

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

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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⁻¹ (strongest in winter/transition months,
35 peaking around April at ~0.48°C and November at ~0.35°C decade⁻¹) 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 3×3 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, 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 ∇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 ≥ 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 ± 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 ~ 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 (≥ 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 ∇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 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>). All processed data and analysis scripts are referenced
564 in the manuscript and are available upon reasonable request.

565 **Author contribution:**

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

574 **Competing interests:**

575 The authors do not declare conflicts of interest.

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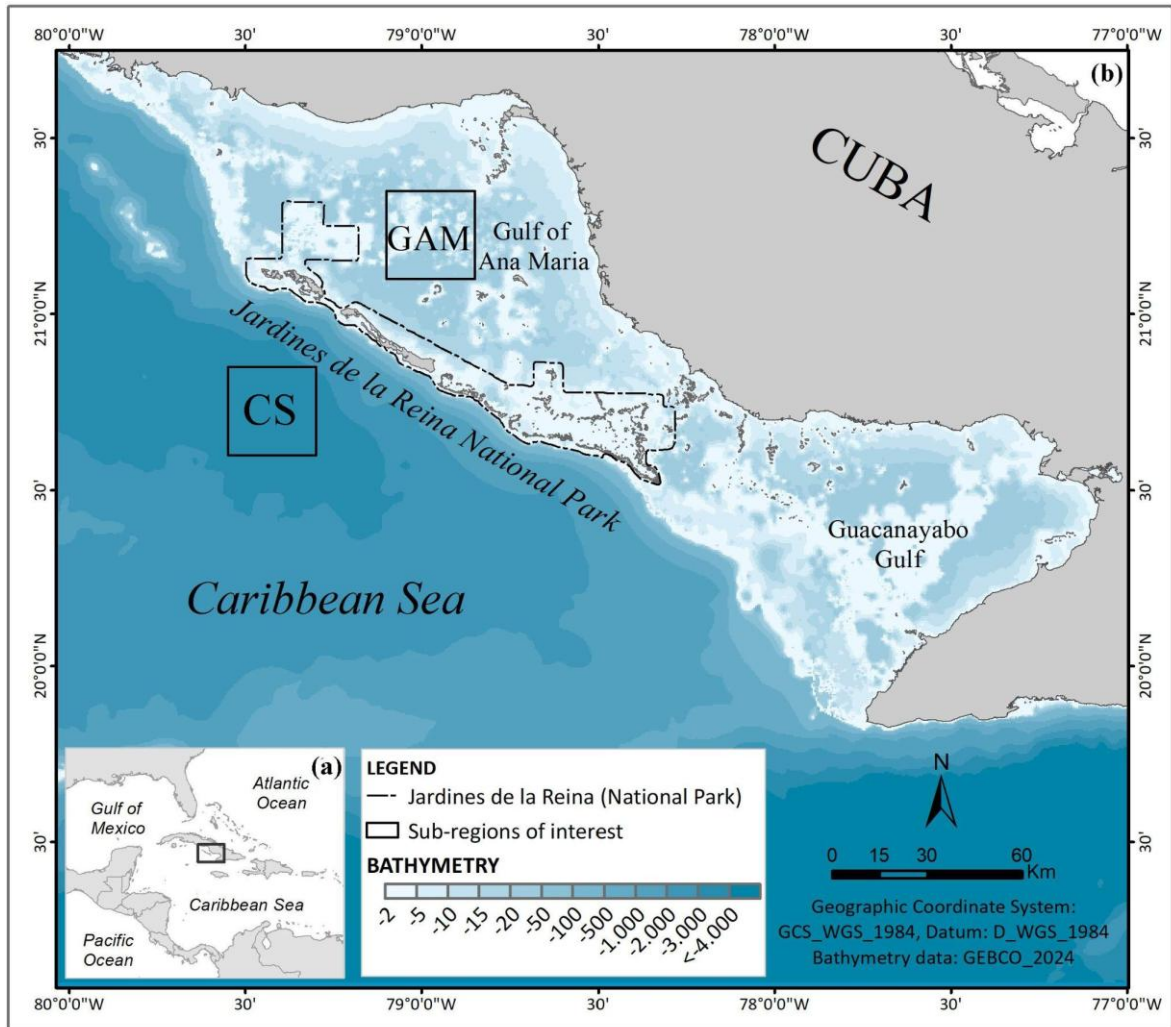
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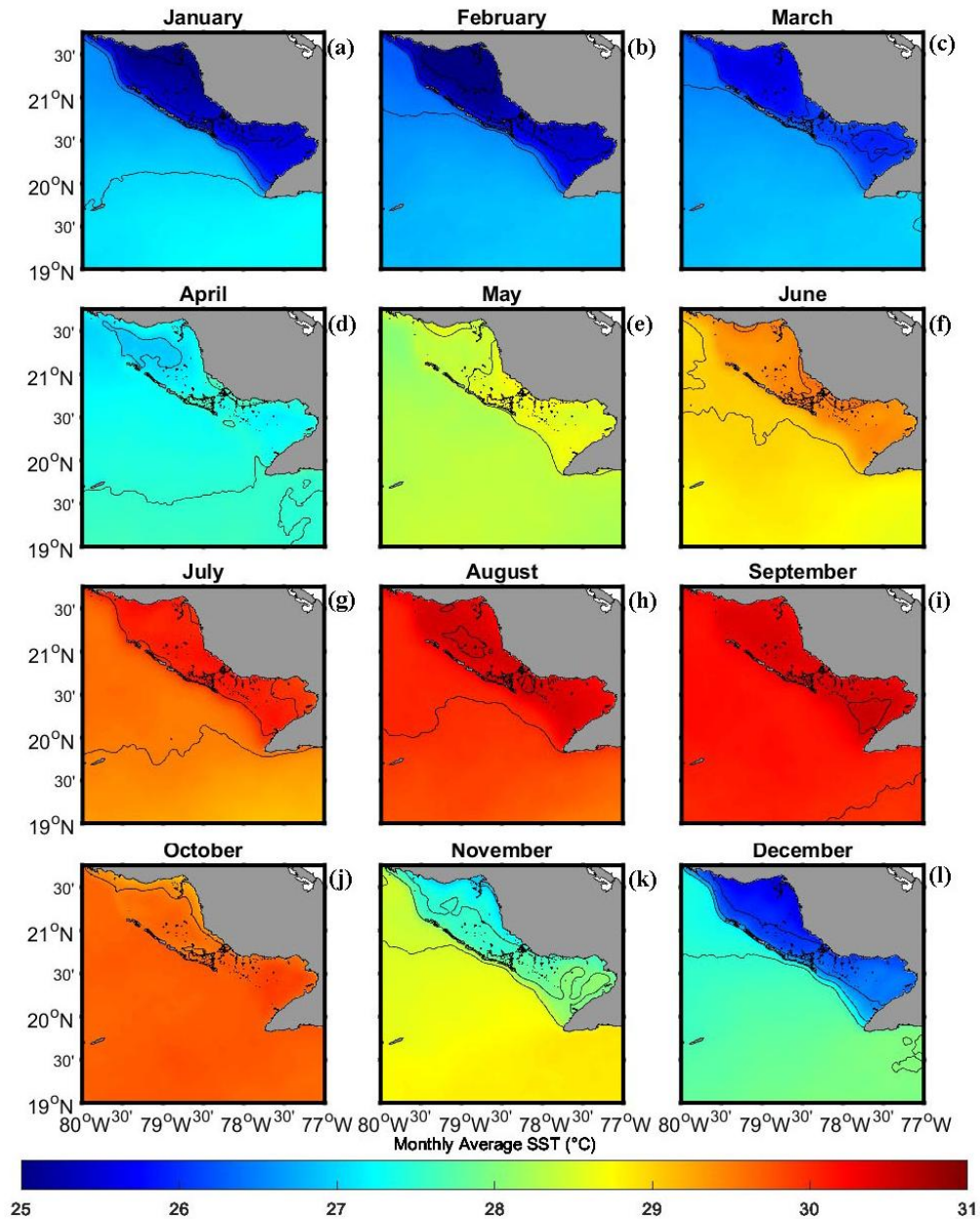
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 715 **Figure 1.** Study area and sub-regions. (a) Regional setting: Cuba in the Caribbean Sea (CS), with the study
 716 domain indicated by the black rectangle. (b) Southeastern Cuban shelf showing the Jardines de la Reina National
 717 Park (black polygon) and neighbouring gulfs: Gulf of Ana María (GAM) and Gulf of Guacanayabo (GG). Black
 718 boxes mark the two analysis sub-regions: GAM (shelf) and CS (oceanic). Colour shading shows bathymetry
 719 (m) from GEBCO_2024.
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Figure 2. Monthly SST climatology (based on period 2003–2022). Panels (a–l) show monthly mean sea-surface

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

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

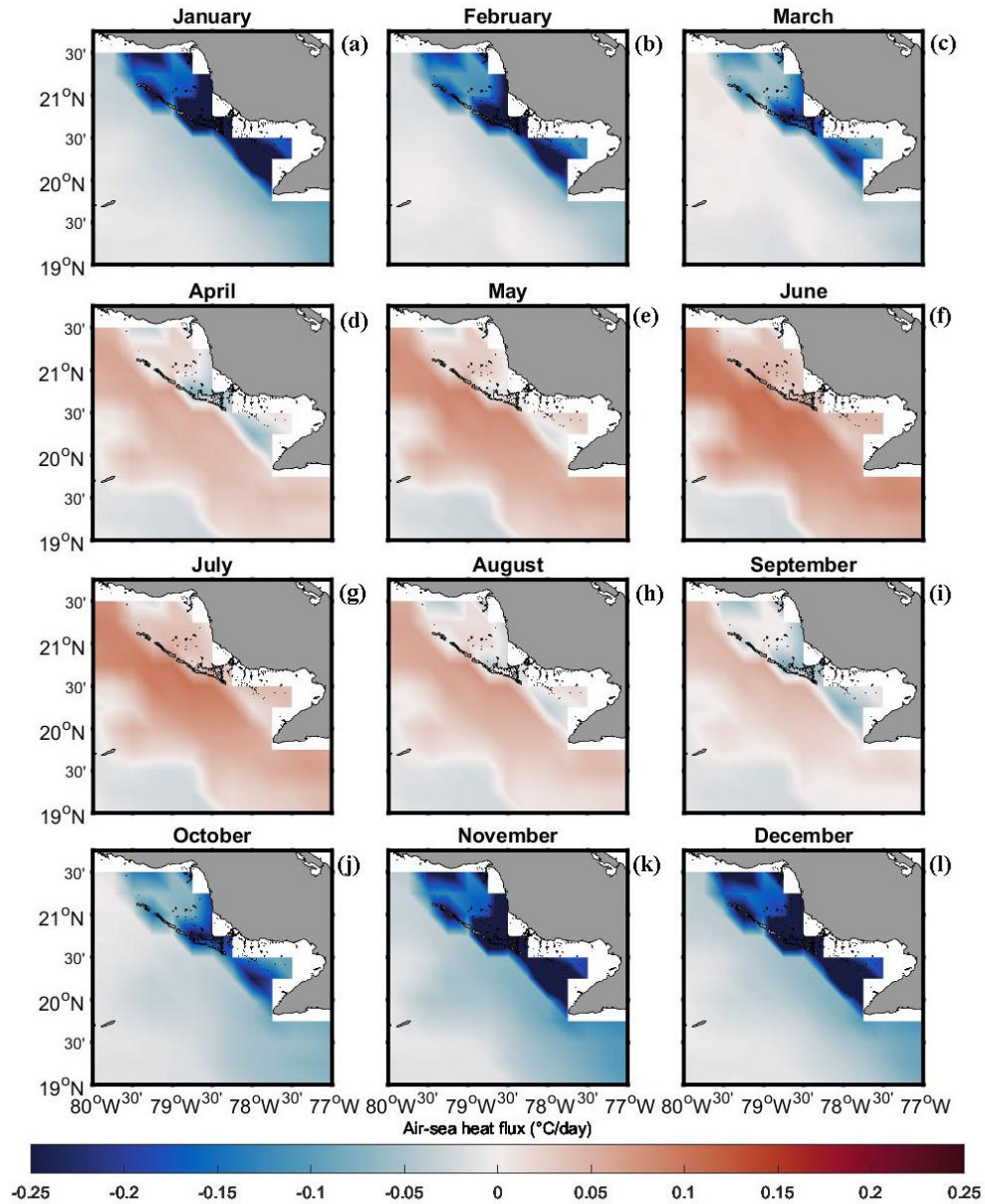
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summer (JAS), and (j–l) autumn (OND). The colour bar indicates monthly mean SST (°C); land is masked in

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

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

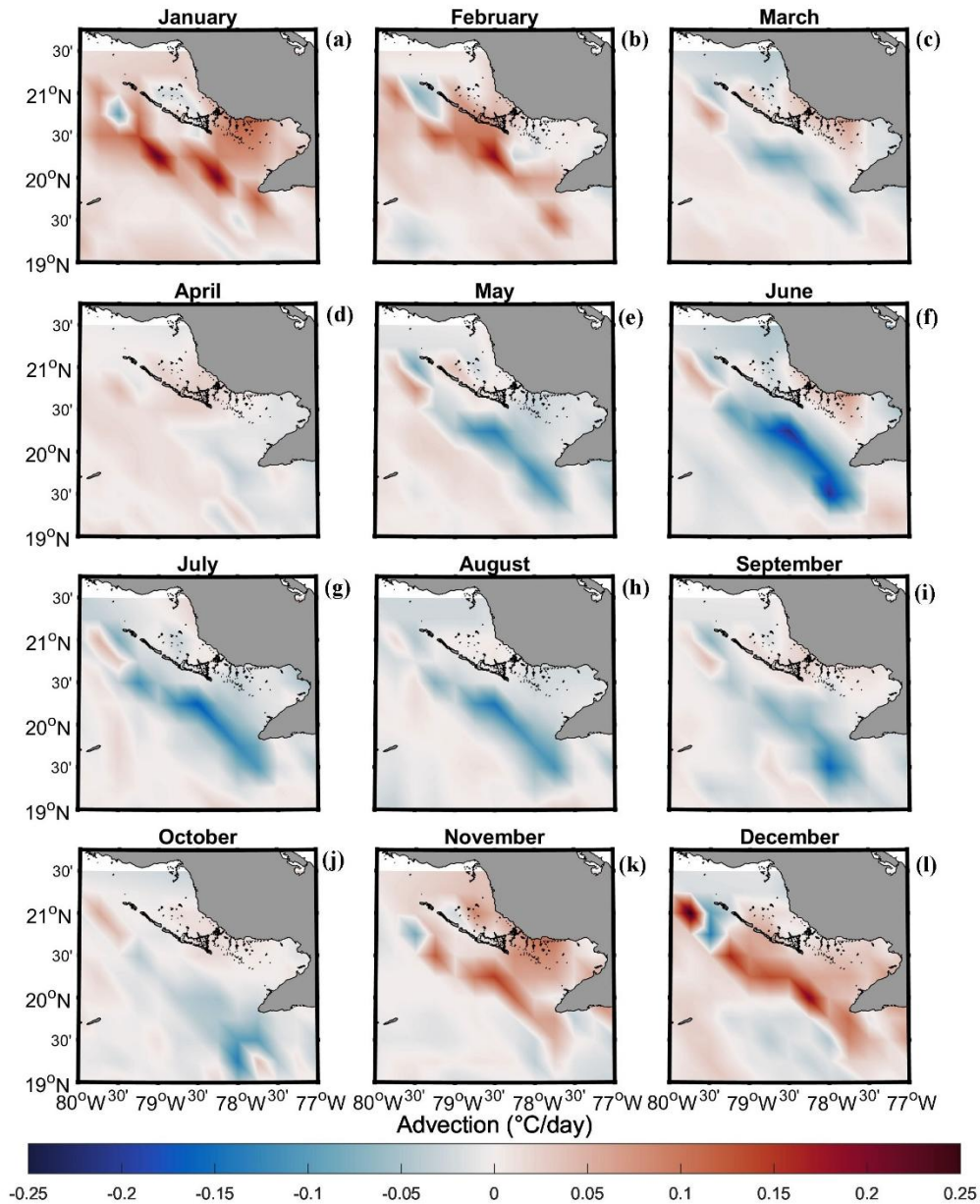
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Flux components are from ERA5, mixed-layer depth h from GLORYS12 all variables are for the period 2003–2022; land is masked in grey.

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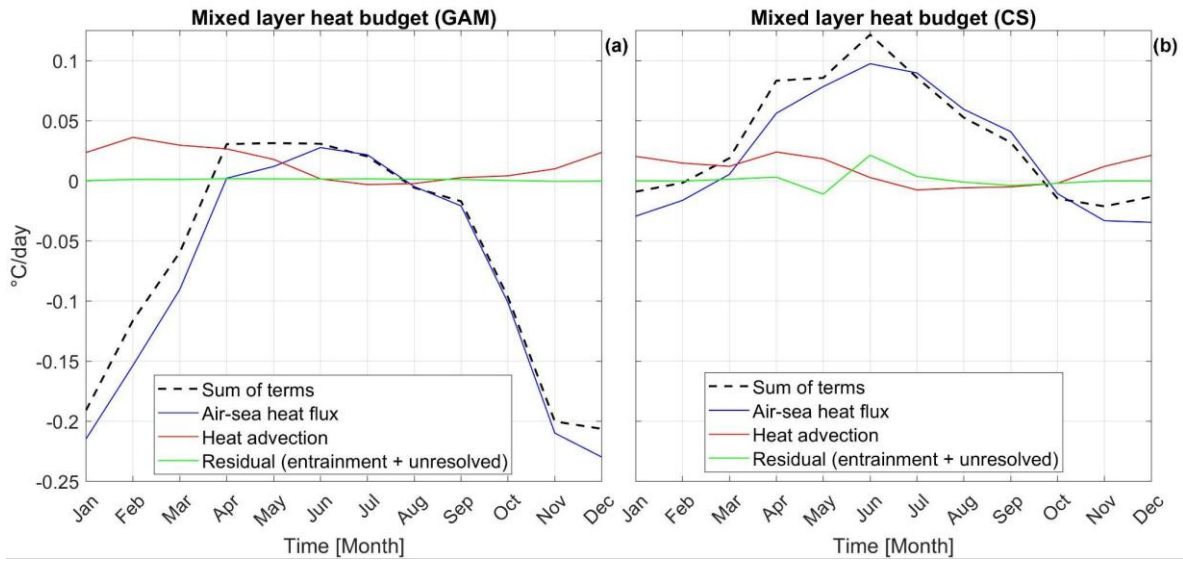
740 **Figure 4.** Monthly horizontal heat-advection tendency term. Panels (a–l) show the monthly mean mixed-layer741 temperature tendency due to horizontal advection, expressed as $^{\circ}\text{C day}^{-1}$ and computed as742 $(\partial T/\partial t)|_{adv} = -U \cdot \nabla T$. Positive (red) warms the mixed layer; negative (blue) cools it. Currents and

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

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

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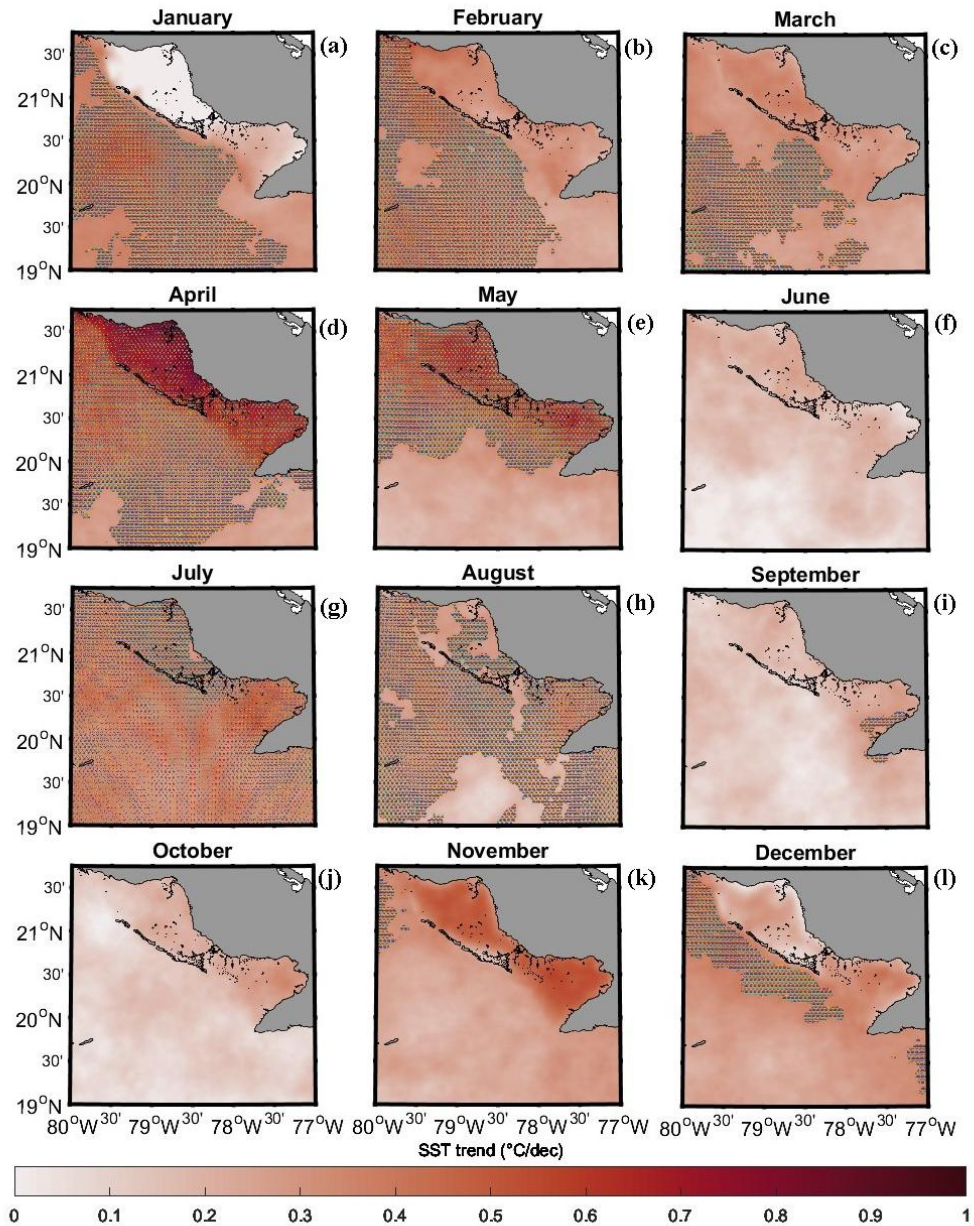
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Figure 5. Seasonal mixed-layer heat budget (2003–2022). Monthly climatologies of mixed-layer temperature tendencies ($^{\circ}\text{C day}^{-1}$) for (a) GAM and (b) CS. Blue line: air–sea heat-flux tendency $(\partial T/\partial t)|_Q = Q_{net}/(\rho C_p h)$. 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.



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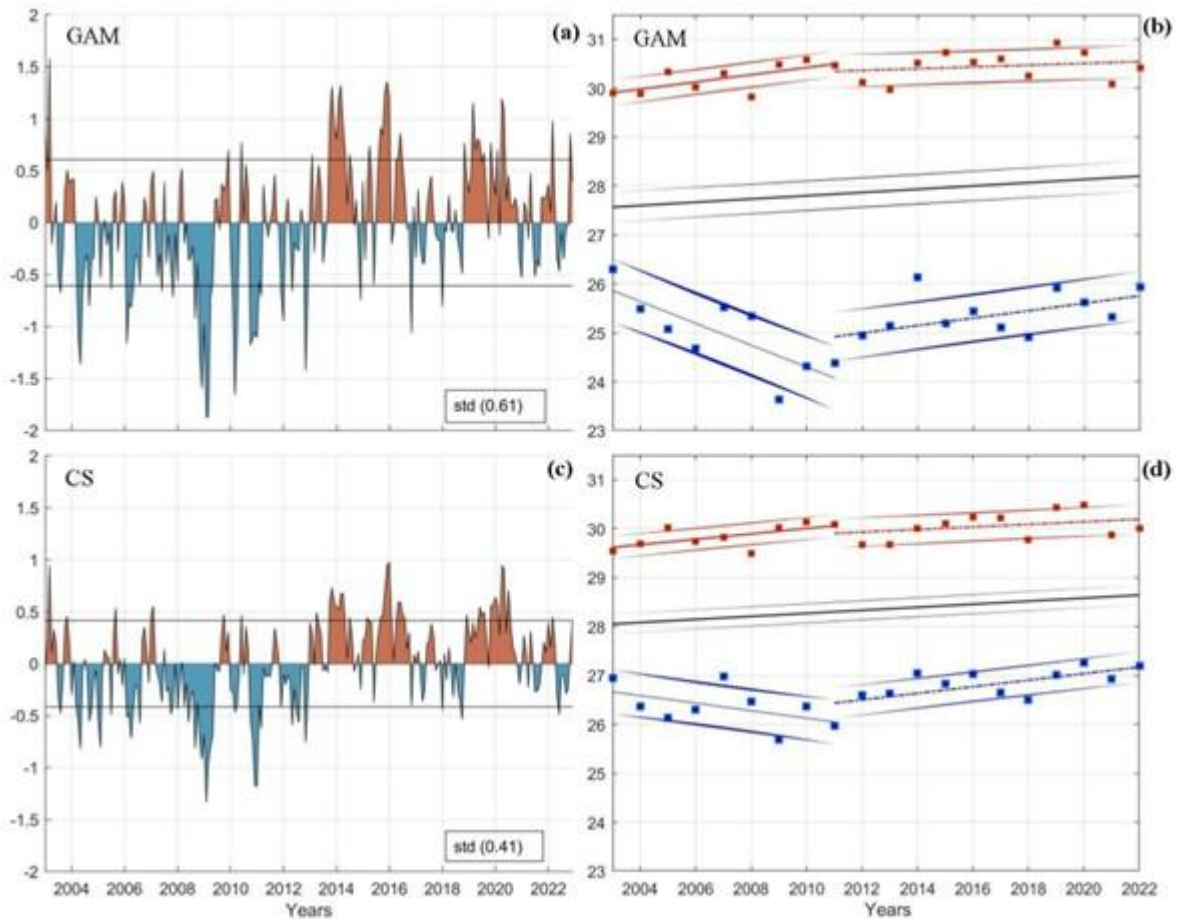
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Figure 6. Monthly SST trends (2003–2022). Linear trends of monthly SST anomalies ($^{\circ}\text{C decade}^{-1}$) for January–December (panels a–l). Trends are estimated by ordinary least squares applied to monthly anomalies at each grid point. Stippling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

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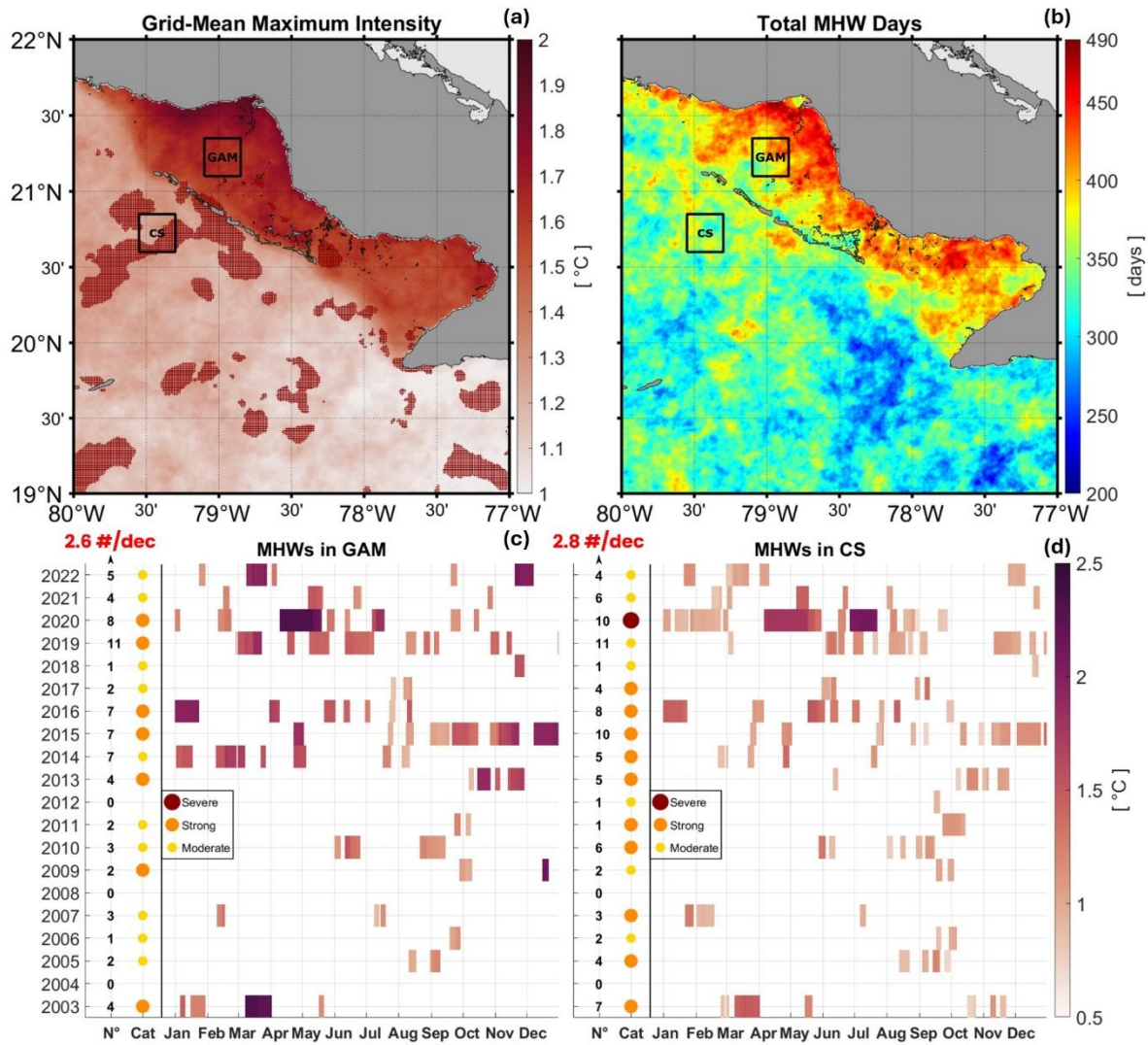
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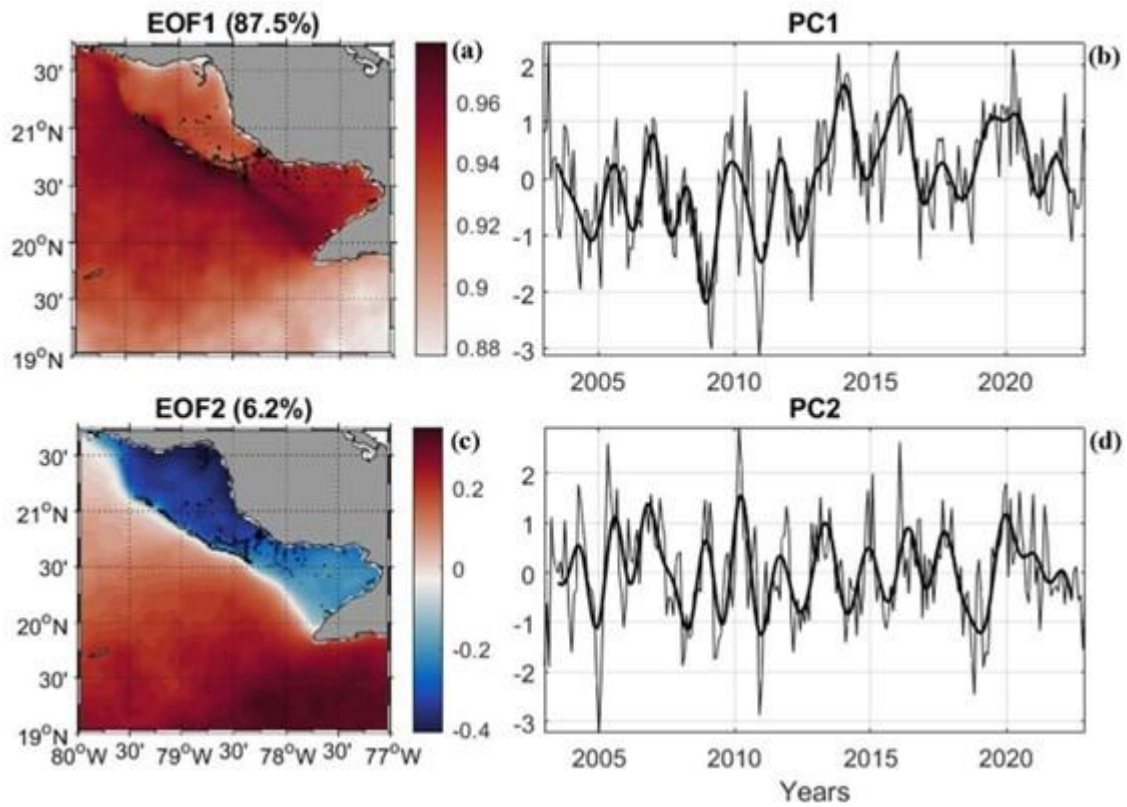
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768 **Figure 7.** (a,c) Monthly SST anomalies ($^{\circ}\text{C}$) for the Gulf of Ana María (GAM) and the Caribbean Sea (CS),
 769 respectively, 2003–2022. Thin horizontal black lines indicate ± 1 standard deviation over the full period (value
 770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

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 778 **Figure 8.** Marine heatwave (MHW) characteristics between 2003–2022. (a) Mean of event-wise maximum
 779 intensity (°C) at each grid point. Grid cells that experienced Severe category events at least once
 780 (reddish shading). (b) Total MHW days per grid point accumulated from 2003 to 2022. Black boxes mark the
 781 GAM and CS sub-regions. (c–d) Event calendars for GAM and CS, respectively: coloured rectangles denote
 782 individual events by month, with darker shading indicating increased intensity (°C). Left-hand columns
 783 indicate, for each year, the number of events (N°) and the maximum category reached (circle colour:
 784 Moderate/Strong/Severe). At the top left of c-d, the trend in event frequency is shown as the number of events
 785 per decade (#/dec).
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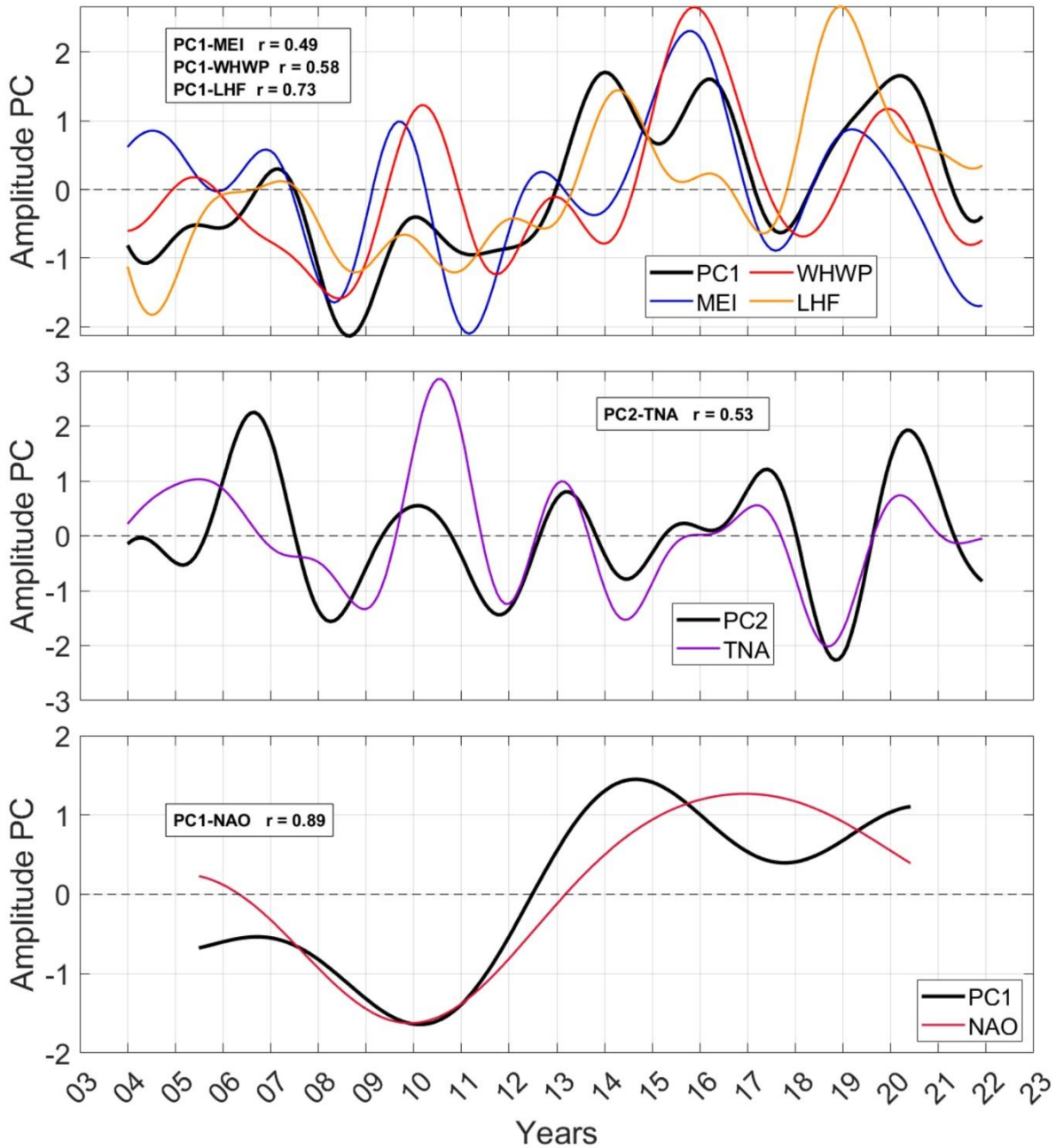
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Figure 9. EOF analysis of monthly SST anomalies for 2003–2022. Left: spatial patterns of EOF1 (87.5 %) and EOF2 (6.2 %). Right: Corresponding principal components (PC1, PC2); thick black curve represents a two-year low-pass filter to emphasize interannual variability. (PC signs are arbitrary and chosen so that positive PCs correspond to warm anomalies in EOF1).



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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.