1980s (**Supplementary Figure 8**;
187 **Supplementary Table 4**), while the change in frequency of MHWs was the lowest on
188 Western Caribbean reefs (**Supplementary Figure 8**; **Supplementary Table 4**). Such
189 variations in MHW events across ecoregions further highlights differences in subregional
190 warming patterns that impact the future success of coral reefs on both regional and local
191 scales.

192 These acute MHW events, often lasting days to weeks, are believed to be the
193 primary cause of mass-coral mortality across the Caribbean. In fact, a recent study
194 demonstrated a positive correlation between MHW duration and the frequency of coral
195 bleaching across the Caribbean and Gulf of Mexico ³⁴. However, these severe heating
196 events are often missed with current coral bleaching monitoring in place, such as DHWs,
197 because of the cumulative nature of these alert systems ^{35,36}. Even with longer MHW events
198 being detected through these traditional coral bleaching monitoring systems, the ecological
199 impact MHWs have on coral reef ecosystems are distinct. MHWs are known to trigger rapid
200 bleaching and mass coral mortality on reefs that impact species with all levels of thermal
201 tolerance and on highly localized spatial scales ^{36,37}.

202

203 **Conclusions**

204 The remarkable collapse of Caribbean coral reef ecosystems began when ocean
205 heating in the region accelerated ~30 years ago. Not only has warming been the primary
206 driver of widespread coral mortality, but it has indirectly (via habitat loss) likely affected
207 countless non-coral reef inhabitants when their own thermal tolerances were exceeded ^{38–41}.
208 And yet, this ecosystem transformation was caused by a mere 1 °C of warming (or
209 substantially less in some ecoregions). This fact strongly suggests that we will lose what little

210 remains in the coming years and decades if the anthropogenic heating of the Caribbean sea
211 continues at this rate ⁴². Another 0.6 or 1.6 °C of warming (which based on our current
212 warming rates would occur mid- and end-of-century, respectively) is likely a best case
213 scenario at this point since oceans will continue to absorb excess heat even if global carbon
214 neutrality goals are met. Despite the uncertainties of future ocean warming patterns, it is
215 clear that the last 150 years of warming on Caribbean coral reefs have drastically altered
216 these ecosystems and it will take significant global efforts to prevent the total loss of these
217 remaining coral reefs.

218

219 **Methods**

220 *Reef Locations*

221 We compiled a Caribbean coral reef location database by sourcing latitude and longitude
222 coordinates for known coral reef locations from the following sources: UNEP World
223 Conservation Monitoring Center ⁴³, the Global Coral Reef Monitoring Program ⁴⁴, the Atlantic
224 and Gulf Rapid Reef Assessment (AGRRA) ⁴⁵, Reef Check (reefcheck.org), Florida's Coral
225 Reef Evaluation and Monitoring Program (CREMP) ⁴⁶, the US Virgin Islands Territorial Coral
226 Reef Monitoring Program (TCRMP) ⁴⁷, and previously published survey data for the region
227 ³⁰. Sites were considered duplicates if they had the same GPS coordinates. In total, we
228 identified 5,326 unique reefs across the Caribbean basin that were assigned to ecoregions
229 based on the World Wildlife Fund (WWF) marine ecoregion classifications ²⁷. Ecoregions
230 contained between 84 (Gulf of Mexico) and 1,277 (Greater Antilles) reef locations (**Figure 1**).
231 This database was used to assess SST and MWH trends across Caribbean coral reefs.

232

233 *Sea Surface Temperature Datasets*

234 Our characterization of the thermal history of the Caribbean was based on three
235 complementary ocean temperature datasets: HadISST from the United Kingdom Met Office
236 ⁴⁸, the Pathfinder satellite temperature records from NOAA/NASA ⁴⁹⁻⁵¹, and NOAA's daily

237 Optimum Interpolation Sea Surface Temperature (OISST)⁵². We combined the HadISST
238 and Pathfinder databases to assess both long-term and high-resolution SST trends across
239 the Caribbean and solely on coral reefs. Additionally, we used the OISST database to
240 identify and assess marine heatwave (MHW) events.

241 We obtained monthly SST from 1871 to 2020 from the HadISST dataset^{53,54} at a
242 resolution of 1° grids across the Caribbean (0°N–40°N; 100°W–55°W). The HadISST data
243 are based on a combination of temperature reconstruction and observational data to
244 produce a long-term record of *in situ* measurements (typically from ships and buoys) and
245 satellite-derived temperatures. HadISST uses *in situ* SST data from the Met Office Marine
246 Data Bank (MDB) and is supplemented with data from the Comprehensive Ocean-
247 Atmospheric Data Set (ICOADS) when missing from the MDB between the years 1871 and
248 1995. Satellite SST data from the Global Telecommunications System are included in the
249 HadISST dataset after 1982, making this database ideal for long-term SST assessments
250^{54,55}.

251 Additionally, we calculated monthly mean SST at 4 km resolution from September
252 1981 to December 2019 using the twice daily (night and day) Pathfinder Version 5.3
253 database^{49,50}. Pathfinder SST data were clipped to the wider Caribbean constraints and
254 quality filtered (quality four or greater^{50,51}) before the mean monthly SST value was
255 calculated per grid cell and concatenated into a single netCDF file. The Pathfinder database
256 is derived from measurements made by the Advanced Very High Resolution Radiometer
257 (AVHRR) instruments aboard NOAA's polar orbiting satellites that combine multiple passes
258 of data. These data were provided by GHRSST and the NOAA National Centers for
259 Environmental Information.

260 We used NOAA's AVHRR 0.25° daily OISST data to determine sea surface
261 temperature climatology and detect MHW events across the Caribbean basin from 1982 to
262 2018^{52,56}. OISST data are constructed by combining both *in situ* (collected via ships and
263 buoys) and infrared satellite (AVHRR instruments) SST, applying a bias adjustment to
264 satellite and ship observation data, and filling gaps as necessary through interpolation. The

265 combination of high resolution and multiple sources of SST observations is ideal for
266 identifying MHWs, and is frequently used for such assessments^{32,57}.

267

268 *Historic SST Assessment*

269 We examined the rate of SST change through time for the wider Caribbean region using the
270 HADISST (1871–2020) and Pathfinder (1981–2019) databases (described above) to
271 evaluate historic SST trends. A simple linear model was applied to each grid cell through
272 time (months each year) of both datasets to calculate the slope and significance of SST
273 increases over time for the full region. Additionally, we extracted SST from the HADISST and
274 Pathfinder datasets using a compiled Caribbean coral reef location database (*raster*
275 package; version 2.9-23⁵⁸). The use of satellite-derived SST measurements to represent
276 benthic temperature patterns has been frequently assessed via comparisons of different
277 databases with *in situ* logger measurements at the same locations. While these studies
278 report that satellite-derived measurements often underestimate *in situ* temperatures^{59,60}, the
279 consensus is that satellite databases accurately reflect temperature conditions on many
280 coral reefs at depth^{60–62} and are a useful tool for identifying global warming signals⁵³.
281 Monthly SST measurements were averaged across all reef locations to assess historic SST
282 trends on Caribbean coral reefs per sampling period (month) as well as within individual
283 ecoregions. We assessed annual SST on coral reefs since 1871 using a generalized
284 additive model (GAM) with a cubic regression spline for year and a cyclic cubic regression
285 spline for month to smooth temperature variability through time for better assessment of
286 temporal SST trends on reefs. We then identified the year in which annual warming rates
287 significantly increased based on the first derivative of the GAM curve for the entire region as
288 well as each ecoregion⁶³. These years were used to calculate the mean warming rate since
289 the identified inflection points for coral reefs within the eight ecoregions. All analyses and
290 visualizations were conducted using R version 3.6.1⁶⁴.

291

292 *Marine Heatwaves Classification*

293 Marine heatwaves (MHW) are defined as anomalously warm sea-surface temperature
294 events, with temperatures warmer than historical climatology for that specific time and
295 location, lasting for at least a 5 day period ³². We used NOAA's OISST data (described
296 above) to identify and assess MHWs across the wider Caribbean from 1982–2018 ⁶⁵. If
297 successive events had less than two days between them, they were considered to be the
298 same event. We used the *heatwaveR* package in R (version 0.4.4) ⁶⁶ and code provided
299 from the marine heatwave working group (www.marineheatwaves.org) to identify marine
300 heatwave events from our OISST dataset and calculate heatwave metrics (**Supplementary**
301 **Table 1**).

302 For each pixel, we aggregated a list of distinct MHW events between 1982 and 2018,
303 which included the start and end date of the event (see **Supplementary Table 1** for all MHW
304 properties obtained). We calculated frequency of events per pixel by summing the total
305 number of MHW events per year and the total number of MHW days as the sum of the
306 duration of all events that year. Return time was calculated as the number of days elapsed
307 between each unique MHW event. All other metrics were averaged annually.

308

309 *Caribbean Marine Heatwave Trends*

310 To evaluate MHW trends across the Caribbean basin, we created an annual time series for
311 each MHW pixel that contains the number of distinct MHW events, total number of MHW
312 days experienced, the average maximum (peak) intensity (°C) for all events that year, the
313 average duration (days) of all events that year, the average onset rate for all events that year
314 (°C per day), and the average time elapsed since a previous event (days). We then
315 calculated a history of MHW events for each coral reef location using a nearest neighbor
316 analysis to match reef locations to MHW events identified from the OISST grids.

317 We quantified the temporal trends for each MHW metric using ordinary least squares
318 (OLS) models, except for event frequency and total number of MHW days, as these

319 variables are count data and best analyzed using generalized linear models (GLM) (*lme4*;
320 version 1.1-23)⁶⁷. The response variables for OLS models were log transformed to meet
321 model assumptions when necessary. For MHW trends on coral reefs, the level of
322 observation was each unique MHW pixel that overlapped coral reef habitat and we modeled
323 trends for each ecoregion to account for potential spatial differences in MHW metrics across
324 the Caribbean basin. Significance and R^2 values are obtained to evaluate the strength of
325 each trend. For GLM trends, we report the Nagelkerke pseudo R^2 value.

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335

336 **Data Accessibility:** HadISST data can be accessed at
337 www.metoffice.gov.uk/hadobs/hadisst/, Pathfinder data can be accessed at
338 www.ncei.noaa.gov/data/oceans/pathfinder/Version5.3/L3C/, and OISST data can be
339 accessed at www.ncdc.noaa.gov/oisst/data-access. All data and code compiled for this
340 manuscript can be freely accessed on GitHub (github.com/seabove7/CaribbeanSST) and
341 Zenodo (DOI: 10.5281/zenodo.4751658), including links to the compiled databases used here
342 from the three sources listed above.

343

344 **Author Contributions:** All authors conceived the idea and contributed intellectually to its
345 development. CBB led the SST analyses and LM led the MHW analyses. CBB and JFB led
346 the manuscript preparation with contributions from LM.

347

348 **Competing Interests statement:** The authors declare no conflicts of interest.

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531 **Figure Captions**

532 **Figure 1. Caribbean coral reef site locations and ecoregion designation.** The colour of
533 each reef represents the designated ecoregion and n denotes the number of unique reef
534 locations within that ecoregion.

535

536 **Figure 2. Historic SST trend on Caribbean coral reefs (1871–2020).** Long-term SST
537 records (HadISST) on Caribbean coral reefs depicting **A**) mean monthly SST each year
538 (represented by line colour: blue to red) and **B**) GAM smoothed annual mean SST time
539 (black line), annual maximum (red line), and annual minimum (blue line) SST. The grey
540 dashed horizontal line denotes the overall mean SST for all sites over the entire period (27.3
541 °C) and the grey ribbon represents the 95% confidence interval around the annual mean
542 SST through time.

543

544 **Figure 3. Historic SST trends on coral reefs within ecoregions (1871–2020).** Long-term
545 SST records (HadISST) on Caribbean coral reefs separated by ecoregion depicting GAM
546 smoothed annual mean SST time (black line), annual maximum (red line), and annual
547 minimum (blue line) SST. The grey dashed horizontal line denotes the mean SST over the
548 entire period and the grey ribbon represents the 95% confidence interval around the true
549 annual SST mean for each ecoregion.

550

551 **Figure 4. Warming patterns throughout the Caribbean Sea.** Increasing warming events
552 across the Caribbean depicted through **A**) rate of SST change (°C per decade) from 1981 to
553 2019 (Pathfinder; mean slope 0.23 ± 0.07 °C per decade) and **B**) increasing marine

554

555 **Figure 5. MHW trends (1981–2018) across Caribbean coral reefs.** Temperature data are
556 based on OISST gridded data to determine **A**) marine heat wave (MHW) frequency (number

557 events per year) with Nagelkerke pseudo R^2 ; **B)** MHW duration (number days per event) with
558 linear model R^2 ; and **C)** return time (number days per event) since the previous MHW event
559 with linear model R^2 reported. Points denote annual mean values ($\pm SD$) and blue lines
560 represent linear (lm or glm) trends.

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567 **Tables**

568 **Table 1.** Estimated warming rates from both HadISST and Pathfinder databases for different
569 temporal ranges. Values are means of all 5,326 reef locations included in the study. The
570 year 1987 was estimated as the beginning of the most recent period of warming across all
571 Caribbean coral reefs (see **Supplementary Figure 1**).

Temperature parameter	HadISST (1871–2020)	HadISST (1981–2020)	HadISST (1987–2020)	Pathfinder (1981–2019)	Pathfinder (1987–2019)
Caribbean Basin (°C per decade)	0.04	0.17	0.18	0.23	NA
Caribbean Basin (total °C for period)	0.60	0.68	0.61	0.90	NA
Caribbean Reefs (°C per decade)	0.04	0.15	0.16	0.19	0.20
Caribbean Reefs (total °C for period)	0.60	0.60	0.54	0.74	0.66

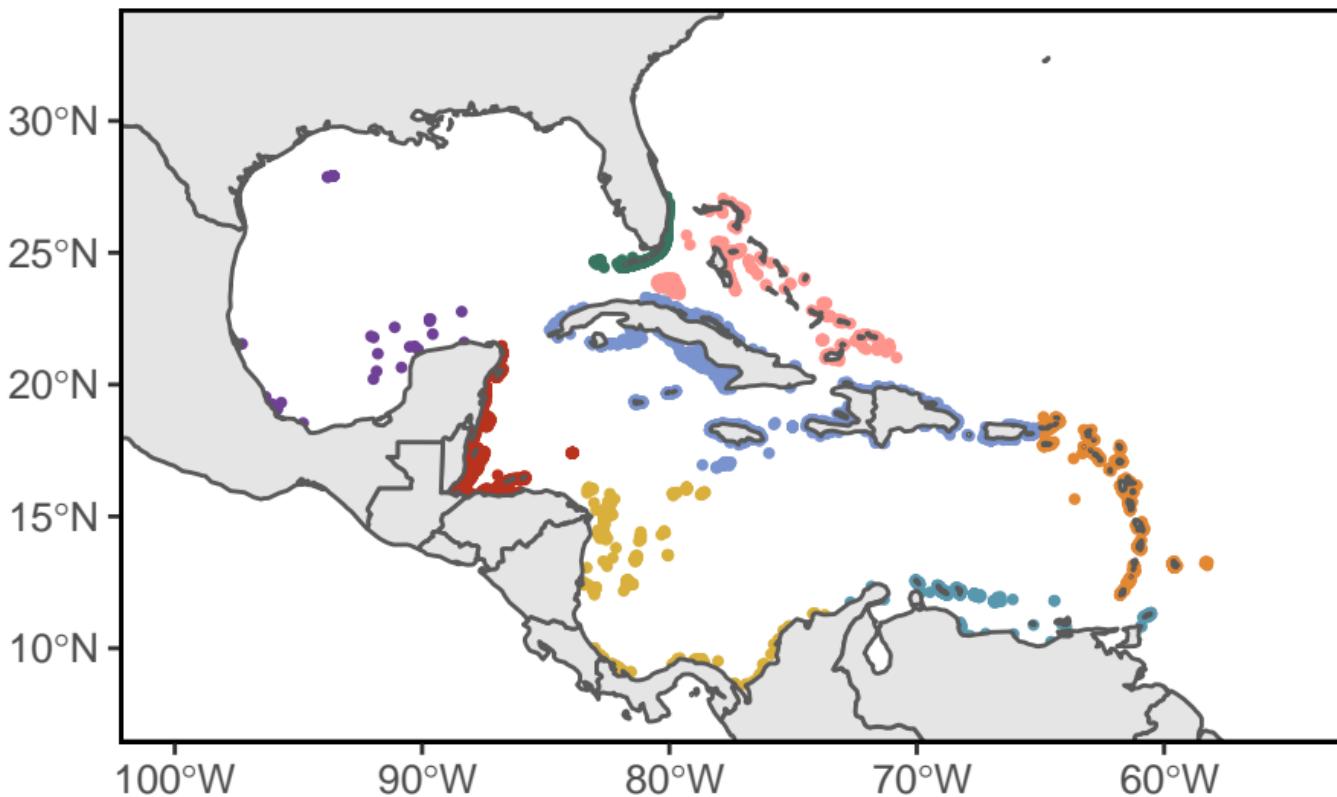
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574 **Table 2.** Published reports of global ocean surface warming rates.

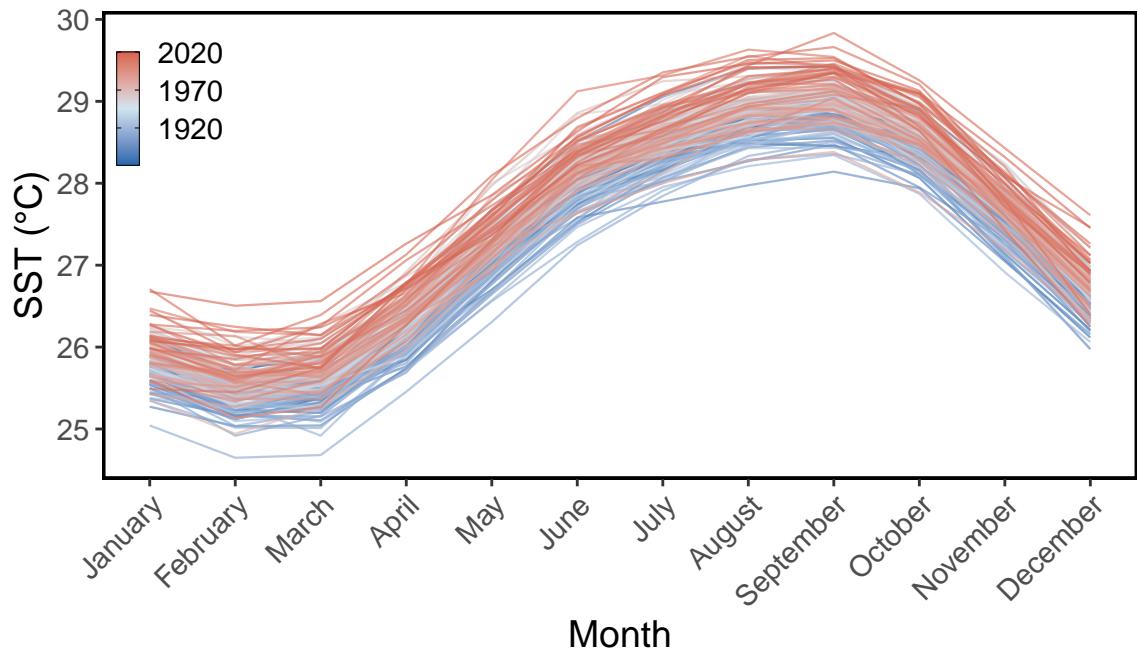
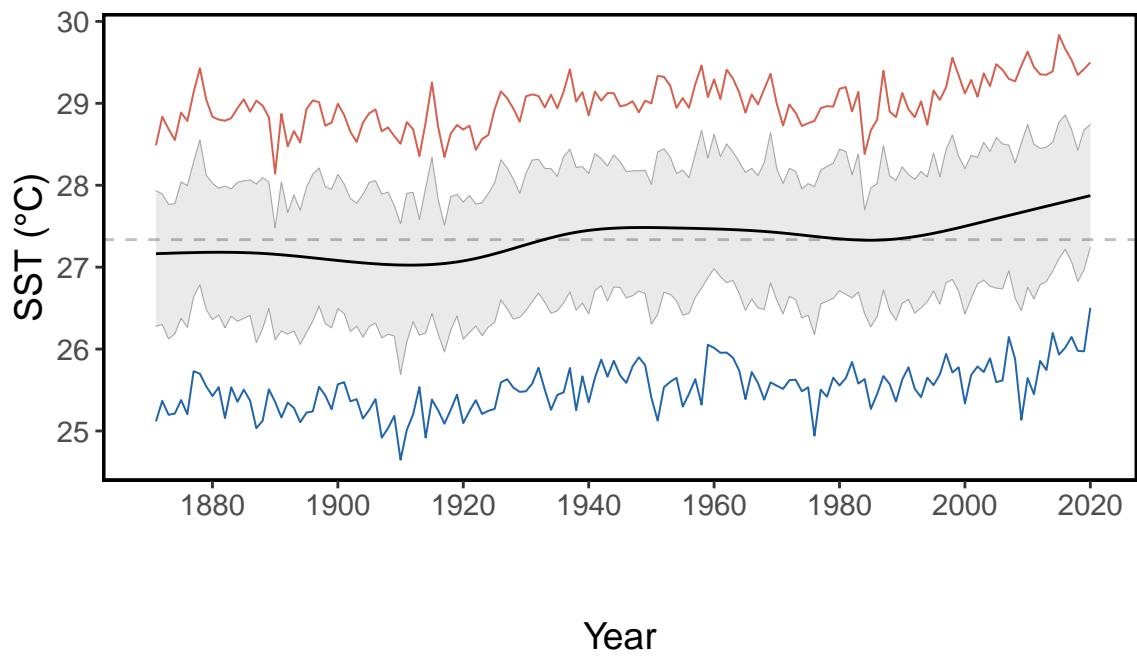
Study	°C per decade	Years
Casey and Cornillon 2001 ⁶⁸	0.14	1960–1990
Lawrence et al. 2004 ⁶⁹	0.09 and 0.13	1985–2000
Good et al. 2007 ⁷⁰	0.17	1985–2004
Burrows et al. 2011 ⁷¹	0.07	1960–2009
USGCRP 2017 ⁷²	0.15	1900–2016

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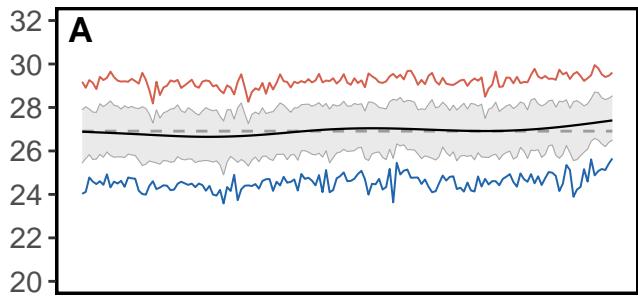


Ecoregion

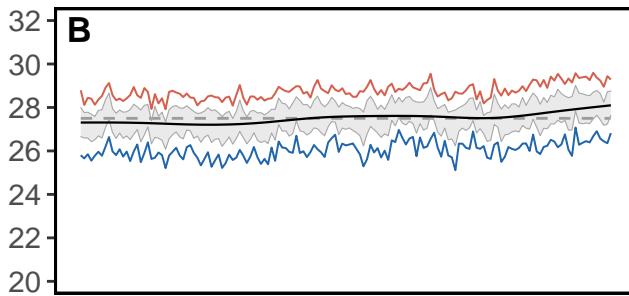
- Bahamian (n=407)
- Eastern Caribbean (n=914)
- Floridian (n=880)
- Greater Antilles (n=1277)
- Gulf of Mexico (n=84)
- Southern Caribbean (n=367)
- Southwestern Caribbean (n=365)
- Western Caribbean (n=1032)

A HadISST (1871...2020)**B**

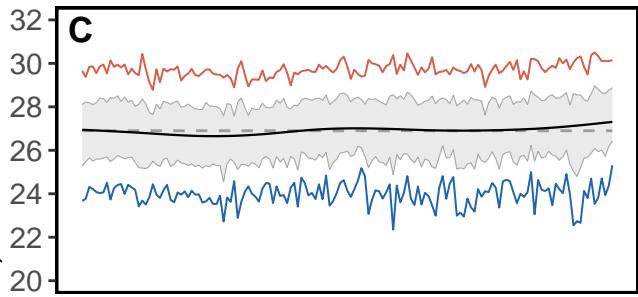
Bahamian



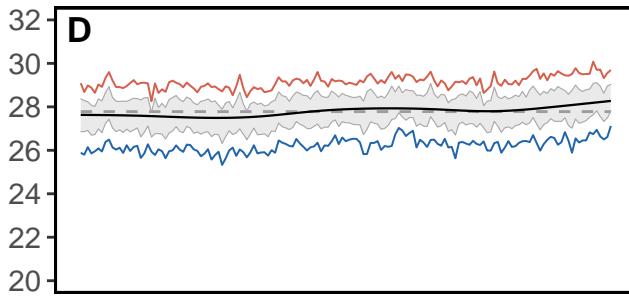
Eastern Caribbean



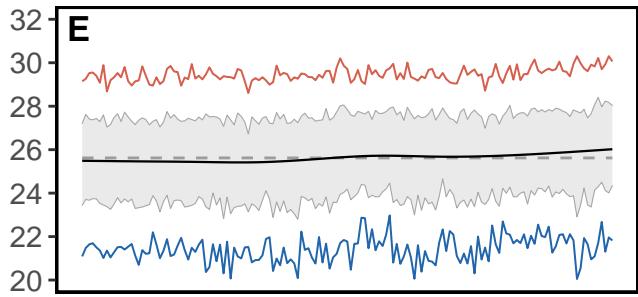
Floridian



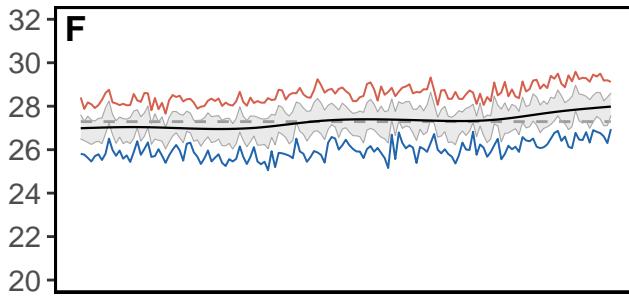
Greater Antilles



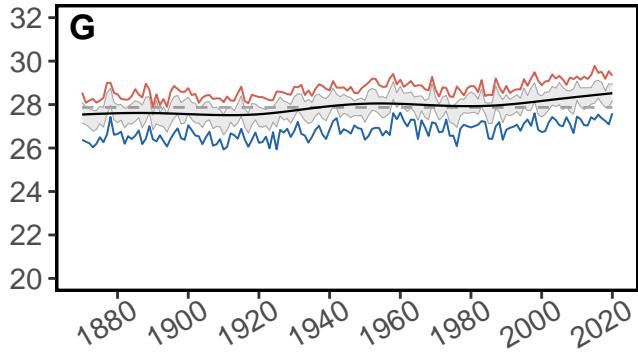
Gulf of Mexico



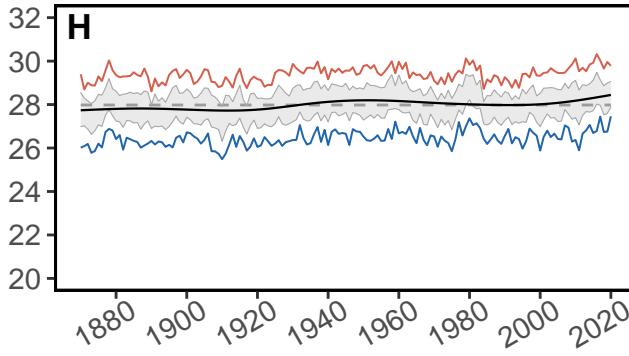
Southern Caribbean



Southwestern Caribbean



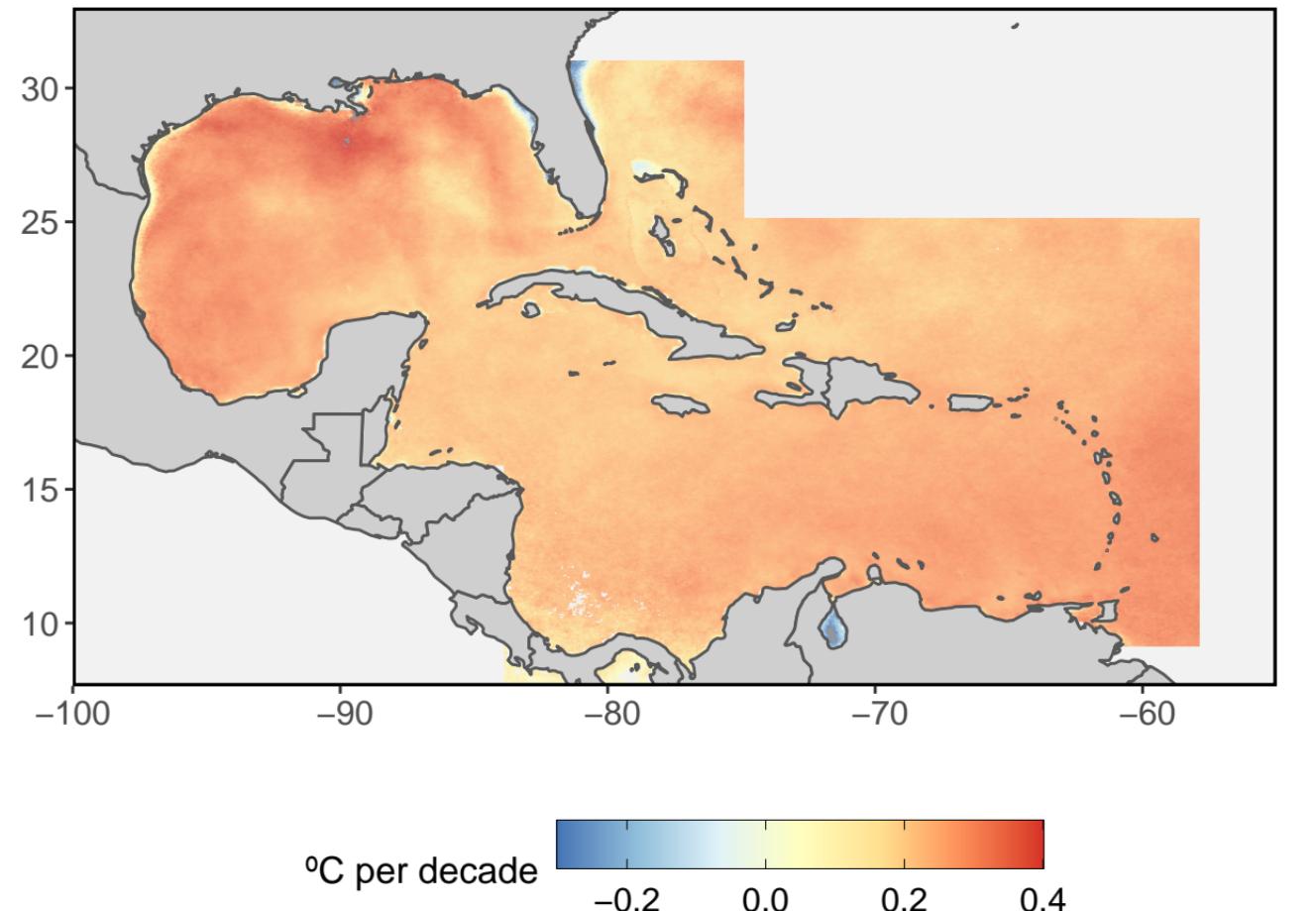
Western Caribbean



SST (°C)

A

Caribbean warming rate (1981–2019)

**B**

Change in marine heat wave frequency (1981–2018)

