

# 1 Sea-surface temperature variability and climate drivers in 2 Cuba's Jardines de la Reina National Park (2003–2022)

3  
4 Maibelin Castillo-Alvarez<sup>1,2</sup>; Oscar Pizarro<sup>2,3</sup>; Alain Muñoz-Caravaca<sup>4</sup>; Iván Pérez-Santos<sup>5,6</sup>;  
5 David Carrasco<sup>2</sup>; David Francisco Bustos-Usta<sup>1,6</sup>; Laura Castellanos-Torres<sup>1,2,4</sup>

6  
7 <sup>1</sup> Postgraduate Program in Oceanography, Department of Oceanography, Faculty of Natural Sciences and  
8 Oceanography. Universidad de Concepción, Chile.

9 <sup>2</sup> Millennium Institute of Oceanography (IMO), Universidad de Concepción, Chile.

10 <sup>3</sup> Department of Geophysics, Universidad de Concepción, Chile.

11 <sup>4</sup> Centro de Estudios Ambientales de Cienfuegos. AP 5, 59350, Ciudad Nuclear, Cienfuegos, Cuba.

12 <sup>5</sup> Centro i-mar, Universidad de los Lagos, Puerto Montt 5480000, Chile

13 <sup>6</sup> Center for Oceanographic Research COPAS Sur-Austral and COPAS COASTAL (FB210021), Universidad  
14 de Concepción, Chile.

15  
16  
17 *Correspondence to:* [mcastilloa@udec.cl](mailto:mcastilloa@udec.cl) and [opizarro@udec.cl](mailto:opizarro@udec.cl)

18  
19 **Abstract.** Coral reef systems on the southeastern Cuban shelf are exposed to rapid warming and increasingly  
20 frequent marine heatwaves (MHWs). However, the physical drivers of local sea-surface temperature (SST)  
21 variability remain poorly quantified. The present study examines seasonal-to-decadal SST variability in and  
22 around the Jardines de la Reina National Park (JRNP) and investigates the extent to which atmospheric–ocean  
23 processes and large-scale climate modes influence that variability. The study analyses daily 1-km Multi-Scale  
24 Ultra High Resolution (MUR) SST from 2003–2022, in conjunction with ERA5 surface heat fluxes and  
25 GLORYS12 mixed-layer fields. A mixed-layer heat budget, compiled from daily values and averaged to  
26 monthly values, is used to attribute the seasonal cycle; long-term trends, MHWs and modes of variability  
27 (Orthogonal Functions) can be used to explain interannual to decadal changes and their links to El Niño  
28 Southern Oscillation (ENSO), the Western Hemisphere Warm Pool (WHWP), the Tropical North Atlantic  
29 (TNA) and the North Atlantic Oscillation (NAO).

30 Net air–sea heat exchange sets the seasonal evolution of SST, whereby horizontal advection provides a smaller  
31 modulation near the shelf break; a characteristic ~2-month lead of heat flux over temperature is consistent with  
32 mixed-layer heat storage. This thermodynamic control explains a marked autumn–winter shelf–offshore  
33 contrast between the shallow gulfs (Gulfs of Ana María and Guacanayabo) and the adjacent Caribbean Sea.  
34 Superimposed over this area is a warming trend of ~0.28°C decade<sup>-1</sup> (strongest in winter/transition months,  
35 peaking around April at ~0.48°C and November at ~0.35°C decade<sup>-1</sup>) and a step-like shift in 2011–2013 towards  
36 a persistently warmer state. MHWs intensified during the second decade; the mean event-wise maximum  
37 intensity was higher inside GAM, while upper categories occurred more frequently offshore. EOF1 (87.5%) is  
38 a basin-wide mode linked on an interannual basis to ENSO/WHWP and latent-heat flux and at low frequency  
39 to the NAO, while EOF2 (6.2%) captures a shelf–offshore dipole related to TNA.

40 Our results provide a physical basis for which to issue early warnings from forecasts of net heat flux and mixed-  
41 layer depth, thus encouraging the use of regional high-resolution modeling and targeted observations. Key  
42 limitations to the present study include a 20-year MHW baseline and an under-resolution of currents in highly  
43 shallow and complex bathymetry.

## 44 **1. Introduction**

45 Sea surface temperature (SST) is a key regulator of marine ecosystems, since it drives physical, chemical and  
46 biological processes. Its variability has profound implications for coastal and oceanic regions in a warming  
47 climate (Venegas et al., 2023). Since the industrial era, anthropogenic pressures have altered ocean dynamics  
48 and accelerated habitat degradation (Jackson et al., 2014; Lotze et al., 2006). Rising SSTs are closely linked to  
49 coral bleaching, habitat fragmentation and biodiversity loss in tropical regions (Bruno et al., 2019; Hughes et  
50 al., 2003). Coral reef ecosystems are susceptible to temperature fluctuations and to co-occurring stressors,  
51 including light, sedimentation and chemical changes (Cramer et al., 2020). As a result, understanding the  
52 patterns and drivers of SST variability has become crucial in order to predict ecological impacts and inform  
53 conservation efforts.

54 The Caribbean Sea (CS) hosts extensive coral reefs and numerous marine protected areas (MPAs), which are  
55 central to regional conservation and livelihoods. The Jardines de la Reina National Park (JRNP), the largest  
56 marine reserve in Cuba and one of the largest in the Caribbean, is notable due to its exceptional reef conditions  
57 and biodiversity (Appeldoorn and Lindeman, 2003; Linton et al., 2002; Gerhartz-Muro et al., 2018). Yet, JRNP  
58 faces a number of challenges typical of Caribbean reefs, including the dramatic decline of historically dominant  
59 species, such as *Acropora palmata*, now classified as critically endangered (Caballero-Aragón et al., 2020).  
60 Prior work at JRNP has focused primarily on reef ecology and conservation status (Hernández-Fernández et al.,  
61 2011, 2016, 2019a; Pina-Amargós et al., 2011), with fewer studies addressing the physical drivers that modulate  
62 local thermal stress and ecosystem vulnerability. This research gap is significant, since thermal extremes and  
63 the persistence thereof increasingly govern the risk of coral bleaching across the region (van Hooidek et al.,  
64 2015; Graham et al., 2015; Mumby et al., 2014).

65 At a broader scale, southern Cuba exhibits warmer SST than the northern shelf of the island, influenced by  
66 exchanges with the CS (Cerqueira-Estrada et al., 2005; Chollett et al., 2012; Caravaca et al., 2022; González-De  
67 Zayas et al., 2022). Basin-wide analyses also point to a significant warming trend during recent decades, which  
68 are particularly pronounced to the south of Cuba (Avila-Alonso et al., 2020). However, existing studies provide  
69 merely a partial view of SST variability on the southeastern Cuban shelf and seldom disentangle the relative  
70 roles of air–sea heat fluxes, horizontal advection and large-scale climate modes in shaping local conditions  
71 within and adjacent to JRNP.

72 Large-scale atmospheric variability modulates Caribbean SST through several well-documented pathways. The  
73 El Niño Southern Oscillation (ENSO) influences trade winds and latent heat flux over the Western Hemisphere  
74 Warm Pool (WHWP), defined as the region warmer than 28.5°C in the Western Tropical Atlantic and in the

75 eastern North Pacific, which alter regional SST at interannual scales (Wang and Enfield, 2001, 2003; Czaja et  
76 al., 2002). The North Atlantic Oscillation (NAO) affects wind patterns, precipitation and heat exchange across  
77 the North Atlantic–Caribbean system, including via the Caribbean Low-Level Jet (Hurrell, 1995; Wang et al.,  
78 2007; Cook & Vizu, 2010). Additional variability arises from the Tropical North Atlantic (TNA) and WHWP  
79 indices, which capture shifts in regional SST (Enfield et al., 1999; Enfield and Lee, 2005). The process of  
80 clarifying how these climate modes project onto local SST in the shelf versus adjacent oceanic waters near  
81 JRNP is crucial for efforts to link physical forcing with ecological risk.

82 In the present study, we investigate seasonal-to-decadal variability of sea-surface temperature in and around  
83 JRNP and its controlling mechanisms using daily 1-km Multi-Scale Ultra High Resolution (MUR) SST (2003–  
84 2022), ERA5 dataset surface heat fluxes, and GLORYS12 (1/12°) dataset currents/temperature by: (i) resolving  
85 the seasonal cycle and diagnosing the mixed-layer heat budget to gauge air–sea heat exchange versus horizontal  
86 advection; (ii) quantifying long-term trends and testing for regime shifts; (iii) detecting and characterizing  
87 marine heatwaves (MHWs); and (iv) extracting dominant modes via Empirical Orthogonal Functions (EOFs)  
88 and relating them to the El Niño–Southern Oscillation, the North Atlantic Oscillation, the Tropical North  
89 Atlantic, and the Western Hemisphere Warm Pool.

90 Accordingly, we address three working hypotheses: (1) at seasonal scales, air–sea heat fluxes dominate SST  
91 variability, with shallow shelf waters exhibiting stronger amplitude and faster cooling/warming than adjacent  
92 oceanic waters; (2) interannual variability shows modulation by ENSO/WHWP and TNA via latent-heat-flux  
93 anomalies and circulation changes; and (3) decadal changes in the region, including post-2010 regime shifts,  
94 are consistent with NAO-related variations in atmospheric forcing. By resolving shelf–offshore contrasts and  
95 attributing variability across time scales, the analysis herein provides a physical basis for interpreting recent  
96 and future thermal stress in this MPA in addition to anticipating ecosystem responses under continued warming.

## 97 **2. Data and methods**

### 98 **2.1 Study region: Jardines de la Reina National Park (JRNP)**

99 The JRNP lies on the southeastern Cuban shelf, bordered to the north by the Gulf of Ana María (GAM), to the  
100 east by the Gulf of Guacanayabo (GG) and to the south by the CS (Figure 1). The archipelago comprises ~661  
101 cays (keys) that extend east–west and which are fringed by mangroves. According to Pina Amargós et al.  
102 (2011), the protected area covers 217,036 ha, of which 200,957 ha are marine hectares. The seafloor shows a  
103 marked north–south contrast: to the north, the shallow GAM is characterized by extensive flat banks, seagrass  
104 beds and soft sediment with a general depth of < 20 m; to the south, the shelf edge transitions abruptly to a steep  
105 continental slope descending to > 3,000 m. This sharp gradient underpins a mosaic of habitats, from shallow  
106 coastal ecosystems to deep-sea environments.

107 The region has a tropical climate with two boreal seasons: a wet season (May–October) and a dry season  
108 (November–April). Prevailing trade winds are generally northeasterly and strengthen during the dry season  
109 (Pérez-Santos et al., 2010). Sea-level pressure follows a seasonal cycle, with higher values in boreal winter

110 (January–March) under the influence of the subtropical high, and lower values in summer (July–September) as  
111 the intertropical convergence zone approaches (Waliser and Jiang, 2015). Air temperatures are warm year-  
112 round (~24–30°C) and there is modest interannual variability, despite pronounced diurnal and seasonal cycles.  
113 Summer is warmest while winter is slightly cooler (Caravaca et al., 2022). On the southeastern Cuban shelf, the  
114 mean flow is westward under the prevailing easterlies (Emilsson and Tápanes, 1971). It is modulated by tides  
115 and currents from the adjacent ocean, notably the Caribbean Current Arriaza et al., 2008). Tides are mixed and  
116 exert little direct control on the mean shelf circulation, although tidal currents can enhance vertical mixing  
117 (Emilsson and Tápanes, 1971; Arriaza et al., 2008).

## 118 **2.2 SST data**

119 Sea-surface temperature was obtained from the Group for High Resolution Sea Surface Temperature MUR  
120 Level-4 analysis produced by the NASA Jet Propulsion Laboratory. This product provides daily global fields  
121 at ~1 km (0.01°) by blending multiple infrared and microwave satellite sensors (Chin et al., 2017) and is widely  
122 used in tropical reef and coastal studies (for example, Kumagai and Yamano, 2018; Skerrett et al., 2024). The  
123 present study analyzed data from 2003 to 2022 and subsequently subset the domain, as shown in Figure 1.

124 All processing was performed on the native 1km grid, unless otherwise specified. Daily fields were: (i) land-  
125 masked and quality-screened using the product masks; (ii) averaged to monthly means for the long-term,  
126 seasonal and EOF analyses; and (iii) converted to monthly anomalies by removing the 2003–2022 monthly  
127 climatology (further details are provided in Section 2.5). For diagnostics requiring co-location with reanalyses  
128 (mixed-layer heat budget and horizontal advection), SST was bilinearly remapped to the target grid  
129 (GLORYS12 at 1/12° or ERA5 at 1/4°) to avoid artificial gradients from mismatched resolutions. All  
130 temperatures are reported in °C.

131 We retained the 1-km fields to show frontal structures in Figure 2; frontal overlays are computed from local  
132 SST differences (threshold  $\geq 0.5^\circ\text{C}$ ) and lightly smoothed with a  $3\times 3$  neighbourhood operator to suppress pixel-  
133 scale noise.

134 It should be noted that MUR SST was not used in the mixed-layer heat budget (Section 2.6); there, we diagnosed  
135 temperature tendencies ( $\partial T/\partial t$ ) using the GLORYS12 mixed-layer temperature (MLT), depth and currents for  
136 reasons of internal consistency with regards to the terms. At monthly scales, MUR SST and GLORYS12 MLT  
137 were correlated throughout the study area, thus, variability in MLT is interpreted as the explanation for the  
138 observed SST variability.

139 To assess the internal consistency of the SST variability represented by the different products used in this study,  
140 we performed a quantitative intercomparison between MUR SST, ERA5 SST, and GLORYS12 mixed-layer  
141 temperature (MLT) over the full analysis domain and period (2003–2022). The agreement is summarized in  
142 Supplementary Note 1 and Figure S1 using a Taylor diagram (correlation, normalized standard deviation, and  
143 cantered RMSD referenced to MUR), which provides an objective measure of how well the coarser-resolution  
144 products reproduce the temporal variability and amplitude of the satellite-based SST anomalies. In addition, an

145 independent consistency check using short-term in situ temperature time-series available within the Jardines de  
146 la Reina region is presented in Supplementary Figure S2. Although these comparisons do not constitute a full  
147 in situ validation for the region, they support the suitability of MUR SST for describing spatial and temporal  
148 variability and provide a transparent characterization of cross-product differences relevant to the interpretation  
149 of our results.

### 150 **2.3 Atmospheric fluxes (ERA5) and ocean reanalysis (GLORYS12)**

151 The present study used ERA5 surface flux components (shortwave, longwave, latent and sensible) and 10 m  
152 winds at native hourly resolution, aggregated to daily and then monthly means for the period 2003–2022. The  
153 upper-ocean state was characterized with GLORYS12 at daily resolution (temperature, horizontal currents and  
154 Ocean Mixed Layer Thickness), with monthly means used for non-budget diagnostics. Heat flux was measured  
155 in  $W m^{-2}$ . The oceanographic convention that holds that positive net heat flux warms the ocean was adopted  
156 throughout the course of the present research.

157 The upper-ocean state was characterized by GLORYS12 (eddy-resolving,  $1/12^\circ$ , 50 vertical levels, daily), from  
158 which potential temperature, horizontal currents and mixed layer depth and temperature were extracted over  
159 the same period. Fields were subset to the domain shown in Figure 1 and, where necessary, bilinearly remapped  
160 to a standard grid (ERA5-GLORYS12) for the mixed-layer heat budget and advection diagnostics. Regarding  
161 the budget, ERA5 fluxes were first aggregated to daily values and then bilinearly remapped to the GLORYS12  
162 grid; the results were subsequently averaged to a monthly basis. For descriptive analyses, monthly fields were  
163 utilized.

### 164 **2.4 Climate indices**

165 The present study used a monthly time series of large-scale climate indices known to modulate Caribbean SST.  
166 The ENSO was represented by the Multivariate ENSO Index v2 (MEI.v2) (Zhang et al., 2019; Wolter, 1993),  
167 obtained from the NOAA Physical Sciences Laboratory (PSL). The WHWP index (Wang and Enfield, 2001,  
168 2003; Enfield and Lee, 2005; Wang et al., 2006) and the TNA index (Enfield et al., 1999; Chen et al., 2021)  
169 were also taken from NOAA PSL. The NAO index was obtained from the NOAA Climate Prediction Center  
170 (CPC) (Barnston and Livezey, 1987; Chen and Van den Dool, 2003; Van den Dool et al., 2000).

171 All indices were analyzed at monthly resolution pertaining to the period 2003–2022, to match the SST analysis  
172 period. Prior to correlation and filtering analyses (Section 2.9), each index was standardized (zero mean, unit  
173 variance) over the 2003–2022 period. Provider sign conventions were retained.

### 174 **2.5 Statistical analysis**

175 All analyses were performed over the domain  $19\text{--}21.75^\circ N$ ,  $77\text{--}80^\circ W$  (Figure 1). Land points were masked.  
176 Daily fields were aggregated to monthly means, while monthly anomalies were computed by removing the

177 2003–2022 monthly climatology. Unless otherwise specified, statistics refer to the aforementioned monthly  
178 anomalies.

179 Long-term monthly means were used to show the seasonal cycle of SST and surface heat fluxes (Figures 2–4).  
180 To contrast shelf and offshore regimes, we computed time series over the two small boxes shown in Figure 1:  
181 GAM (shelf) and CS (oceanic). For each box, monthly anomalies, standard deviations and seasonal composites  
182 were calculated. To verify that our GAM and CS time series are not sensitive to the exact choice of box location  
183 and size, we repeated the analysis using multiple alternative boxes within GAM and offshore in the CS (Note  
184 S2 and Figure S3 in the supplementary material). The resulting SST-anomaly time series remain highly  
185 consistent with the reference series (all correlations significant at  $\geq 95\%$  confidence; Table S1), indicating that  
186 the reported shelf–offshore contrasts are robust to reasonable variations in box definition.

187 Linear trends were estimated using ordinary least squares applied to monthly anomalies at each grid point,  
188 separately for each calendar month. Slopes are reported in  $^{\circ}\text{C}/\text{decade}^{-1}$ . Statistical significance was assessed at  
189 the 95% level using a two-sided Student’s t-test. To account for serial autocorrelation inherent in geophysical  
190 time series, we calculated the effective degrees of freedom ( $N^*$ ) following the approximation by Thomson and  
191 Emery (2024).  $N^*$  was estimated using the lag-1 autocorrelation coefficient ( $r_1$ ):

$$192 \quad N^* = N \frac{1 - |r_1|}{1 + |r_1|}$$

193 Thus, the significance tests for trends and correlations use an effective degrees-of-freedom estimate, yielding  
194 more conservative  $p$ -values under serial correlation.

195 To quantify coupling between SST and different drivers, cross-correlations between SST anomalies and net  
196 surface heat flux were computed (and, where relevant, horizontal heat advection; Section 2.6) using monthly  
197 data, by scanning lags from  $-6$  to  $+6$  months. Reported lags correspond to the peak absolute correlation.  
198 Significance was evaluated using the t-test for the correlation coefficient and the effective degrees of freedom  
199 approach. Where budget terms are summed (Section 2.6; Figure 5), the uncertainty of the sum was obtained by  
200 root-sum-of-squares, assuming weak covariance between terms at monthly resolution. All computations and  
201 figure generation were carried out via the MATLAB computing platform using standard scientific libraries.

## 202 **2.6 Mixed-layer heat budget**

203 To identify the processes governing the seasonal variability of SST, we applied a standard mixed-layer  
204 (ML) heat budget (for example, Moisan and Niiler, 1998). Since the budget is defined in relation to the  
205 bulk mixed layer, the GLORYS12 MLT and mixed-layer depth (MLD) were used to ensure physical and  
206 numerical consistency among terms (flux  $\rightarrow$  heating rate via  $h$ ; advection using currents acting on the same  
207 temperature field). At monthly scales, MUR SST and GLORYS12 MLT were well correlated over the domain  
208 (Section 2.2). Therefore, accounting for MLT variability was taken as providing an explanation for the  
209 observed SST variability.

210 The prognostic equation for ML temperature  $T$  is

211

212 
$$\frac{\partial T}{\partial t} = \frac{Q_{net}}{\rho C_p h} - \mathbf{U} \cdot \nabla T - \frac{(\frac{\partial h}{\partial t} + \mathbf{U}_{-h} \cdot \nabla h + w_{-h}) \Delta T}{h} + R,$$

213

214 where  $\rho = 1025 \text{ kg m}^{-3}$  is seawater density,  $C_p = 3990 \text{ J kg}^{-1} \text{ K}^{-1}$  is the specific heat capacity,  $h$  is the MLD,  
 215  $Q_{net}$  is the net downward surface heat flux (into the ocean,  $\text{W m}^{-2}$ ),  $\mathbf{U} = (U, V)$  is the horizontal current vector  
 216 representative of the ML. The entrainment (positive downward) velocity at the ML base is calculated as follows.  
 217 The term  $\mathbf{U}_{-h} \cdot \nabla h$  represents the contribution to vertical advection associated with horizontal flow ( $\mathbf{U}_{-h}$ ) moving  
 218 over an inclined bottom, where  $\mathbf{U}_{-h}$  is the horizontal velocity evaluated at the bottom and  $\nabla h$  the horizontal  
 219 gradient of the bathymetry,  $w_{-h}$  is obtained by vertically integrating the horizontal velocity divergence from  $-$   
 220  $h$  to the surface.,  $\Delta T = T_{ML} - T_{below}$  is the temperature jump across the base of the ML, and  $R$  collects  
 221 unresolved terms (for example, diffusion, sub-monthly variability and analysis noise). All heating rates are  
 222 reported in  $^{\circ}\text{C day}^{-1}$ . Conversion from flux to heating rate follows, whereby

223

224 
$$1 \text{ W m}^{-2} \equiv \frac{86400}{\rho C_p h} \text{ K day}^{-1},$$

225

226 so, for example, with  $h = 20 \text{ m}$ ,  $1 \text{ W m}^{-2} \sim 0.0011^{\circ}\text{C day}^{-1}$ .

227 All budget terms were computed from daily fields and then averaged to monthly means for analysis and  
 228 plots. MLD  $h$  was obtained from GLORYS12 “mixed layer thickness”. This estimate is based on a density  
 229 criterion ( $\Delta\sigma_{\theta} = 0.03 \text{ kg m}^{-3}$ ), following the approach proposed by de Boyer Montégut et al. (2004). Daily  
 230 horizontal velocities from GLORYS12 were vertically averaged from the surface to the local ML base,  
 231 approximated by thickness-weighted averaging across GLORYS12 levels within the ML.

232 Surface fluxes ( $Q_{net}$ ) were estimated from ERA5 shortwave (SW) and longwave (LW) radiation, latent (LHF)  
 233 and sensible (SHF) heat fluxes on the  $1/4^{\circ}$  grid. To reiterate, we adopted herein the oceanographic convention  
 234 that positive  $Q_{net}$  warms the ocean:  $Q_{net} = (\text{SW}\downarrow - \text{SW}\uparrow) + (\text{LW}\downarrow - \text{LW}\uparrow) - \text{LHF} - \text{SHF}$ . The ERA5 native  
 235 signs (upward positive for turbulent fluxes) are converted accordingly. Fluxes were bilinearly remapped to  
 236 the GLORYS12 grid prior to the application of Equation (1).

237 Horizontal gradients  $\partial T/\partial x$ ,  $\partial T/\partial y$  were computed with centered finite differences on the GLORYS12 grid. At  
 238 a monthly resolution, the flux and advection tendencies in addition to their sum are presented. Furthermore, the  
 239 entrainment plus unresolved tendency is treated as a residual (for example, the difference between the observed  
 240 monthly MLT tendency and the sum of resolved terms).

241 **2.7 Marine heatwaves**

242 MHWs were detected from daily 1-km MUR SST data, following the hierarchical definition provided by  
243 Hobday et al. (2016, 2018), which contends that an MHW occurs when SST exceeds the seasonally varying  
244 90th percentile threshold for  $\geq 5$  consecutive days. For each grid point, we computed a day-of-year (DOY)  
245 climatology and corresponding 90th percentile threshold over the period 2003–2022. The DOY climatology  
246 and threshold were formed using a  $\pm 5$ -day moving window in order to smooth sampling noise. Events were  
247 characterized according to their intensity (absolute anomaly relative to the DOY climatology), duration,  
248 frequency, total MHW days and cumulative intensity. MHW categories (Moderate/Strong/Severe/Extreme)  
249 were assigned using the factor-of-rule relative to the local threshold exceedance (Hobday et al., 2018).  
250 All diagnostics were computed per grid cell and subsequently summarized for the sub-regions (GAM and CS,  
251 Figure 1). Figure 8 shows the following: (i) maps pertaining to the mean maximum intensity and total MHW  
252 days (2003–2022); and (ii) an annual time series of the number of events, mean maximum intensity and  
253 maximum category for GAM and CS. It should be noted that the 20-year baseline (2003–2022) used in the  
254 present study corresponds to the period during which 1-km MUR SST data were available. Although shorter  
255 than the conventional 30-year climatology, the present research does, nevertheless, provide consistent  
256 thresholds across the study period. Schlegel et al. (2019) evaluated the impact of time-series length on MHW  
257 detection and found that, in general, event durations and intensities derived from a 10-year baseline are not  
258 appreciably different from those obtained using a standard 30-year baseline. In addition, to quantify the  
259 influence of our 20-year baseline and improve comparability with studies using 30-year climate normals, we  
260 performed a sensitivity analysis using GLORYS12, which provides a 30-year record (1993–2022). Following  
261 the Hobday et al. MHW definition, we computed MHW thresholds using a 30-year baseline (1993–2022) from  
262 GLORYS12 and re-detected MHWs over 2003–2022, then compared the number of days with MHW per year,  
263 mean intensity and the standard deviation of the intensity. Results are shown in Table S2. Differences were  
264 relatively small, indicating that our conclusions regarding the increase in MHWs during the second decade and  
265 the spatial contrasts within JRNP are not sensitive to baseline choice.

## 266 **2.8 Empirical orthogonal functions**

267 The present study used EOFs to extract the dominant space–time patterns of SST variability over the study  
268 domain ( $19\text{--}21.75^\circ\text{ N}$ ,  $77\text{--}80^\circ\text{ W}$ ). The input field was monthly MUR SST anomalies (Section 2.2), i.e.,  
269 monthly means with the 2003–2022 monthly climatology removed. Unless otherwise specified, anomalies time  
270 series were not detrended to ensure that the modes were able to capture the interannual–decadal variability  
271 previously discussed in Section 3.4. For comparison, we also include EOF results computed after removing the  
272 linear trend (Figure S4). All calculations were performed on the native  $\sim 1$  km grid. EOFs were obtained from  
273 the covariance matrix of the anomalies, computed via singular-value decomposition. Spatial patterns (EOFs)  
274 were scaled to the unit variance of their associated principal components (PCs) and the fraction of total variance  
275 explained by each mode. The sampling uncertainty of eigenvalues was estimated using North’s rule of thumb,  
276 and whereby modes were treated as distinct when the eigenvalue separation exceeded such uncertainty. PCs  
277 were standardized to zero mean and unit variance; their sign was arbitrary and was chosen so that positive EOF

278 loadings corresponded to positive PC anomalies during warm events. For correlation analyses in Section 3.5,  
279 both the raw monthly PCs and low-pass filtered PCs were used to isolate variability bands. Specifically, a 2-  
280 year cutoff was employed to emphasize interannual variability (ENSO/WHWP/TNA) and a 5-year cutoff for  
281 decadal/interdecadal variability (NAO). EOF analysis was carried out in MATLAB using standard linear-  
282 algebra routines.

### 283 3. Results

#### 284 3.1 Seasonal cycle and mixed-layer heat budget (GAM vs CS)

##### 285 3.1.1 SST and flux climatologies

286 Monthly SST climatologies (Figure 2) exhibited the expected annual cycles, with boreal summer–early autumn  
287 (August–September) temperatures reaching ~30–33 °C, and winter (January–March) readings dropping to ~22–  
288 26 °C. A pronounced shelf–offshore contrast emerged from November to March, when the GAM/GG shallow  
289 waters are cooler than the adjacent CS, while from April to October this contrast weakened and was virtually  
290 absent in certain months (for example, April and September–October). SST fronts ( $\geq 0.5$  °C) aligned with the  
291 shelf edge and were most frequent/intense during the transition and winter months, consistent with stronger  
292 horizontal gradients at that time.

293 Air–sea flux climatologies (Figure 3) indicated net ocean cooling from October to March and net warming from  
294 April to September. Winter cooling was strongest within the gulf, whereas summer heat peaked near the shelf  
295 break and CS. Cross-correlations between SST and net heat flux reveal a high degree of coupling ( $r$  between  
296 0.6–0.9), with a characteristic lag of ~2 months (flux leads SST; see Figure S5), consistent with mixed-layer  
297 heat storage. Seasonal maps of horizontal heat advection (Figure 4) reveal smaller-magnitude, spatially patchy  
298 tendencies that warm during cold months (November–February) and cool during warm months (May–October),  
299 thus reflecting the seasonal reversal of horizontal temperature gradients. Advection effects were most  
300 significant along the gulf–ocean boundary.

##### 301 3.1.2 Mixed-layer heat budget for the seasonal cycle

302 To attribute the seasonal evolution mechanistically, the mixed-layer heat budget (Section 2.6) was applied and  
303 GAM and CS were compared (Figure 5). It was found that the air–sea heat-flux tendency  $(\partial T/\partial t)|_Q =$   
304  $Q_{net}/(\rho C_p h)$  dominates the seasonal cycle in both regions. The horizontal advection term  $(\partial T/\partial t)|_{adv} = -U \cdot$   
305  $\nabla T$ ) is generally an order of magnitude smaller, although it modulates the signal near the shelf edge. The  
306 summed tendency (flux + advection) term reproduces the observed monthly mixed-layer temperature tendency  
307 with a ~2-month lag (flux leads), which confirms that surface heat exchange sets the seasonal cycle, while  
308 advection acts in a secondary manner.

309 Seasonal extremes occur as follows: maximum warming rates from fluxes took place in June–July, and  
310 maximum cooling rates occurred in November–December, with stronger magnitudes recorded over GAM in  
311 winter and greater summer warming registered nearer to the CS. Advection is more energetic in GAM than in  
312 CS (notably during January–June and November–December), which resulted in warming during the cold season  
313 and cooling during the warm season. This is consistent with the sign of horizontal SST gradients. The residual  
314 (entrainment plus unresolved terms) is small at monthly scales, thus indicating that the flux and advection terms  
315 essentially achieve budget closure. It should be noted that the mixed-layer heat budget was applied solely to the  
316 seasonal cycle; longer-term variability is addressed in Sections 3.2–3.4 without a heat-budget decomposition.

### 317 **3.2 Interannual variability, long-term trends and the 2011-2013 regime shift**

318 Monthly linear trends of SST anomalies (Figure 6) reveal spatially coherent warming across the domain from  
319 2003 to 2022, with the largest magnitudes occurring in the transition and winter months. Peak grid-point trends  
320 occur in April and November, consistent with the domain-mean results, and were more pronounced along the  
321 shelf edge compared to offshore waters. Summer trends were weaker and spatially smoother, with local minima  
322 in June and July. By conducting stippling, we highlight grid cells that are statistically significant at the 95%  
323 confidence level after adjusting for serial autocorrelation. Significant warming dominated most months,  
324 particularly from November to March and April.

325 Monthly SST anomalies (Figure 7a,c) show greater variability on the shelf (GAM) than offshore (CS), with  
326 standard deviations of 0.61°C and 0.41°C, respectively. Several cold winters marked the first half of the record  
327 (for example, 2004, 2009, 2011), which were more pronounced in GAM. An additional cold event in 2010 was  
328 evident in GAM but weak/absent in CS. In the second decade of study, warm winters predominated (for  
329 example, 2014, 2016, 2019, 2020), with stronger occurrences over GAM. Despite not every year conforming  
330 to the general trend, results demonstrate an overall evolution that is shifting from predominantly cool to  
331 predominantly warm conditions.

332 Seasonal means by year (Figure 7b,d) confirm that winter (January to March) drives most of the low-frequency  
333 change. Piecewise linear fits prior to and after 2011 indicate a winter cooling tendency during 2003–2011,  
334 followed by a marked winter warming during 2012–2022. Summer (July to September) warmed throughout the  
335 record, albeit with smaller slopes than winter in both regions. The black line in panels (b) and (d) of Figure 7  
336 shows the yearly linear trend, which is positive for both GAM and CS. In conjunction, these patterns indicate a  
337 step-like transition from 2011 to 2013 to a persistently warmer state, which is coherent across both shelf and  
338 offshore boxes. To formally assess whether the apparent transition toward a warmer state is statistically  
339 significant, we applied a changepoint test based on a two-phase regression with a common trend (XLW), which  
340 is designed to detect a step-like shift in the mean level while allowing for an underlying linear trend. The test  
341 was performed on the monthly SST anomaly series for the two representative subregions (GAM and CS; Fig.  
342 7a,c), scanning all admissible changepoint times and using the maximum F statistic ( $F_{\max}$ ; see Reeves et al.,  
343 2007); significance was estimated via Monte Carlo simulation under the null with serial autocorrelation  
344 accounted for in the residual structure. The analysis identifies an optimal changepoint in December 2012 in

345 both subregions, consistent with the step-like transition highlighted visually in Fig. 7b,d. The estimated mean-  
346 level increase after the changepoint is 0.67 °C for CS ( $F_{\max} = 53.45$ ; 98% confidence) and 0.84 °C for GAM  
347 ( $F_{\max} = 35.75$ ; 95% confidence). These results provide quantitative support that the late-2012 shift represents a  
348 statistically significant transition toward persistently warmer conditions in both shelf and offshore  
349 environments.

350 In summary, the shelf exhibits larger variance and a stronger wintertime response than the adjacent CS,  
351 consistent with Section 3.1 (shallower mixed layers and stronger air–sea coupling). This transition foreshadows  
352 the increase in marine heatwave activity (see below Section 3.3) and is consistent with the low-frequency  
353 modulation captured by the EOF analysis (Section 3.4).

### 354 **3.3 Marine heatwaves**

355 Spatially, the mean of event-wise maximum intensity ranges from  $\sim 1\text{--}2^\circ\text{C}$  across the domain (Figure 8a), with  
356 a regional mean of  $1.3 \pm 0.2^\circ\text{C}$ . Intensities were systematically higher inside the gulf than offshore. Events in  
357 GAM tended to have higher absolute intensity, whereas the CS, which experienced lower background variance,  
358 more often reached higher MHW categories under the Hobday scheme. The total number of MHW days from  
359 2003 to 2022 exceeds 200 at every grid cell and surpasses 400 over most of the GAM (Figure 8b).

360 The year-by-year event calendars for the representative boxes (Figure 8c, d) show broadly similar annual  
361 frequencies in GAM and CS (typically 4–5 events  $\text{yr}^{-1}$ ), with a marked increase in frequency and intensity  
362 during the second decade. The most active period is 2019–2020, followed by 2015–2016, in both regions. The  
363 years 2004 and 2008 are the only ones in which no MHW was detected in either box. Accordingly, a key shelf–  
364 offshore contrast emerges: Events in GAM tended to be more intense, while more high-category events were  
365 registered in the CS; over the entire period, 73 events were recorded in GAM compared to 90 in CS. These  
366 patterns are consistent with the seasonal contrasts established in Section 3.1, i.e., shallow, strongly forced shelf  
367 waters favour larger absolute temperature anomalies (higher intensity), while offshore, the background  
368 threshold and variance regime support more frequent escalation to higher categories.

### 369 **3.4 Modes of variability**

370 EOFs of monthly SST anomalies (2003–2022) indicate that the first two modes account for 93.7% of the total  
371 variance (EOF1: 87.5%, EOF2: 6.2%) and possess clear physical significance (Figure 9). EOF1 displays a  
372 monopole pattern with positive loadings across the domain, slightly enhanced toward the shelf edge and  
373 offshore. This mode represents coherent warming/cooling of the entire region. Its principal component (PC1)  
374 exhibits low-frequency variability with a pronounced minimum during the 2009–2011 period and positive  
375 excursions in the 2013–2016 and 2019–2020 periods. The 2-year low-pass PC1 highlights the step-like  
376 transition to a warmer state after the 2011–2013 period, consistent with Section 3.2 and with the increase in  
377 MHW activity (Section 3.3).

378 EOF2 is a dipole that opposes the shallow shelf (GAM/GG) to the adjacent CS, with larger amplitudes along  
379 the shelf break. This mode captures differential heating/cooling between coastal and oceanic waters, consistent

380 with the seasonal mechanisms diagnosed in Section 3.1 (stronger air–sea coupling over the shelf and modulation  
381 by horizontal advection). PC2 fluctuates primarily at interannual timescales, exhibiting alternating  
382 positive/negative phases throughout the period of study, with no persistent trend identified. This indicates  
383 variability that redistributes anomalies between the shelf and offshore regions, rather than warming the entire  
384 region.  
385 Overall, EOF1 reflects basin-wide anomalies that underpin the regime shift, whereas EOF2 explains spatial  
386 structure related to the shelf–offshore gradient. In Section 3.5, these modes are related to large-scale climate  
387 indices in order to assess likely drivers of the interannual–decadal variability.

### 388 **3.5 Climate drivers: EOF PCs vs large-scale indices**

389 A relationship was established between the leading SST modes and climate variability by comparing PC1/PC2  
390 with standard indices (ENSO [MEI], WHWP, TNA and NAO, Section 2.4) and with domain-mean latent heat  
391 flux (LHF, ERA5). Interannual variability was isolated with a 2-year running-mean low-pass, and low-  
392 frequency variability with a 5-year running-mean low-pass (zero-lag correlations reported; significance  
393 assessed with effective degrees of freedom; Section 2.5).

394 At interannual scales (Figure 10a), PC1 co-varies with MEI ( $r \approx 0.49$ ), WHWP ( $r \approx 0.58$ ), and especially with  
395 LHF ( $r \approx 0.73$ ), consistent with an air–sea heat-flux pathway linking climate modes to regional SST. At low  
396 frequencies (Figure 10c), PC1 closely tracks the NAO ( $r \approx 0.90$ ), consistent with the step-like warming observed  
397 after 2011–2013 (Section 3.2). The effective degrees of freedom ( $N^*$ ) and associated significance levels for all  
398 correlations (computed after low-pass filtering) are summarized in Table S3.

399 At interannual scales (Figure 10b), PC2 correlates with the TNA index ( $r \approx 0.53$ ), consistent with variability  
400 that redistributes anomalies between shelf and offshore rather than producing basin-wide warming. In  
401 conjunction, these results indicate that ENSO/WHWP modulates basin-wide anomalies (PC1) via latent heat  
402 flux on interannual scales and through the NAO on low-frequency scales. Simultaneously, the shelf–offshore  
403 contrast (PC2) is tied to TNA-related variability. Physical mechanisms are discussed in Section 4.

## 404 **4. Discussion**

### 405 **4.1 Seasonal and low-frequency drivers of SST variability**

406 The seasonal evolution of SST in and around JRNP is primarily controlled, with net air–sea heat exchange  
407 setting both the sign and timing of the mixed-layer temperature tendency, and horizontal advection providing a  
408 secondary modulation near the shelf break. This behaviour is consistent with mixed-layer heat-budget theory,  
409 in which surface fluxes dominate the seasonal cycle and heat storage produces an intrinsic lag between forcing  
410 and response (De Boyer Montégut et al., 2004; Moisan and Niiler, 1998). The pronounced autumn–winter  
411 shelf–offshore contrast arises naturally from mixed-layer-depth differences: for comparable surface forcing, the  
412 shallow mixed layer inside the Gulf of Ana María yields larger temperature tendencies ( $\propto Q_{net}/h$ ), thereby

413 producing faster cooling and stronger gradients than in the adjacent Caribbean Sea. The observed persistence  
414 of frontal structures aligned with the shelf edge supports a regime in which thermodynamic forcing establishes  
415 the large-scale seasonal baseline, while circulation refine the spatial structure. This interpretation is coherent  
416 with prior descriptions of SST variability around Cuba and the southern Cuban shelves, where shelf-ocean  
417 contrasts and regional exchange with the Caribbean Sea shape the spatial pattern of SST (González-De Zayas  
418 et al., 2022; Caravaca et al., 2022; Cerdeira-Estrada et al., 2005).

419 Superimposed on this seasonal baseline, the dominant interannual-decadal signal is captured by a coherent  
420 basin-wide mode (EOF1) that covaries with ENSO/WHWP and, most directly, with latent-heat-flux variability.  
421 This is physically consistent with established Caribbean air-sea coupling pathways, whereby ENSO-related  
422 atmospheric anomalies modulate trade winds and near-surface humidity over the warm-pool region, altering  
423 evaporative cooling and thus SST at interannual time scales (Wang et al., 2006; Enfield and Lee, 2005; Wang  
424 and Enfield, 2003; Czaja et al., 2002; Wang and Enfield, 2001). In this framework, latent heat flux acts as an  
425 efficient bridge between large-scale atmospheric variability and local SST anomalies: weaker trades and/or  
426 reduced air-sea humidity gradients reduce evaporation, thereby decreasing upward latent-heat loss and  
427 favouring SST warming. The strong co-variability between PC1 and latent heat flux in our results is consistent  
428 with this pathway and supports an interpretation in which basin-wide SST anomalies are primarily  
429 atmospherically forced through surface turbulent fluxes.

430 This mechanistic perspective also provides a coherent explanation for the step-like transition toward a  
431 persistently warmer state during 2011–2013. The transition is spatially coherent across both, the shelf and  
432 offshore subregions and projects strongly onto EOF1/PC1, indicating that it reflects a regional scale forcing  
433 rather than a local artefact of subregion selection. At low frequencies, PC1 closely tracks the NAO, suggesting  
434 that Atlantic-scale atmospheric variability modulates the background state of surface forcing over the Intra-  
435 American Seas (Cook and Vizy, 2010; Wang et al., 2007; Hurrell, 1995). We therefore interpret the 2011–2013  
436 shift as the manifestation of a low-frequency change in atmospheric conditions, which is consistent with NAO-  
437 related variability, that favours reduced net surface heat loss (through changes in winds and turbulent fluxes),  
438 allowing heat to accumulate and the system to transition into a warmer mean state. This interpretation is further  
439 supported by the timing of the transition in the low-pass PC1 and its correspondence with the increase in MHW  
440 activity during the second decade of the record. While the present analysis cannot establish causality, the  
441 proposed mechanism is physically grounded and consistent with the documented influence of ENSO/WHWP  
442 and Atlantic variability on Caribbean air-sea coupling and evaporative cooling (Cook and Vizy, 2010; Wang et  
443 al., 2007; Wang et al., 2006; Enfield and Lee, 2005; Wang and Enfield, 2003; Czaja et al., 2002; Wang and  
444 Enfield, 2001; Hurrell, 1995).

445 Finally, the secondary mode (EOF2) helps interpret how large-scale variability translates into spatial structure  
446 at local scales. Its shelf–offshore dipole and relationship with the Tropical North Atlantic index indicate  
447 variability that redistributes anomalies between the semi-enclosed gulfs and the adjacent open Caribbean Sea

448 rather than warming the entire region uniformly. Physically, such redistribution is consistent with differential  
449 mixed-layer coupling and with the role of horizontal gradients and shelf-break dynamics in shaping SST  
450 patterns. Importantly for JRNP, this multi-scale framework implies that MHW risk is conditioned by (i) the  
451 local thermodynamic sensitivity of shallow shelf waters to surface forcing and (ii) large-scale atmospheric  
452 variability that favours persistent warm anomalies, both of which are relevant for coral-reef thermal stress and  
453 associated ecological impacts (Cramer et al., 2020; Bruno et al., 2019; Van Hooidek et al., 2015; Hughes et  
454 al., 2003). From an applied perspective, these results support monitoring surface heat fluxes and mixed-layer  
455 depth alongside large-scale indices (ENSO/WHWP and NAO) to provide a physically informed context for  
456 early-warning assessments in the JRNP under continued warming.

#### 457 **4.2 Marine heatwaves: intensity, category and recent escalation**

458 Marine heatwaves increased in frequency and intensity during the second decade, with 2019–2020 being the  
459 most active period, followed by 2015–2016 as the second most active. MHW detection and categorization  
460 follow Hobday et al. (2016, 2018). Relative to the local 90th-percentile threshold, the mean of event-wise  
461 maximum intensity is greater in GAM than offshore, while the total number of MHW days surpasses 400 across  
462 large areas of the gulf. However, the higher category scales (for example, Severe) occur comparatively more  
463 often offshore (CS). This contrast is expected under the Hobday scheme, in which categories are defined by the  
464 magnitude of local threshold exceedance. Thus, regions with lower background variance can experience higher  
465 categories, even for more minor absolute anomalies. Physically, GAM develops larger °C anomalies due to  
466 shallow, strongly forced mixed layers, while CS more readily crosses category thresholds owing to tighter local  
467 variability.

468 The warmer background state after the 2011–2013 period effectively preconditions the region for MHW  
469 development, increasing both the likelihood and persistence of threshold exceedances. Mechanistically, this  
470 links back to Sections 3.1 and 3.5, whereby flux-dominated seasonality sets the baseline and phase, and large-  
471 scale atmospheric variability modulates the probability of sustained warm anomalies that seed or prolong  
472 events. These patterns echo broader reef-climate concerns in the Caribbean, where rising SSTs and  
473 compounding stressors have been associated with bleaching and ecological change (Hughes et al., 2003; Bruno  
474 et al., 2019; Cramer et al., 2020; van Hooidek et al., 2015), including at JRNP and neighbouring MPAs (Pina  
475 Amargós et al., 2011; Hernández-Fernández et al., 2011, 2016, 2019a; Gerhartz-Muro et al., 2018; Caballero-  
476 Aragón et al., 2020).

#### 477 **4.3 Limitations, assumptions and robustness**

478 Several methodological choices bound the interpretation. The budget is formulated for the bulk mixed layer  
479 and, as a consequence, we used GLORYS12 mixed-layer temperature, depth and currents for internal  
480 consistency among terms, by computing all tendencies on a daily basis and averaging these to monthly values.  
481 MUR SST was reserved for descriptive and MHW analyses. At monthly scales, MLT and SST are well  
482 correlated; however, residual differences may persist at daily scales due to skin effects and diurnal warming.

483 ERA5 and GLORYS12 may exhibit coastal biases. Particularly, it was not possible to directly evaluate the  
484 realism of GLORYS12 currents in the gulfs or the adjacent CS because no in-situ velocity observations (for  
485 example, those undertaken by Acoustic Doppler Current Profiler moorings or high-frequency radars) were  
486 available for the study period. This is a non-trivial caveat: reproducing circulation in highly shallow, embayed  
487 shelves, such as the GAM and the GG, is notoriously challenging for global reanalyses. This is because the  
488 effective  $1/12^\circ$  (~8–9 km) resolution and required bathymetric smoothing under-resolve narrow channels, weak  
489 pressure-gradient flows and small eddies. Moreover, the abrupt depth changes along the shelf break and the  
490 roughness and enhanced bottom friction associated with coral-reef frameworks further challenge the  
491 representation by the model of nearshore dynamics. Accordingly, the advective term in the mixed-layer budget  
492 herein should be interpreted as a conservative lower bound, which captures sign and seasonality but, potentially,  
493 underestimates magnitudes close to the coast. Targeted in-situ current measurements and/or nested higher-  
494 resolution regional modelling would help refine the role of advection within the gulfs.

495 Trends and correlations account for serial autocorrelation through effective degrees of freedom. EOFs were  
496 analyzed from raw data as well as from data to which 2-year and 5-year low-pass filters were applied. While  
497 filtering choices can shift correlation maxima to a certain degree, they do not alter the physical interpretation.  
498 The 1-km MUR record dictates the 20-year baseline (2003–2022) and is shorter than the canonical 30-year  
499 climatology. Thresholds and category counts may therefore be modestly sensitive to baseline choice; extending  
500 thresholds with longer-record products (for example, coarser-resolution SST) would represent a more thorough  
501 sensitivity check.

502 Overall, such limitations do not alter the headline result: that surface heat flux dominates the seasonal cycle,  
503 that basin-wide anomalies are atmospherically forced, and that shelf–offshore contrasts arise from the interplay  
504 of mixed-layer depth and horizontal gradients.

#### 505 **4.4 Implications for JRNP and outlook**

506 Two immediate implications follow. First, the strong coupling between net heat flux and temperature, in  
507 conjunction with the typical ~two-month lag, suggest that simple seasonal outlooks based on forecasts of  
508 radiative and turbulent fluxes and mixed-layer depth could offer early warning of forthcoming warming or  
509 cooling within GAM. Second, routine tracking of ENSO/WHWP (interannual) and NAO (low-frequency)  
510 provides a large-scale context for risk assessment. Consequently, positive phases aligned with reduced latent-  
511 heat loss increase the likelihood of basin-wide warmth (PC1) and, consequently, of MHW occurrence and  
512 persistence.

513 Moving forward, the following aspects have the potential to directly contribute to improving knowledge and  
514 forecasting capacity in the region: (a) in-situ observation of currents and conductivity, temperature and depth  
515 (from moorings or gliders transects) within JRNP and across the shelf break; (b) extended MHW climatologies,  
516 for example, by deriving thresholds from longer-record SST products, while retaining MUR for spatial detail;  
517 (c) targeted analyses of regional circulation features, such as shelf-break jets or eddy interactions, that may  
518 enhance advection during transition seasons at the local level; and (d) a practical next step is to implement a

519 regional, high-resolution ocean model (for example, CROCO) nested in GLORYS12/ERA5 and tailored to the  
520 JRNP–GAM–GG system. A horizontal resolution of ~1 km or finer (with tidal forcing, realistic bathymetry/reef  
521 roughness and bulk fluxes) would enhance efforts to resolve shelf-break jets, gulf exchanges and frontal  
522 dynamics that are under-represented in global reanalyses. Such steps would not only consolidate the  
523 mechanistic framework presented herein, but also help to translate it into operational guidance for conservation  
524 and management within the national park.

## 525 **5. Conclusions**

526 The present study has quantified seasonal-to-decadal variability of sea-surface temperature (SST) in and around  
527 the Jardines de la Reina National Park (JRNP), with the primary objective to identify the mechanisms and  
528 climate drivers that shape this variability, using daily 1-km MUR SST (2003–2022), ERA5 surface fluxes and  
529 GLORYS12 mixed-layer fields.

530 A mixed-layer heat budget shows that net surface heat flux sets the seasonal evolution of SST, with horizontal  
531 advection providing a smaller modulation near the shelf break; a characteristic ~2-month lead of flux over  
532 temperature is consistent with mixed-layer heat storage and explains the enhanced winter cooling and stronger  
533 thermal gradients along the shelf edge. A clear shelf–offshore contrast emerges: the shallow gulfs (GAM/GG)  
534 markedly differ from the adjacent Caribbean Sea (CS) in autumn–winter (November–March), whereas  
535 conditions during spring–summer are comparatively homogeneous. This reflects shallower mixed layers and  
536 greater flux sensitivity inside the gulfs, with advection adding local modulation. Superimposed on this baseline  
537 is a warming trend of  $\sim 0.28^{\circ}\text{C}/\text{decade}^{-1}$  (2003–2022), which is strongest in winter and transition months, with  
538 monthly maxima around April ( $\sim 0.48^{\circ}\text{C}/\text{decade}^{-1}$ ) and November ( $\sim 0.35^{\circ}\text{C}/\text{decade}^{-1}$ ), and a step-like transition  
539 in 2011–2013 towards a persistently warmer state. The warming trend is predominantly driven by the phase  
540 shift of the NAO, since the study period begins in a negative phase and ends in a positive phase. In addition,  
541 the interannual to decadal modulation of other dominant climatic oscillations in the region (ENSO, WHWP),  
542 in conjunction with latent heat fluxes, favours the progressive accumulation of heat in the ocean surface layer.  
543 Marine heatwaves intensified during the second decade (with the 2019–2020 period the most active, followed  
544 by 2015–2016). Mean event-wise maximum intensity is higher within GAM, whereas upper categories occur  
545 relatively more often offshore, consistent with lower background variance in the area, while total MHW days  
546 exceed 200 across the domain and 400 over much of the gulf. EOFs separate a basin-wide mode (EOF1, 87.5%),  
547 co-varying interannually with ENSO/WHWP and latent-heat flux and at low frequencies with the NAO, from  
548 a shelf–offshore dipole (EOF2, 6.2%) linked most clearly to TNA. This indicates atmospheric forcing of basin-  
549 wide anomalies with regional thermodynamics and advection setting spatial structure.

550 Practically, seasonal outlooks based on forecasts of net heat flux and mixed-layer depth, in addition to routine  
551 monitoring of ENSO/WHWP and NAO, can help to inform MHW risk in relation to JRNP. Indeed, a regional  
552 high-resolution ocean model (for example, ROMS/CROCO at ~1 km or finer), combined with targeted in-situ  
553 observations, would further improve prediction and attribution. In conjunction, the results of the present

554 research provide a physically grounded baseline for anticipating future thermal stress and for guiding  
555 conservation and management efforts within JRNP in response to continued climate warming.  
556

557 **Code and data availability:**

558 The data supporting the findings of this study are openly available from public repositories. Sea surface  
559 temperature data from the MUR dataset can be accessed at the JPL Physical Oceanography Distributed Active  
560 Archive Center (PODAAC, <https://podaac.jpl.nasa.gov>). The GLORYS12 ocean reanalysis data used are  
561 available through the Copernicus Marine Environment Monitoring Service (<https://marine.copernicus.eu>).  
562 ERA5 reanalysis data can be obtained from the European Centre for Medium-Range Weather Forecasts  
563 Climate Data Store (<https://cds.climate.copernicus.eu>).

564 **Author contribution:**

565 MC conceived the original idea, performed data analysis and image visualization and was responsible for  
566 writing the manuscript. OP co-conceived the original idea, helped interpret the results and provided key input  
567 in discussions and further writing. He also served as supervisor. AM contributed with the preparation of the  
568 original idea and conducted a review of the results and discussions. He was co-supervisor. IPS undertook data  
569 analysis and result interpretation and played a key role in discussions pertaining to heat balance. DC  
570 performed analysis of the MHWs and heat balance and supported the writing and interpretation of the results  
571 and discussions. DB endorsed the analysis and interpretation of SST trends and assisted in reviewing the  
572 manuscript. LC provided support with image processing using the geographic information system (QGis).

573 **Competing interests:**

574 The authors do not declare conflicts of interest.

575 **Acknowledgements:**

576 We thank all the centres listed above (Code and data availability section) by providing the data that support  
577 this research. Special thanks to Roberto González de Zayas y Julio Antonio Lestayoy by providing in situ  
578 temperature data. The discussion and technical support in the analysis of the data provided by staff of the  
579 Oceanographic Instrumentation Center (CIO, ANID grant CCSS210020) is greatly appreciated. We thank  
580 also the anonymous reviewers for their comments, which contributed significantly to the improvement of the  
581 quality of the manuscript. We used Grammarly, DeepL, and MS Word corrector during the writing of the  
582 manuscript.

583 *Data access notes:* MEI.v2 and the WHWP/TNA indices were retrieved from the NOAA PSL portals; the  
584 NAO index was retrieved from NOAA CPC (accessed in 2024–2025; URLs listed in the Data Availability  
585 statement).

586 **Financial support:**

587 The first author was supported by the National Agency for Research and Development of Chile (ANID), grant  
588 21211088 as part of the PhD grant program. This research was partially funded by the Chilean Millennium

589 Institute of Oceanography (IMO) (grant IC-120019). OP and MC thank also support from FONDECYT  
590 1241203. IP-S was funded by COPAS COASTAL (ANID FB210021) and FONDECYT 1251038

591

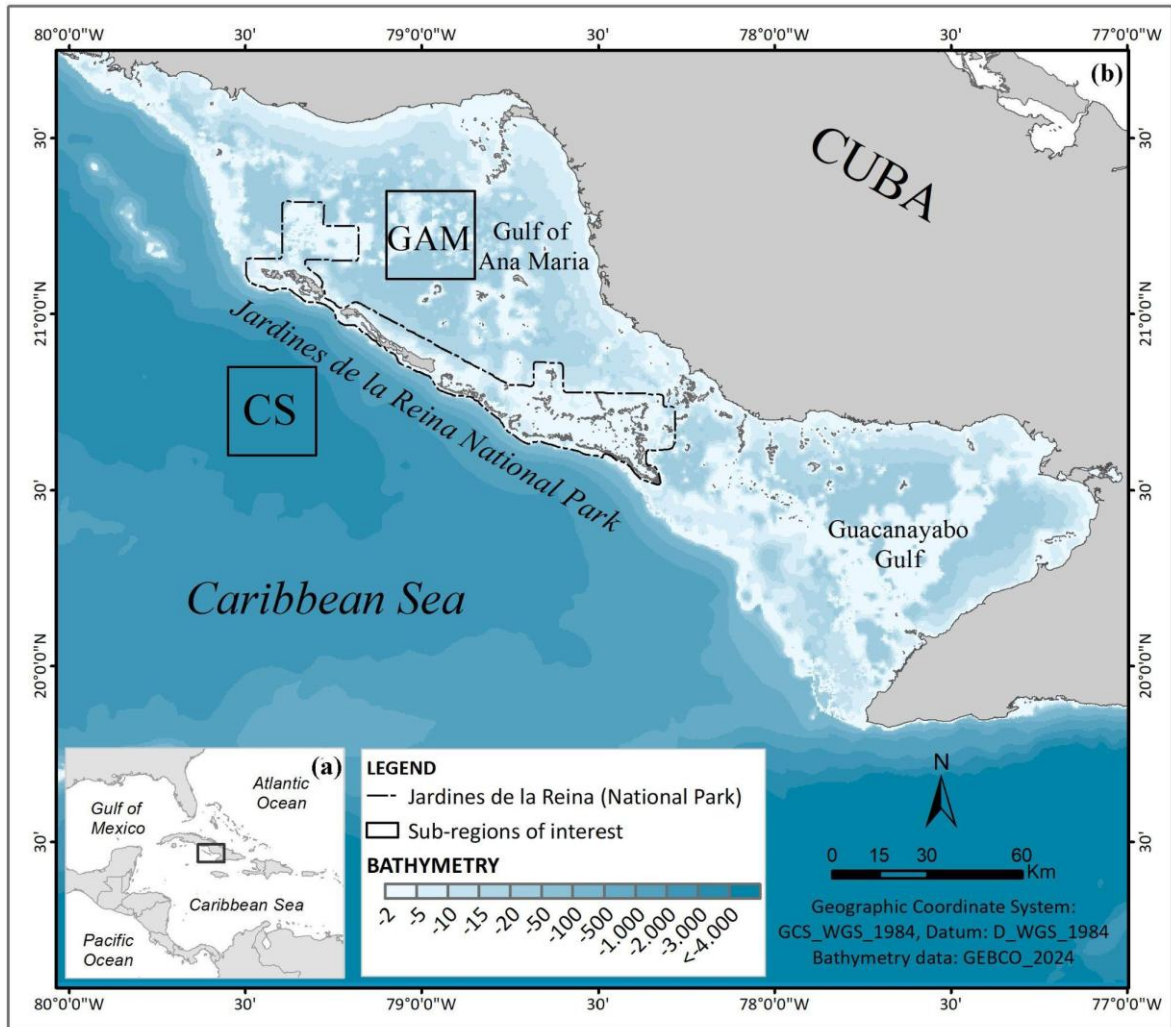
592 **References**

- 593 Appeldoorn, R. S. and Lindeman, K. C.: A Caribbean-wide survey of marine reserves: spatial coverage and  
594 attributes of effectiveness, *Gulf and Caribbean Research*, 14, 139–154, 2003.
- 595 Arriaza, L., Simanca, J., Rodas, R., Lorenzo, S., Hernández, M., Linares, E. O., Milian, D., and Romero, P.:  
596 Corrientes marinas estimadas en la plataforma suroriental cubana, *Serie Oceanológica*, 4, 1-10, 2008.
- 597 Avila-Alonso, D., Baetens, J. M., Cardenas, R., and De Baets, B.: Spatio-temporal variability of oceanographic  
598 conditions in the Exclusive Economic Zone of Cuba, *Journal of Marine Systems*, 212, 103416, 2020.
- 599 Barnston, A. G. and Livezey, R. E.: Classification, seasonality and persistence of low-frequency atmospheric  
600 circulation patterns, *Monthly Weather Review*, 115, 1083–1126, 1987.
- 601 Bruno, J. F., Côté, I. M., and Toth, L. T.: Climate change, coral loss, and the curious case of the parrotfish  
602 paradigm: why don't marine protected areas improve reef resilience?, *Annual Review of Marine Science*, 11,  
603 307–334, 2019.
- 604 Caballero-Aragón, H., Perera-Valderrama, S., Rey-Villiers, N., González-Méndez, J., and Armenteros, M.:  
605 Population status of *Acropora palmata* (Lamarck, 1816) in Cuban coral reefs, *Regional Studies in Marine*  
606 *Science*, 34, 101029, <https://doi.org/10.1016/j.rsma.2019.101029>, 2020.
- 607 Caravaca, A. M., Torres, L. C., and Alfonso, L. V.: Sea Surface Temperature Trends in the Southern Cuban  
608 Shelves for the Period 1982–2018, *Cham*, 81-90, 2022.
- 609 Cerdeira-Estrada, S., Müller-Karger, F. E., and Gallegos-García, A.: Variability of the sea surface temperature  
610 around Cuba, *Gulf of Mexico Science*, 23, 2, 2005.
- 611 Chang, Y.-L. and Oey, L.-Y.: Coupled response of the trade wind, SST gradient, and SST in the Caribbean Sea,  
612 and the potential impact on Loop Current's interannual variability, *Journal of Physical Oceanography*, 43,  
613 1325–1344, 2013.
- 614 Chen, H. C., Jin, F.-F., and Jiang, L.: The phase-locking of tropical North Atlantic and the contribution of  
615 ENSO, *Geophysical Research Letters*, 48, e2021GL095610, 2021.
- 616 Chen, W. Y. and Van den Dool, H.: Sensitivity of teleconnection patterns to the sign of their primary action  
617 center, *Monthly Weather Review*, 131, 2885–2899, 2003.
- 618 Chin, T. M., Vazquez-Cuervo, J., and Armstrong, E. M.: A multi-scale high-resolution analysis of global sea  
619 surface temperature, *Remote Sensing of Environment*, 200, 154–169, <https://doi.org/10.1016/j.rse.2017.07.029>,  
620 2017.
- 621 Chollett, I., Mumby, P. J., Müller-Karger, F. E., and Hu, C.: Physical environments of the Caribbean Sea,  
622 *Limnology and Oceanography*, 57, 1233–1244, 2012.
- 623 Cook, K. and Vizy, E.: Hydrodynamics of the Caribbean low-level jet and its relationship to precipitation,  
624 *Journal of Climate*, 23, 1477–1494, 2010.
- 625 Cramer, K. L., Jackson, J. B. C., Donovan, M. K., Greenstein, B. J., Korpanty, C. A., Cook, G. M., and Pandolfi,  
626 J. M.: Widespread loss of Caribbean acroporid corals was underway before coral bleaching and disease  
627 outbreaks, *Science Advances*, 6, eaax9395, <https://doi.org/10.1126/sciadv.aax9395>, 2020.
- 628 Czaja, A., Van der Vaart, P., and Marshall, J.: A diagnostic study of the role of remote forcing in tropical  
629 Atlantic variability, *Journal of Climate*, 15, 3280–3290, 2002.

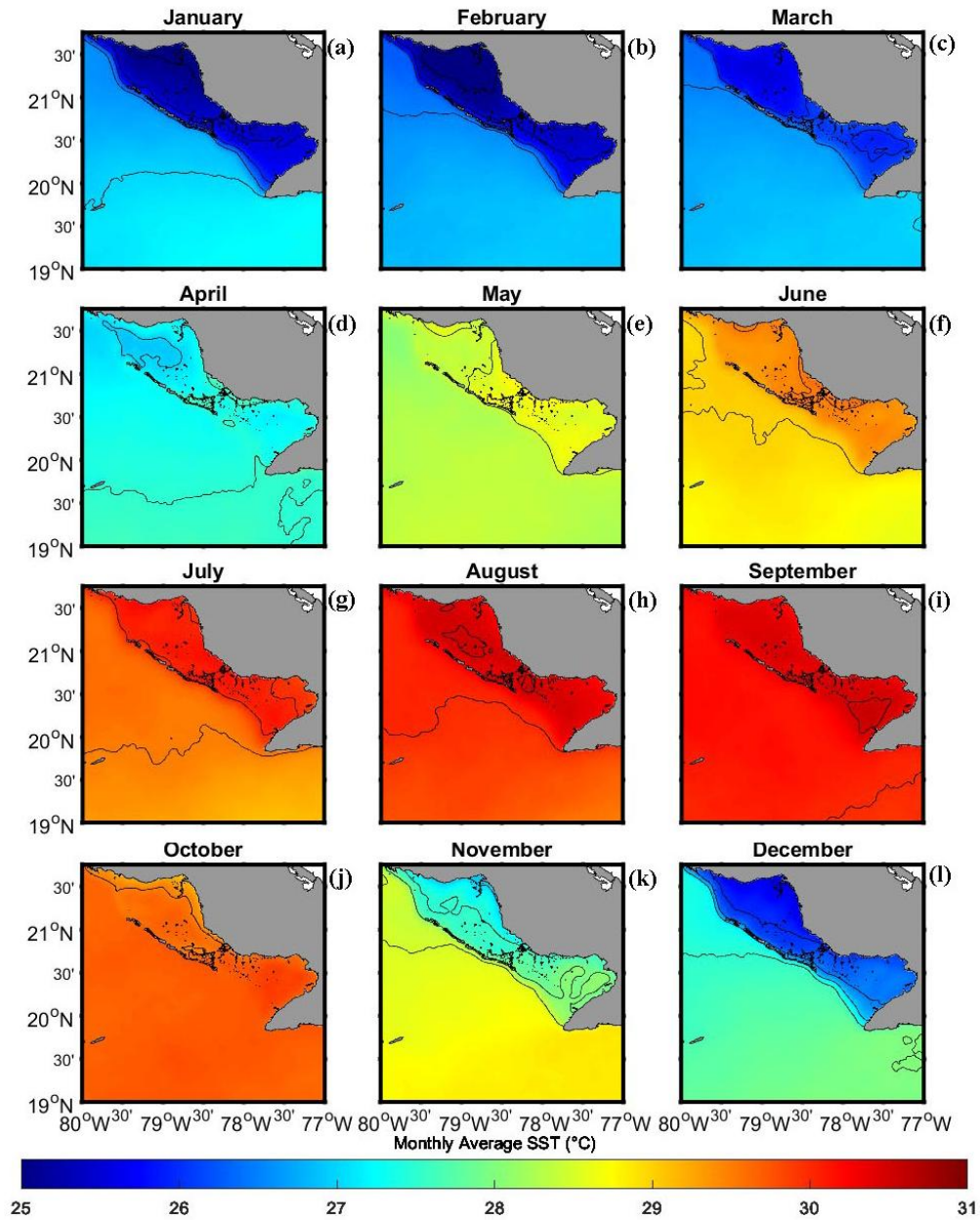
- 630 de Boyer Montégut, C., Madec, G., Fischer, A. S., Lazar, A., and Iudicone, D.: Mixed layer depth over the  
631 global ocean: An examination of profile data and a profile-based climatology, *Journal of Geophysical Research: Oceans*, 109, 2004.  
632
- 633 Emilsson, I. and Tápanes, J. J.: Contribución a la hidrología de la plataforma sur de Cuba, *Serie Oceanológica*,  
634 9, 1971.
- 635 Enfield, D. B. and Lee, S.-K.: The heat balance of the Western Hemisphere warm pool, *Journal of Climate*, 18,  
636 2662–2681, 2005.
- 637 Enfield, D. B., Mestas-Núñez, A. M., Mayer, D. A., and Cid-Serrano, L.: How ubiquitous is the dipole  
638 relationship in tropical Atlantic sea surface temperatures?, *Journal of Geophysical Research: Oceans*, 104,  
639 7841–7848, 1999.
- 640 Fernández, L. H. and López, C. B.: Condición de la población de ACROPORA PALMATA LAMARCK, 1816  
641 en arrecifes del Parque Nacional Jardines de la Reina, Cuba, *Revista de Investigaciones Marinas*, 37, 2017.
- 642 Gerhartz-Muro, J. L., Kritzer, J. P., Gerhartz-Abraham, A., Miller, V., Pina-Amargós, F., and Whittle, D.: An  
643 evaluation of the framework for national marine environmental policies in Cuba, *Bulletin of Marine Science*,  
644 94, 443–459, 2018.
- 645 González-De Zayas, R., Pupo, F. M., González, J. A. L., and Hernández-Fernández, L.: Temporal behavior of  
646 air and sea surface temperature in a marine protected area of Cuba: the Jardines de la Reina National Park,  
647 *Holos Environment*, 22, 46–64, 2022.
- 648 Graham, N. A. J., Jennings, S., MacNeil, M. A., Mouillot, D., and Wilson, S. K.: Predicting climate-driven  
649 regime shifts versus rebound potential in coral reefs, *Nature*, 518, 94–97, 2015.
- 650 Hernández-Fernández, L., González de Zayas, R., Olivera, Y. M., Pina Amargós, F., Bustamante López, C.,  
651 Dulce Sotolongo, L. B., Bretos, F., Figueredo Martín, T., Lladó Cabrera, D., and Salmón Moret, F.: Distribution  
652 and status of living colonies of *Acropora* spp. in the reef crests of a protected marine area of the Caribbean  
653 (Jardines de la Reina National Park, Cuba), *PeerJ*, 7, e6470, 2019.
- 654 Hernández-Fernández, L., Guimaraes Bermejo, M., Arias Barreto, R., and Clero Alonso, L.: Composición de  
655 las comunidades de octocorales y corales pétreos y la incidencia del blanqueamiento del 2005 en Jardines de la  
656 Reina, Cuba, *Journal of Marine and Coastal Sciences*, 3, 77–90, 2011.
- 657 Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C. J., Benthuisen, J. A.,  
658 Burrows, M. T., Donat, M. G., and Feng, M.: A hierarchical approach to defining marine heatwaves, *Progress*  
659 *in Oceanography*, 141, 227–238, 2016.
- 660 Hobday, A. J., Oliver, E. C. J., Sen Gupta, A., Thomas, L., and Benthuisen, J. A.: Categorizing and naming  
661 marine heatwaves, *Oceanography*, 31(2), 162–173, 2018.
- 662 Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., Grosberg, R., Hoegh-  
663 Guldberg, O., Jackson, J. B. C., and Kleypas, J.: Climate change, human impacts, and the resilience of coral  
664 reefs, *Science*, 301, 929–933, 2003.
- 665 Hurrell, J. W.: Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation,  
666 *Science*, 269, 676–679, 1995.
- 667 Jackson, J., Donovan, M., Cramer, K., and Lam, V.: Status and trends of Caribbean coral reefs: 1970–2012,  
668 *Global Coral Reef Monitoring Network (GCRMN)*, IUCN, Gland, Switzerland, 2014.

- 669 Kumagai, N. H. and Yamano, H.: High-resolution modelling of thermal thresholds and environmental  
670 influences on coral bleaching for local and regional reef management, *PeerJ*, 6, e4382, 2018.
- 671 Linton, D., Smith, R., Alcolado, P., Hanson, C., Edwards, P., Estrada, R., Fisher, T., Fernandez, R. G., Gerald  
672 F., and McCoy, C.: 15. Status of coral reefs in the northern Caribbean and Atlantic node of the GCRMN, in:  
673 Status of Coral Reefs of the World: 2002, Australian Institute of Marine Science; Global Coral Reef Monitoring  
674 Network, 277-302, 2002.
- 675 Lotze, H. K., Lenihan, H. S., Bourque, B. J., Bradbury, R. H., Cooke, R. G., Kay, M. C., Kidwell, S. M., Kirby,  
676 M. X., Peterson, C. H., and Jackson, J. B. C.: Depletion, degradation, and recovery potential of estuaries and  
677 coastal seas, *Science*, 312, 1806–1809, 2006.
- 678 Moisan, J. R. and Niiler, P. P.: The seasonal heat budget of the North Pacific: net heat flux and heat storage  
679 rates (1950–1990), *Journal of Physical Oceanography*, 28, 401–421, 1998.
- 680 Mumby, P. J., Flower, J., Chollett, I., Box, S. J., Bozec, Y.-M., Fitzsimmons, C., Forster, J., Gill, D., Griffith-  
681 Mumby, R., and Oxenford, H. A.: Towards reef resilience and sustainable livelihoods: a handbook for  
682 Caribbean coral reef managers, University of Exeter, Exeter, 2014.
- 683 Pérez-Santos, I., Schneider, W., Sobarzo, M., Montoya-Sánchez, R., Valle-Levinson, A., and Garcés-Vargas,  
684 J.: Surface wind variability and its implications for the Yucatán Basin–Caribbean Sea dynamics, *Journal of*  
685 *Geophysical Research: Oceans*, 115, C10052, 2010.
- 686 Skerrett, F., Adelson, A., and Collin, R.: Performance of high-resolution MUR satellite sea surface temperature  
687 data as a proxy for near-surface in situ temperatures on neotropical reefs, *Latin American Journal of Aquatic*  
688 *Research*, 52, 270–288, 2024.
- 689 Thomson, R. E. and Emery, W. J.: *Data Analysis Methods in Physical Oceanography*, 4th edn., Elsevier,  
690 Amsterdam, 2024.
- 691 Van den Dool, H., Saha, S., and Johansson, A.: Empirical orthogonal teleconnections, *Journal of Climate*, 13,  
692 1421–1435, 2000.
- 693 van Hooidonk, R., Maynard, J. A., Liu, Y., and Lee, S. K.: Downscaled projections of Caribbean coral bleaching  
694 that can inform conservation planning, *Global Change Biology*, 21, 3389–3401, 2015.
- 695 Venegas, R. M., Acevedo, J., and Treml, E. A.: Three decades of ocean warming impacts on marine ecosystems:  
696 a review and perspective, *Deep-Sea Research Part II: Topical Studies in Oceanography*, 212, 105318, 2023.
- 697 Waliser, D. and Jiang, X.: Tropical meteorology and climate: Intertropical Convergence Zone, *Encyclopedia of*  
698 *atmospheric sciences*, 6, Elsevier, 121-131, 2015.
- 699 Wang, C. and Enfield, D. B.: The tropical Western Hemisphere warm pool, *Geophysical Research Letters*, 28,  
700 1635–1638, 2001.
- 701 Wang, C. and Enfield, D. B.: A further study of the tropical Western Hemisphere warm pool, *Journal of Climate*,  
702 16, 1476–1493, 2003.
- 703 Wang, C., Enfield, D. B., Lee, S.-K., and Landsea, C. W.: Influences of the Atlantic warm pool on Western  
704 Hemisphere summer rainfall and Atlantic hurricanes, *Journal of Climate*, 19, 3011–3028, 2006.
- 705 Wang, C., Lee, S.-K., and Enfield, D. B.: Impact of the Atlantic warm pool on the summer climate of the  
706 Western Hemisphere, *Journal of Climate*, 20, 5021–5040, 2007.

- 707 Wolter, K.: Monitoring ENSO in COADS with a seasonally adjusted principal component index, in:  
708 Proceedings of the 17th Climate Diagnostics Workshop, 1993.
- 709 Zhang, T., Hoell, A., Perlwitz, J., Eischeid, J., Murray, D., Hoerling, M., and Hamill, T. M.: Towards  
710 probabilistic multivariate ENSO monitoring, *Geophysical Research Letters*, 46, 10532–10540, 2019.
- 711



713  
 714 **Figure 1.** Study area and sub-regions. (a) Regional setting: Cuba in the Caribbean Sea (CS), with the study  
 715 domain indicated by the black rectangle. (b) Southeastern Cuban shelf showing the Jardines de la Reina National  
 716 Park (black polygon) and neighbouring gulfs: Gulf of Ana María (GAM) and Gulf of Guacanayabo (GG). Black  
 717 boxes mark the two analysis sub-regions: GAM (shelf) and CS (oceanic). Colour shading shows bathymetry  
 718 (m) from GEBCO\_2024.  
 719



721

722

**Figure 2.** Monthly SST climatology (based on period 2003–2022). Panels (a–l) show monthly mean sea-surface

723

temperature (°C) from January to December. Black contours mark SST fronts identified, where local horizontal

724

SST differences are  $\geq 0.5$  °C. Seasonal groupings are: (a–c) boreal winter (JFM), (d–f) spring (AMJ), (g–i)

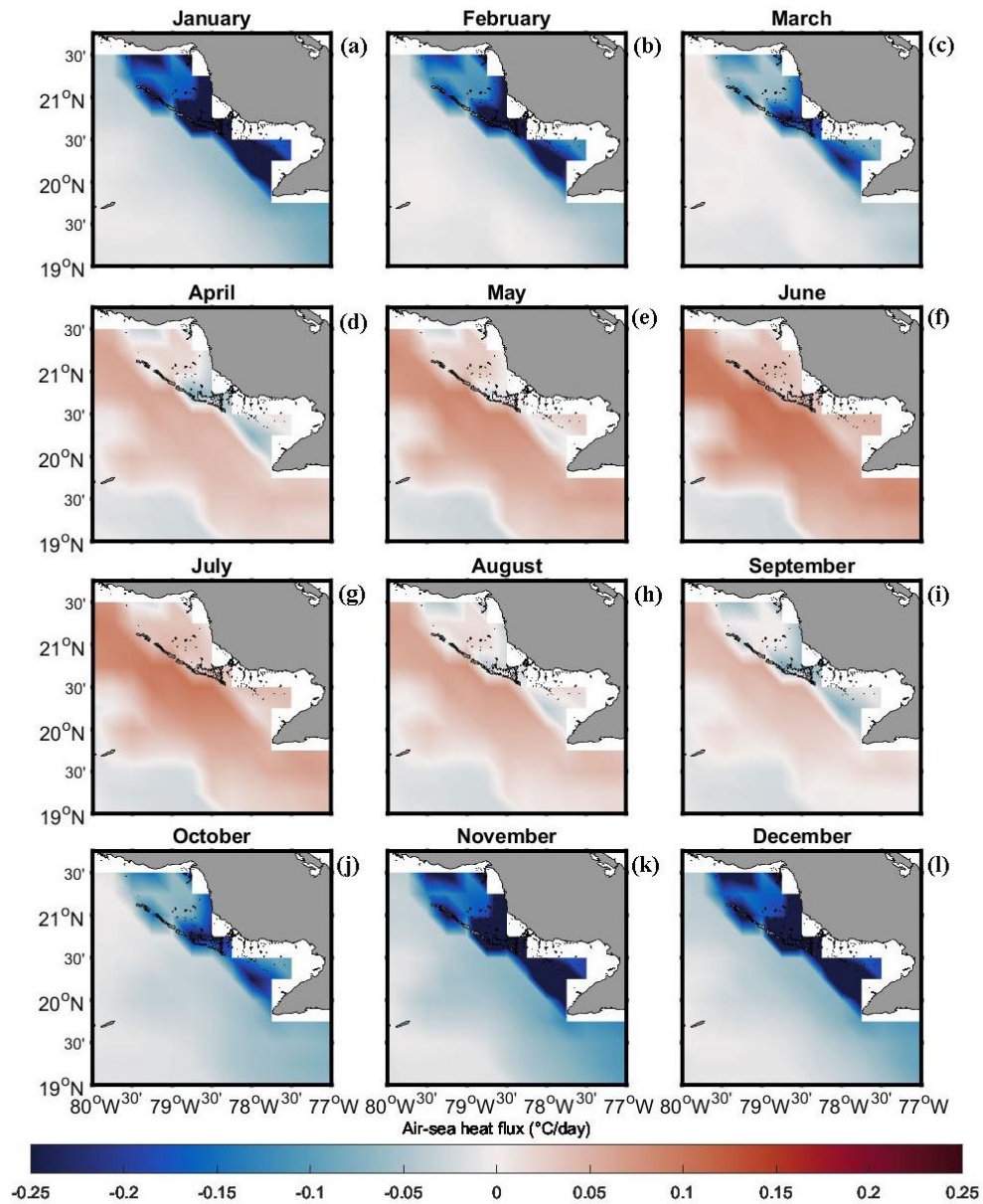
725

summer (JAS), and (j–l) autumn (OND). The colour bar indicates monthly mean SST (°C); land is masked in

726

grey.

727



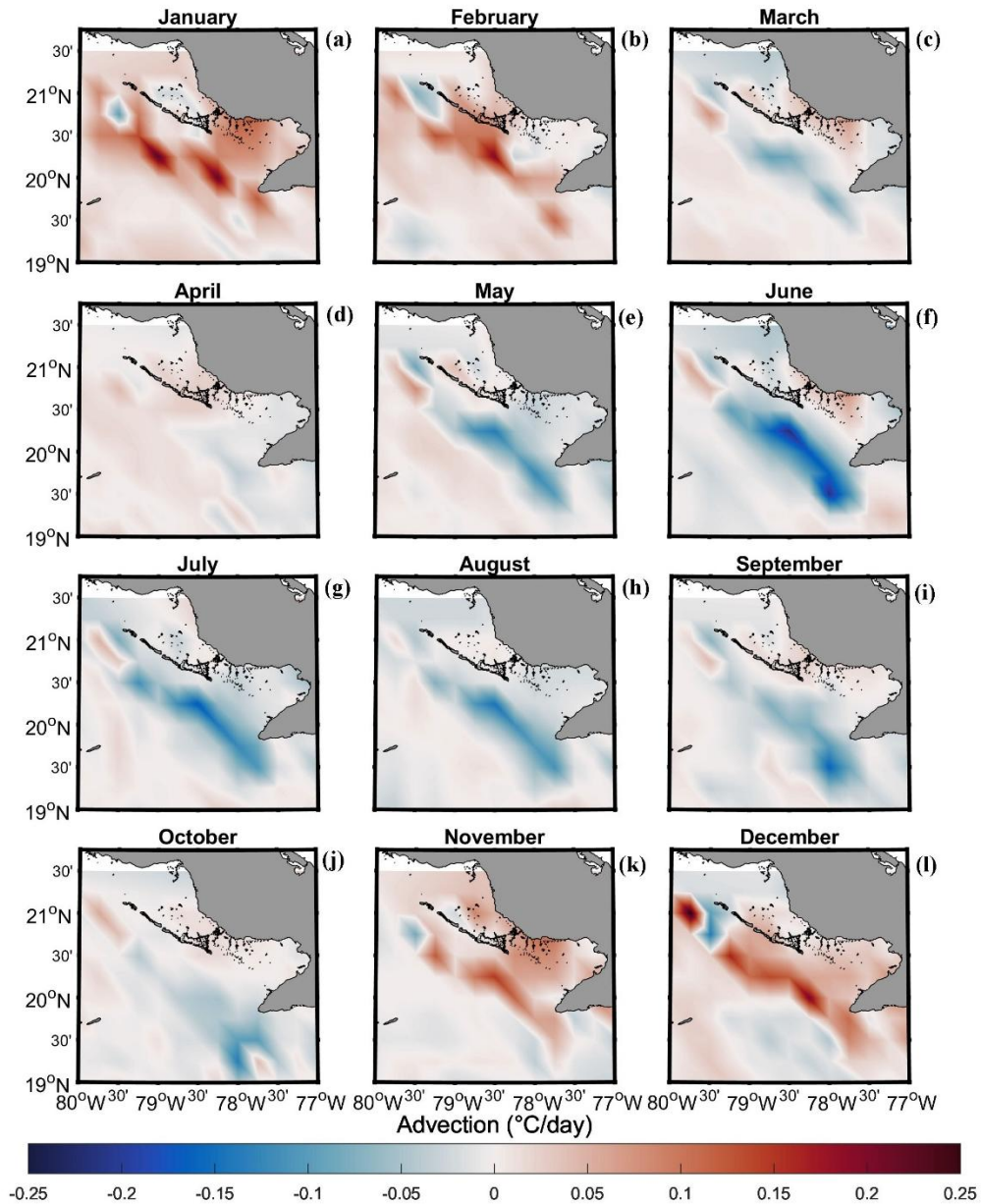
729

730 **Figure 3.** Monthly air-sea heat-flux tendency term. Panels (a–l) show the monthly mean mixed-layer heating  
 731 rate due to net air-sea heat exchange, expressed as  $^{\circ}\text{C day}^{-1}$  and computed as  $(\partial T/\partial t)|_Q = Q_{net}/(\rho C_p h)$ .

732 Positive (red) warms the ocean; negative (blue) cools the ocean. Months run January–December; seasonal  
 733 groupings are (a–c) boreal winter (JFM), (d–f) spring (AMJ), (g–i) summer (JAS), and (j–l) autumn (OND).

734 Flux components are from ERA5, mixed-layer depth  $h$  from GLORYS12 all variables are for the period 2003–  
 735 2022; land is masked in grey.

736



738

739

**Figure 4.** Monthly horizontal heat-advection tendency term. Panels (a–l) show the monthly mean mixed-layer

740

temperature tendency due to horizontal advection, expressed as  $^{\circ}\text{C day}^{-1}$  and computed as

741

$(\partial T/\partial t)|_{adv} = -U \cdot \nabla T$ . Positive (red) warms the mixed layer; negative (blue) cools it. Currents and

742

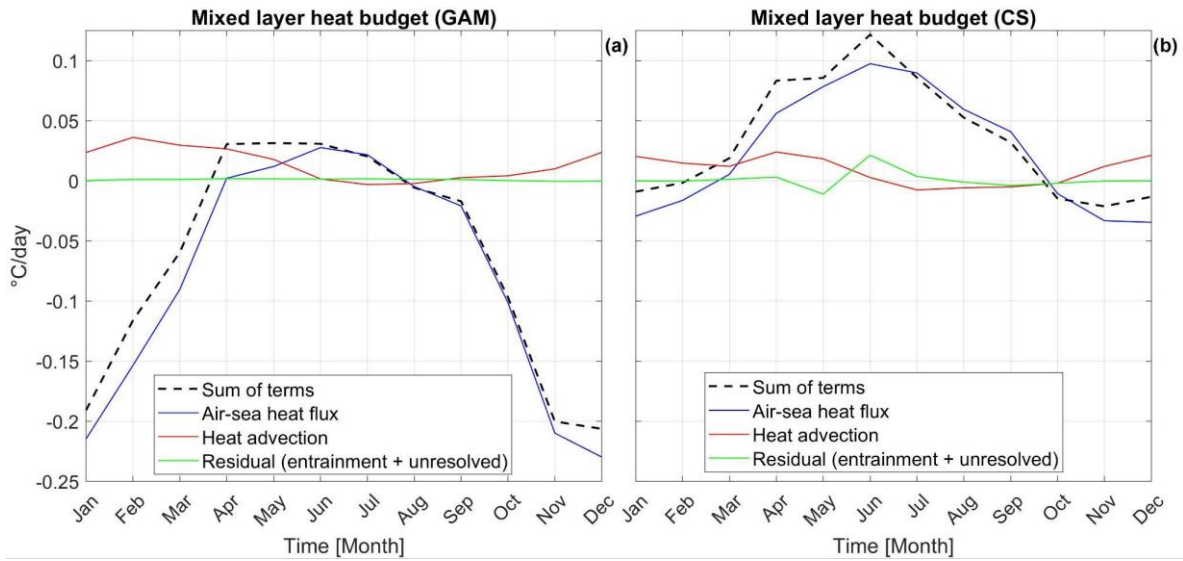
temperature gradients are from GLORYS12 (ML-averaged currents and mixed-layer temperature) all variables

743

are for the period 2003–2022; land is masked in grey.

744

745



747

748

749

750

751

752

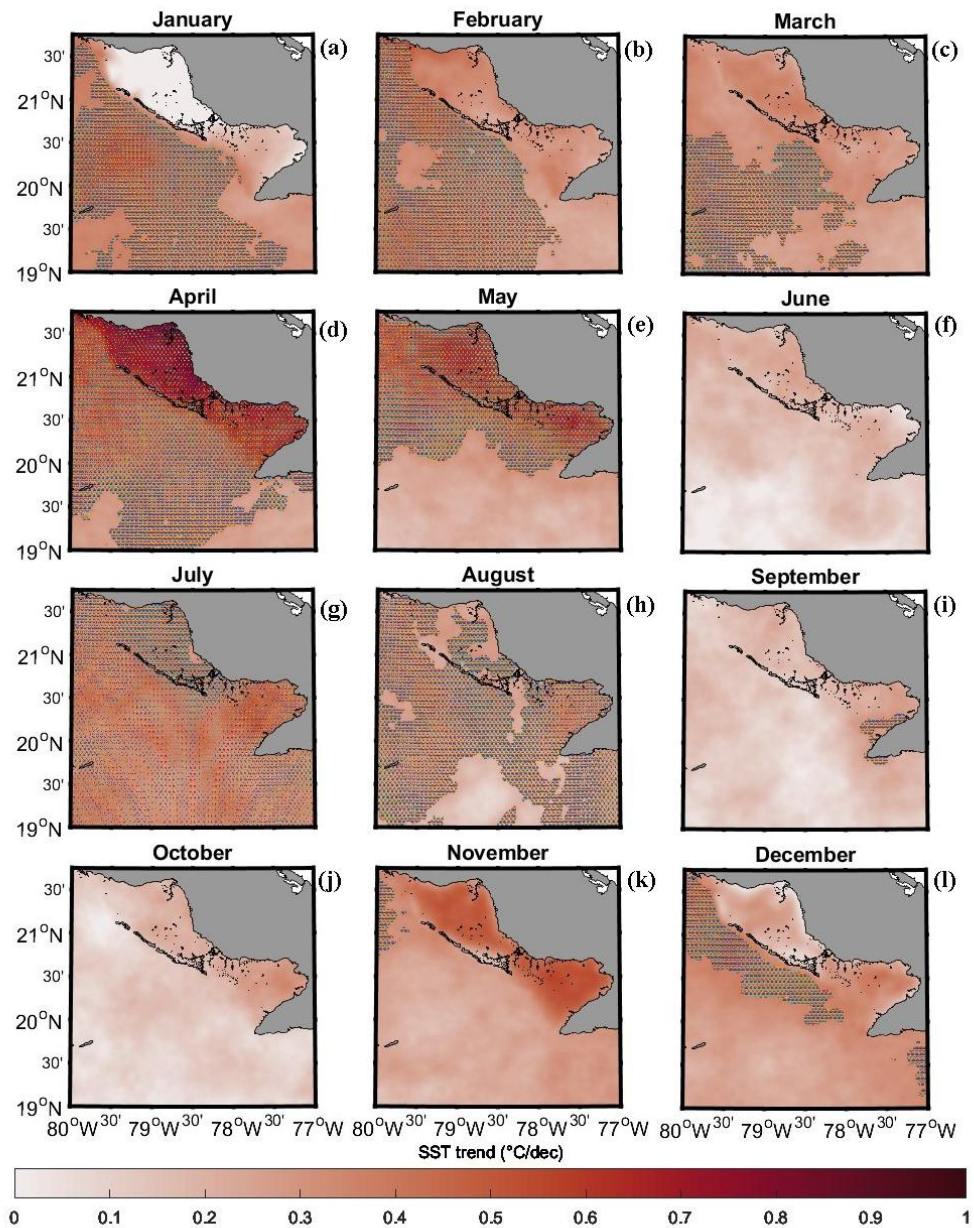
753

754

755

756

**Figure 5.** Seasonal mixed-layer heat budget (2003–2022). Monthly climatologies of mixed-layer temperature tendencies ( $^{\circ}\text{C day}^{-1}$ ) for (a) GAM and (b) CS. Blue line: air–sea heat-flux tendency  $(\partial T/\partial t)|_Q = Q_{net}/(\rho C_p h)$ . Red line: horizontal advection  $(\partial T/\partial t)|_{adv} = -U \cdot \nabla T$ . Dashed black line: sum of resolved terms (flux + advection). Green line: residual (entrainment + unresolved processes), computed as the observed mixed-layer temperature tendency minus the sum of resolved terms. Positive values warm the mixed layer; negative values cool it. All terms were computed from daily fields and averaged to monthly means; see Section 2.6 for data sources and sign conventions.

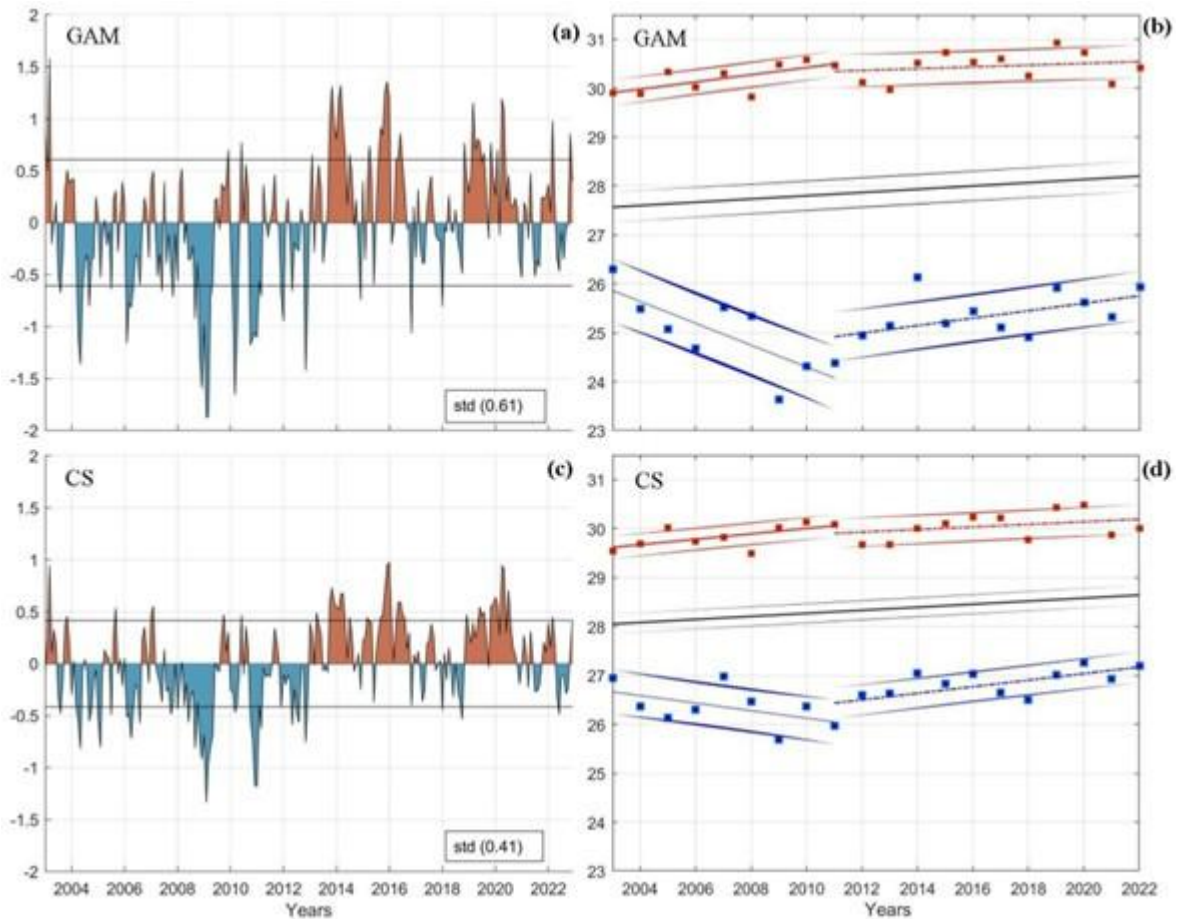


758

759

**Figure 6.** Monthly SST trends (2003–2022). Linear trends of monthly SST anomalies ( $^{\circ}\text{C}$  decade $^{-1}$ ) for  
 760 January–December (panels a–l). Trends are estimated by ordinary least squares applied to monthly anomalies  
 761 at each grid point. Stippling indicates grid cells that are significant at the 95% level (two-sided t-test), using  
 762 effective degrees of freedom to account for autocorrelation. Warming intensifies in winter and transition  
 763 months, with maxima in April and November; land is masked in grey.

764



766

767

768

769

770

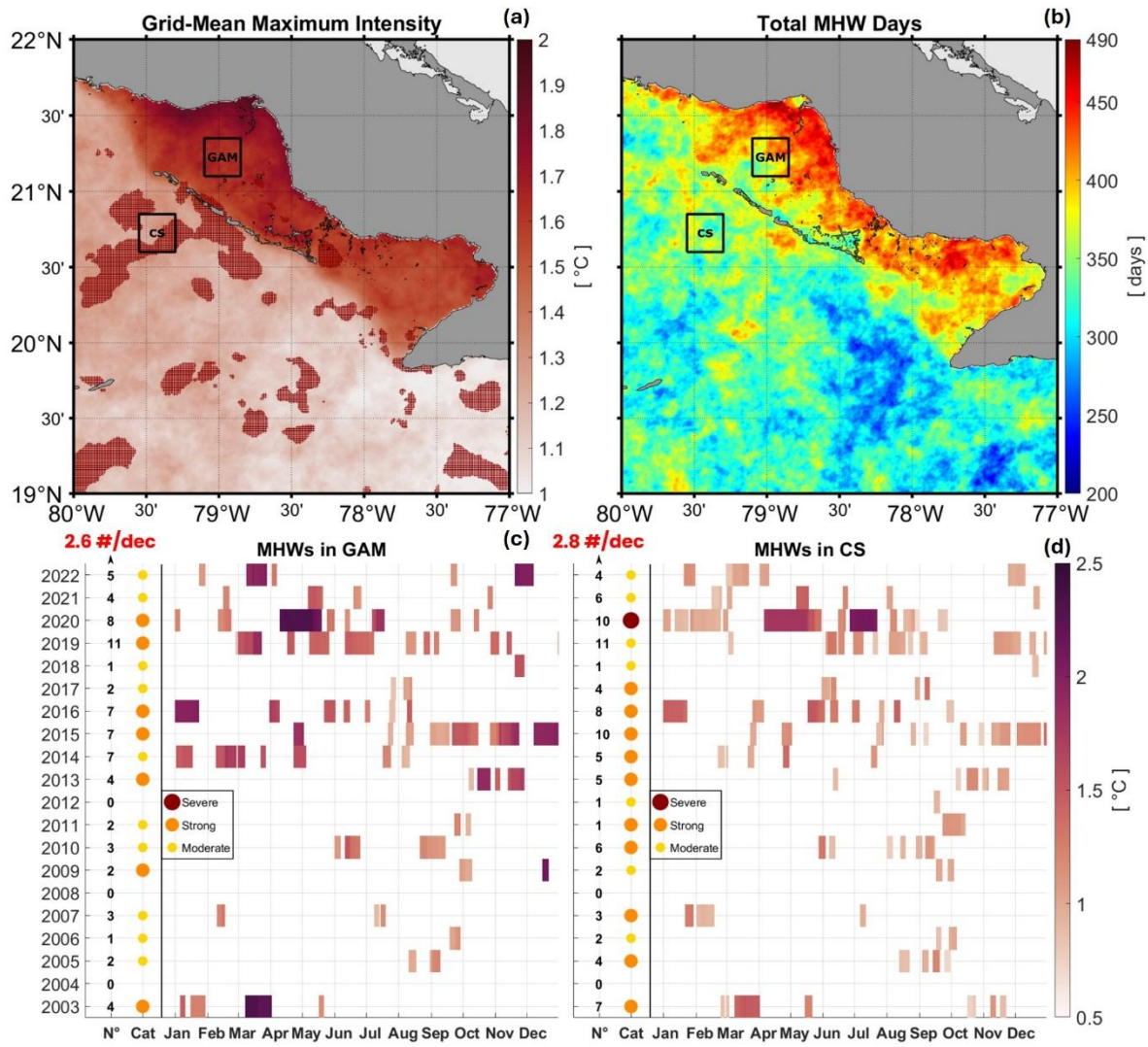
771

772

773

774

**Figure 7.** (a,c) Monthly SST anomalies ( $^{\circ}\text{C}$ ) for the Gulf of Ana María (GAM) and the Caribbean Sea (CS), respectively, 2003–2022. Thin horizontal black lines indicate  $\pm 1$  standard deviation over the full period (value shown in each panel). (b,d) Yearly seasonal means for summer (July–August–September; red squares) and winter (January–February–March; blue squares) in GAM and CS, respectively. Black lines show linear trends of the annual means. Coloured lines show piecewise linear fits to the seasonal means prior to (2003–2011) and after (2012–2022) the 2011 transition. All series represent area averages over the GAM and CS boxes shown in Figures 1a and 1b.



776

777

778

779

780

781

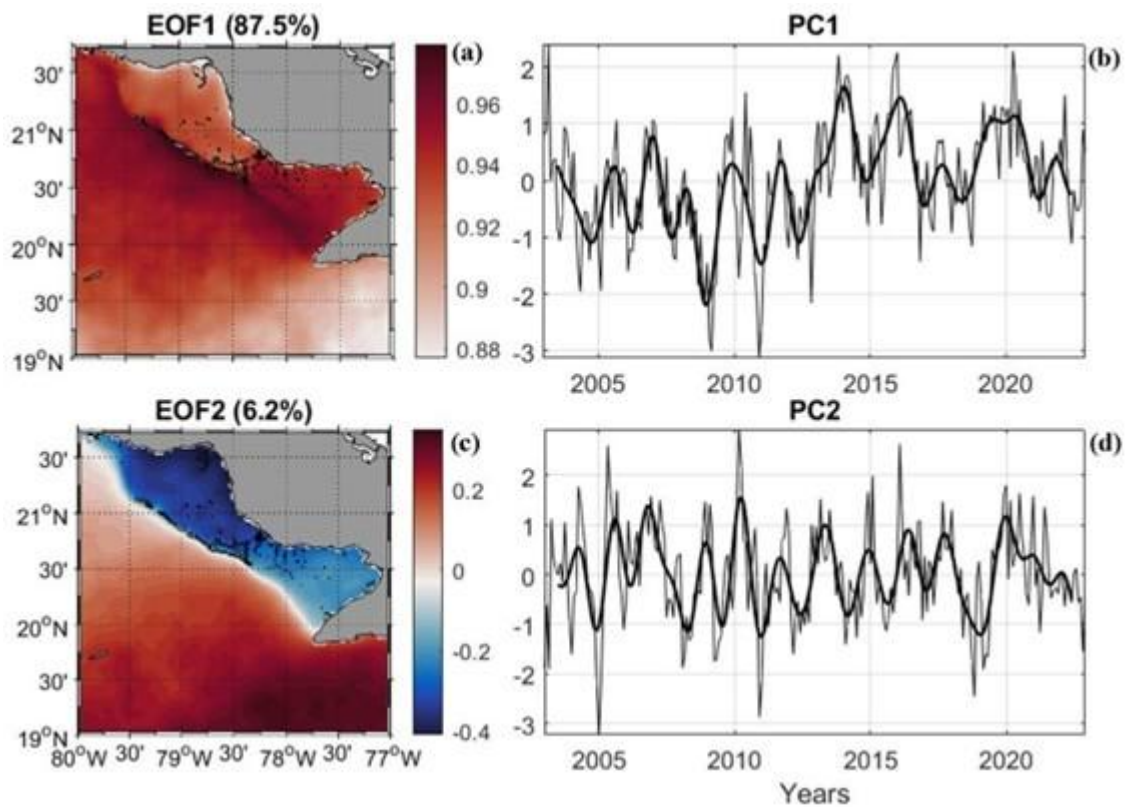
782

783

784

785

**Figure 8.** Marine heatwave (MHW) characteristics between 2003–2022. (a) Mean of event-wise maximum intensity (°C) at each grid point. Grid cells that experienced Severe category events at least once are shaded (reddish shading). (b) Total MHW days per grid point accumulated from 2003 to 2022. Black boxes mark the GAM and CS sub-regions. (c–d) Event calendars for GAM and CS, respectively: coloured rectangles denote individual events by month, with darker shading indicating increased intensity (°C). Left-hand columns indicate, for each year, the number of events (N°) and the maximum category reached (circle colour: Moderate/Strong/Severe). At the top left of c-d, the trend in event frequency is shown as the number of events per decade (#/dec).



787

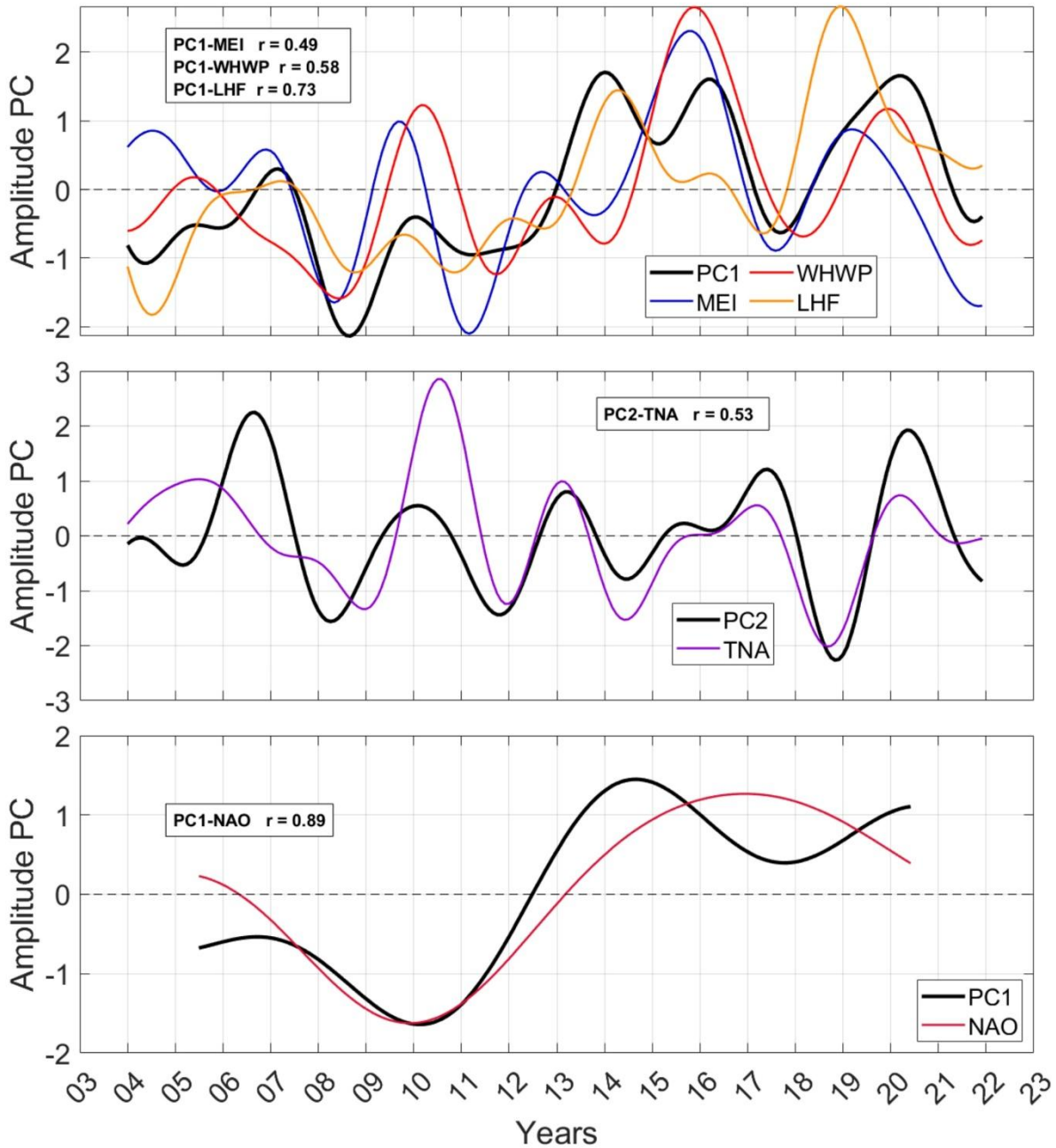
788

789

790

791

**Figure 9.** EOF analysis of monthly SST anomalies for 2003–2022. Left: spatial patterns of EOF1 (87.5 %) and EOF2 (6.2 %). Right: Corresponding principal components (PC1, PC2); thick black curve represents a two-year low-pass filter to emphasize interannual variability. (PC signs are arbitrary and chosen so that positive PCs correspond to warm anomalies in EOF1).



792  
793  
794  
795  
796  
797  
798  
799

**Figure 10.** Co-variability of SST principal components (PCs) with climate drivers. (a) Interannual band: 2-year running-mean low-pass of PC1 (black) plotted with MEI.v2 (blue), Western Hemisphere Warm Pool (WHWP) (red), and domain-mean latent heat flux (LHF) from ERA5 (orange). (b) Interannual band: PC2 (black) with Tropical North Atlantic (TNA) (magenta). (c) Low-frequency band: 5-year running-mean low-pass of PC1 (black) with North Atlantic Oscillation (NAO) (red). Numbers in text boxes denote zero-lag Pearson correlations ( $r$ ) computed on the filtered monthly series. Significance is evaluated using effective degrees of freedom (Section 2.5). Series are standardized.