

## RC1: 'Comment on egosphere-2025-4807',

Anonymous Referee #1, 07 Dec 2025 reply

Review comments on “Sea-surface temperature variability and climate drivers in Cuba’s Jardines de la Reina National Park (2003–2022)” by Castillo-Alvarez et al.

The manuscript analyzes the seasonal-to-decadal sea-surface temperature (SST) variability and its climate drivers within Cuba’s Jardines de la Reina National Park (JRNP) from 2003 to 2022, a region facing increased marine heatwaves (MHWs) and rapid warming. The seasonal cycle is primarily governed by net air-sea heat exchange. Superimposed on this is a warming trend, strongest in winter and transition months, alongside a notable step-like shift towards a persistently warmer state between 2011 and 2013. MHWs intensified during the second decade, with the mean maximum intensity being higher inside the gulfs, while upper categories occurred more frequently offshore. Empirical Orthogonal Function analysis reveals that the dominant, basin-wide warming mode (EOF1) is linked to interannual variability of ENSO/WHWP and latent-heat flux, and to low-frequency variations of the NAO; a secondary shelf-offshore dipole mode (EOF2) is tied to the Tropical North Atlantic (TNA) index. The findings suggest that monitoring net heat flux, mixed-layer depth, and large-scale indices like ENSO/WHWP and NAO can aid in providing early warnings for MHW risk and guiding conservation efforts in the JRNP. This is a well-written manuscript with well-prepared graphs to support the research.

Below are my major and minor comments

### Major comments

**1.- Data Uncertainty and Consistency: The analysis relies on data from diverse sources (remote sensing, reanalysis datasets), which are known to have significant uncertainties/errors, particularly in coastal regions. Crucially, the lack of in situ measurements for validation makes an uncertainties analysis vital. A more detailed comparison of data consistency is necessary. For example, while a correlation between remote sensing Sea Surface Temperature (SST) and reanalysis SST (ERA5, GLORYS12) is mentioned, more in-depth quantitative details of this comparison are required to address the lack of in situ validation.**

R: We thank the reviewer for highlighting the need to better address data uncertainty and cross-product consistency, particularly given the limited availability of long-term in situ observations in the Jardines de la Reina region. While we recognize that some SST products are not fully independent (shared observations/assimilation), they are generated with different methodologies and resolutions (satellite-only vs reanalysis/assimilation), so a quantitative consistency assessment provides an important constraint on the robustness of the inferred variability.

To address this, we added a quantitative intercomparison of SST/upper-ocean temperature variability among MUR SST (our primary high-resolution product), ERA5 SST, and GLORYS12 mixed-layer temperature over the full study domain and 2003 - 2022 period. For comparability across products with different mean states and target depths, we evaluate temporal variability using consistent temporal sampling and anomaly time series. The results are summarized in a Taylor diagram (new Supplementary Figure S1), reporting correlation, normalized standard deviation, and centered RMSD relative to MUR. Both reanalysis products reproduce MUR variability with high correlation ( $r$  typically  $> 0.9$ ), with GLORYS12 generally closer to MUR than ERA5 in terms of variability amplitude (normalized standard deviation closer to 1) and centered misfit (lower centered RMSD).

In addition, although continuous long-term in situ records are not available, we included an independent short-term consistency check using temperature time series from two in situ sensors deployed inside the National Park during February–June 2016 (new Supplementary Figure S2). MUR SST captures the observed temporal variability with  $r \approx 0.80 - 0.85$  and  $RMSE \approx 0.8 - 1.1$  °C, and shows a modest cold bias that is consistent with expected satellite skin versus in situ bulk temperature differences and local coastal subpixel heterogeneity.

We stress that these comparisons do not constitute a full regional validation, but they provide (i) a quantitative consistency check across widely used products and (ii) an independent observational constraint supporting the use of MUR SST to characterize variability in JRNP. Importantly, the principal conclusions (seasonal phasing, shelf -offshore contrasts, dominant EOF modes, and long-term tendencies) are based on coherent spatiotemporal patterns and are robust to the choice of product, rather than relying on absolute SST values at individual grid points. These changes have been incorporated as a new paragraph in Section 2.2 of the revised manuscript, the addition of Figure S2, and an expanded discussion of uncertainties and limitations in Section 4.1.

**Sensitivity of Box Selection: The selection of the two analysis boxes in the GAM and CS appears arbitrary. A sensitivity analysis should be performed to evaluate how the results change based on the location and size selection of these analysis boxes.**

R: To evaluate the robustness of our results, we use multiple alternative subregions both within the Gulf of Ana María (GAM) and outside the gulf in the Caribbean Sea (CS), which were defined with different locations and different spatial extensions (See Supplementary Note S2, Figure S3 and Table S1). The time series of SST anomalies derived from these alternative configurations show consistently high correlations ( $r > 0.95$ ) with the originally selected regions, indicating that the temporal variability captured in our analysis is not sensitive to the exact position or size of the selected subregions.

Furthermore, the EOF analysis (Figure 9) further supports this conclusion. The first EOF mode explains the 87.5% of the total SST variation and exhibits a spatially coherent pattern throughout the Gulf of Ana María and the adjacent Caribbean Sea (Figure 9a, b). The associated principal component (PC1) shows a robust temporal evolution, including a transition towards persistently warmer conditions after approximately 2011, which is consistently observed in both GAM and CS (see Figure 7). This confirms that the dominant SST variability is regional in nature and is well captured by representative subregions within both areas.

It is important to highlight that the selection of a box within the GAM and another outside the CS was intentional, rather than arbitrary. This choice is physically motivated by the second EOF mode (Figure 9c, d), which highlights a clear spatial contrast in SST variability between the semi-closed Gulf and the adjacent open waters of the Caribbean. Furthermore, the exact location of the selected boxes was chosen based on their ecological relevance. The boxes cover the central west PNJR region, which represents one of the most ecologically important sectors of the MPA.

These results show that the selected boxes provide a physical representation and statistically significant SST variability, and the main conclusions of the study are robust to reasonable changes in the location and size of the boxes.

**Repetitiveness and Discussion Depth: Sections 4.1 and 4.2 largely reiterate information already presented in Section 3. These sections should either be combined, or the discussion should be substantially deepened. For instance, the discussion could benefit from comparing the findings to previous studies or similar studies conducted in other regions.**

R: We thank the reviewer for this suggestion. In response, sections 4.1 and 4.2 have been merged into a new unified section to avoid redundancy and improve the clarity of the manuscript (see RM). Additionally, this section has been expanded to include a deeper discussion and comparison of our results with previous studies. These comparisons provide a broader context for the observed patterns and strengthen the interpretation of the regime shift and associated mechanisms.

**Mechanism for Regime Shift: The observed regime shift between 2011 and 2013 is a significant and interesting finding. However, the current paper does not present a mechanism to explain this shift. A more in-depth discussion is needed to explore the potential causes and implications of this regime shift, which would substantially enhance the paper's contribution.**

R: In response to this comment, we have added a new Section 4.1 in the RM, where we provide a discussion of the potential mechanisms driving this regime shift. This new section explores the role of large-scale atmospheric forcing, changes in wind patterns, and associated ocean circulation responses. The inclusion of this new section substantially improves the interpretation of the results and addresses the reviewer's concern.

**Climatology section for MHW: The climatology used for Sea Surface Temperature (SST) analysis, which spans approximately 20 years, deviates from the standard practice of using a 30-year climate normal in Marine Heat Wave (MHW) studies. This choice of a shorter baseline may hinder the comparability of the results with other studies that adhere to the climate normal. It is suggested that the authors either adopt a 30-year climate normal from alternative datasets or, at minimum, quantify the influence of the chosen baseline period on the determination of MHWs.**

R: The primary reason for selecting a 20-year baseline period for the calculation of MHWs is that the MUR dataset does not provide more than 20 years of continuous data over the full study domain. The high spatial resolution of the MUR dataset (~1 km) provides a better representation of mesoscale and submesoscale processes, which is a major advantage when analyzing MHWs affecting a spatially confined region such as the Jardines de la Reina National Park. In this context, preserving spatial resolution is crucial, as coarser-resolution products would excessively smooth thermal gradients and potentially underestimate the intensity and spatial structure of extreme temperature events.

Based on Schlegel et al (2019) we consider a 20-year period to be sufficient for MHW detection. These authors evaluated the impact of using different time-series lengths on MHW detection and concluded that, in general, using a 10-year time series does not produce event durations or intensities that are appreciably different from those detected using a standard 30-year time series.

In addition, to quantify the influence of our 20-year baseline and improve comparability with studies using 30-year climate normals, we performed a sensitivity analysis using GLORYS12, which provides a 30-year record (1993-2022). Following the Hobday et al. MHW definition, we computed MHW thresholds using a 30-year baseline (1993-2022) from GLORYS12 and re-detected MHWs over 2003-2022, then compared the number of days with MHW per year, mean intensity and the standard deviation of the intensity. Results are shown in Table S2.

We added to the new section 2.7 in the RM the following paragraph:

“Schlegel et al. (2019) evaluated the impact of time-series length on MHW detection and found that, in general, event durations and intensities derived from a 10-year baseline are not appreciably different from those obtained using a standard 30-year baseline. In addition, to quantify the influence of our 20-year baseline and improve comparability with studies using 30-year climate normals, we performed a sensitivity analysis using GLORYS12, which provides a 30-year record (1993-2022). Following the Hobday et al. MHW definition, we computed MHW thresholds using a 30-year baseline (1993-2022) from GLORYS12 and re-detected MHWs over 2003-2022, then compared the number of days with MHW per year, mean intensity and the standard deviation of the intensity. Results are shown in Table S2. Differences were relatively small, indicating that our conclusions regarding the increase in MHWs during the second decade and the spatial contrasts within JRNP are not sensitive to baseline choice.”

We also add to the Supplementary Material Table S2.

**Table S2.** Comparison of MHW metrics obtained using a 20-year baseline (2003–2022) versus a 30-year baseline (1993–2022) using GLORYS12 near surface temperature. For each subregion (GAM and CS; Figure 1), we report the mean number of MHW days per year, mean MHW intensity (°C), and the standard deviation of intensity (°C), all evaluated over the periods 2003–2022 (20 years) and 1993–2022 (30 years). Diagnostics follow the Hobday et al. definition of MHWs.

	<i>GAM</i> 20 y	<i>GAM</i> 30 y	<i>CS</i> 20 y	<i>CS</i> 30 y
N° days of MHW per year	38.8	37.5	39.1	39.2
Mean intensity (°C)	0.77	0.78	0.76	0.78
Standard deviation (°C)	0.15	0.15	0.16	0.14

### **Minor Comments**

Line 46: A period is required after the word "progresses."

R: Done.

Lines 164-165: The Access statement should be moved to the Acknowledgement section.

R: Done.

Lines 172-173: This information is redundant as it has already been presented in Section 2.2.

R: Thanks, we removed those lines.

Line 179: More detail is needed regarding the determination of the effective sampling size and effective degree of freedom.

R: We appreciate the reviewer highlighting the need for greater methodological transparency here. We have revised Section 2.5 to explicitly define the formulation used to correct for autocorrelation.

We utilized a standard approximation for discrete time series with persistence, as detailed in Thomson and Emery (2024) and widely applied in climate indices analysis (e.g., Bretherton et al., 1999). We estimated the effective degrees of freedom  $N^*$  based on the lag-1 autocorrelation coefficient ( $r_1$ ) of the series (or the product of the coefficients for cross-correlations,  $r_{1x} r_{1y}$ ):

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

For cross-correlations between two time series X and Y, we used the approximation:

$$N^* = N \frac{1 - r_1^X r_1^Y}{1 + r_1^X r_1^Y}$$

This correction penalizes the sample size when persistence is high, providing a conservative estimate of significance (p-values). We have added this specific mathematical description to the revised manuscript to ensure reproducibility.

Lines 197-199: In the equation, the terms  $\Delta_h$ ,  $u_{-h}$ , and  $w_{-h}$  must be defined.

R: We thank the reviewer for pointing out this omission. In the revised manuscript, we have now provided clear definitions for the terms  $\nabla_h$ ,  $u_{-h}$ , and  $w_{-h}$  in the context of the transformed heat-balance equation. The text has been updated accordingly to ensure that all variables involved in the equation are explicitly described. These definitions have been added in lines 208–212 of the revised manuscript.

Figure 10c: The line is labeled as PC-1, but the legend incorrectly mentions PC-2. PC-2 appears to be an error.

R: Thanks, the legend of Figure 10c was corrected.

## Bibliography

Bretherton, C. S., Widmann, M., Dymnikov, V. P., Wallace, J. M., and Bladé, I.: The effective number of spatial degrees of freedom of a time-varying field, *Journal of climate*, 12, 1990-2009, 1999.

Schlegel, R. W., Oliver, E. C., Hobday, A. J., and Smit, A. J.: Detecting marine heatwaves with sub-optimal data, *Frontiers in Marine Science*, 6, 737, 2019.

Thomson, R. E. and Emery, W. J.: *Data analysis methods in physical oceanography*, Elsevier, 2024.