Marine heatwaves propagation

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What are marine heatwaves (MHWs) ?

Marine heatwaves (MHWs) are **extreme warm water events** in the ocean that have severe impacts on marine ecosystems and ocean-sustained economies.

- They can extend for **thousands of kilometres** and can **last for days to months.**
- They are identified when a given temperature index is above its seasonally varying **percentile** calculated over a **climatological baseline** [1].

1 MOTIVATION

Eulerian vs Tracking

Marine heatwaves are typically studied using an Eulerian approach, focusing on temperature anomalies at fixed locations. However, this overlooks their dynamic nature ([2], [3]), many MHWs move, persist, split, or merge over time. Tracking MHWs as coherent spatiotemporal features offers a richer view of their evolution, spatial extent, and potential ecosystem impact. This approach enables us to investigate MHW structure and mobility, which are critical for understanding their broader effects.

2 METHOD

How do we study MHWs?

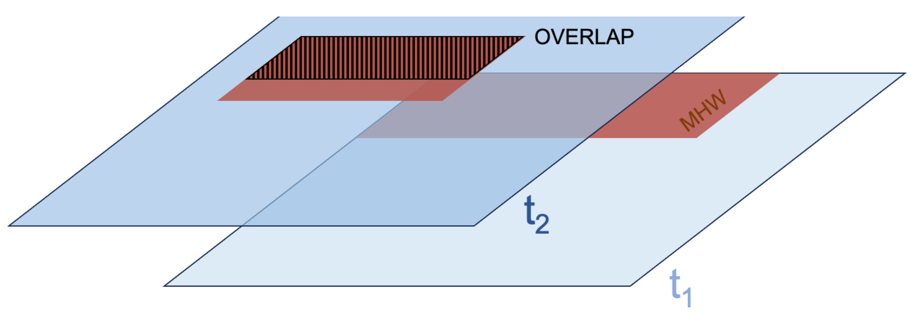
We are identifying and tracking MHWs as they move, rather than studying SST values at one location ([3], [4]). We use the ICON model, and a new tracking algorithm: *marEx* ([4]). The conditions enforced for detection are:

- Compute SST anomalies by removing mean, annual & semi-annual harmonics, linear and quadratic trends.
- Take the **95th percentile** of SST anomalies.
- Keep only the top 50% of largest events.

The detected blobs are then connected in time:

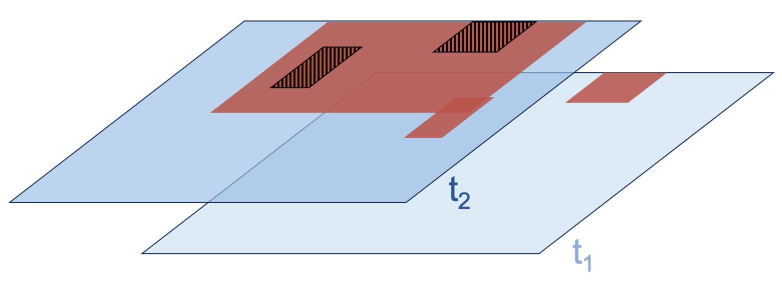
1) TRACK

First, identified extreme grid-cells are **connected in space**: if two or more extreme cells share and edge or a corner, then they are connected spatially. Second, we connect in time:



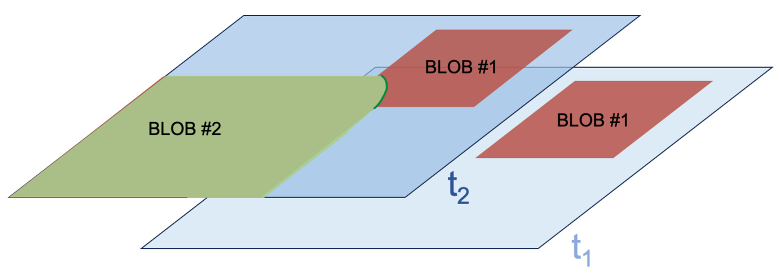
Blobs are connected in time if they share at least one grid cell between consecutive time steps (2 days temporal gap is allowed)

2) MERGE and SPLIT



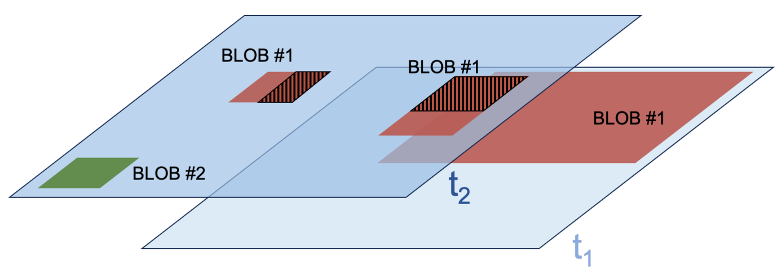
BLOBS MERGE

Blobs at time *t* are considered merged at time *t+1* if their combined overlap with one or more blobs at *t+1* exceeds 50%. This rule ensures that significant shared areas are tracked as part of the same blob.



BLOBS DON'T MERGE

When blobs don't overlap enough to be considered merged, each grid cell at time *t+1* is assigned to the closest blob from time *t*, based on the proximity of each grid cell to the grid cells of the blob in the previous step (modified from the method of Di Sun et al. [3]).

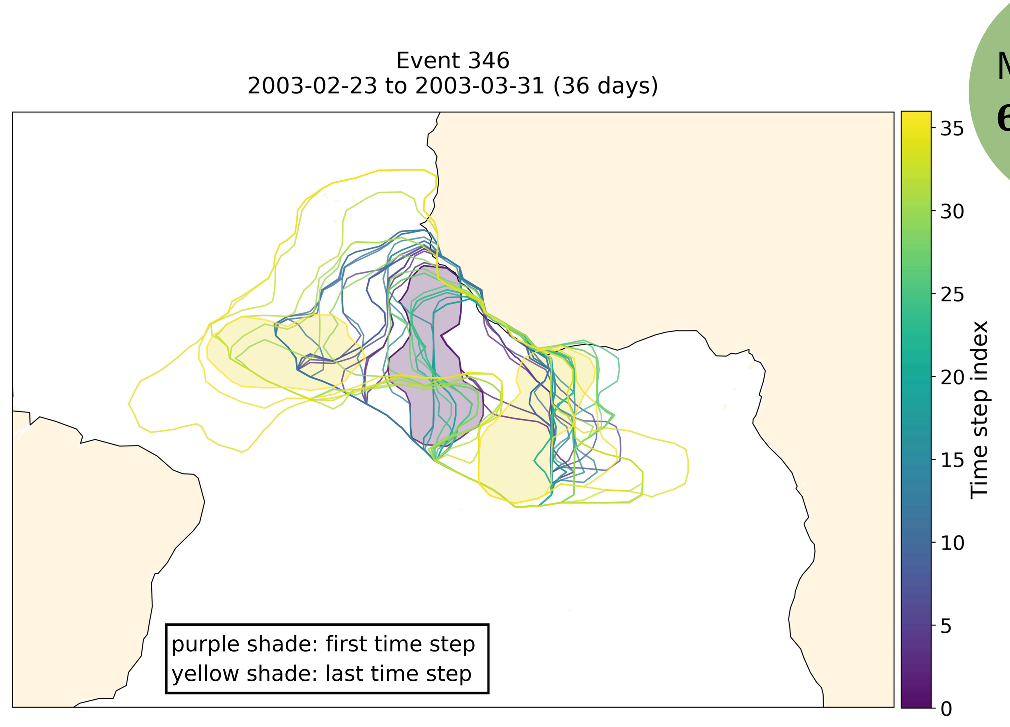


BLOBS SPLIT

A blob at time *t* is considered split at time *t+1* if it overlaps with multiple blobs, each by at least 50% of its area. In this case, the original blob is saved as associated with the resulting blobs, ensuring the split is tracked accurately.

3 RESULTS

EXAMPLE: one event



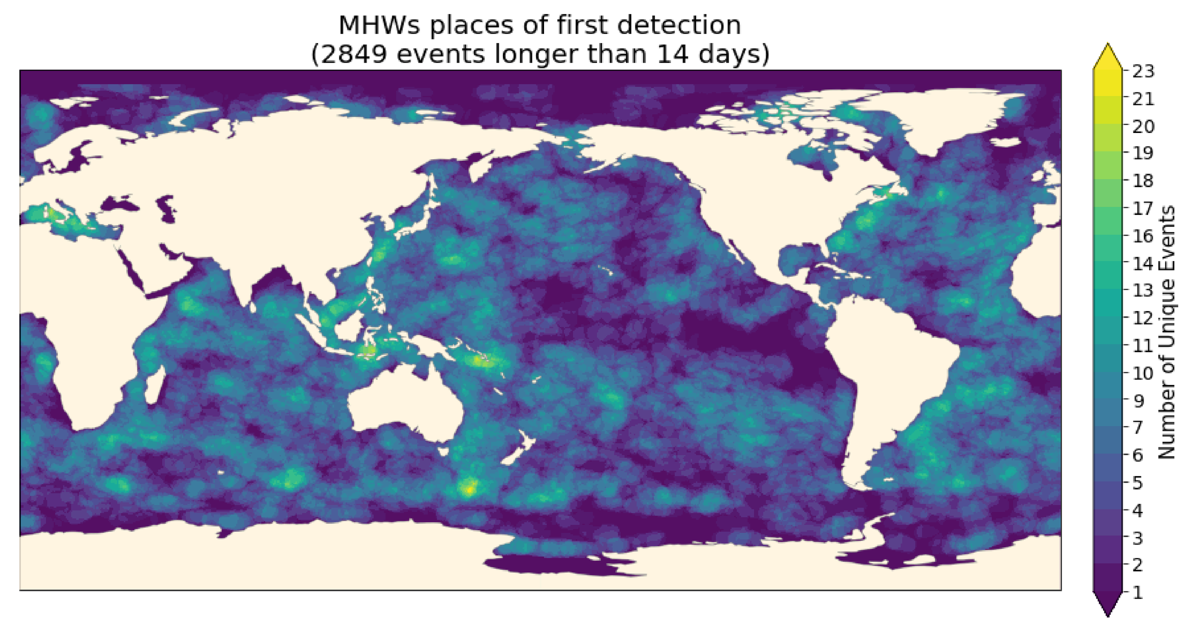
Mean size **6218 km²**

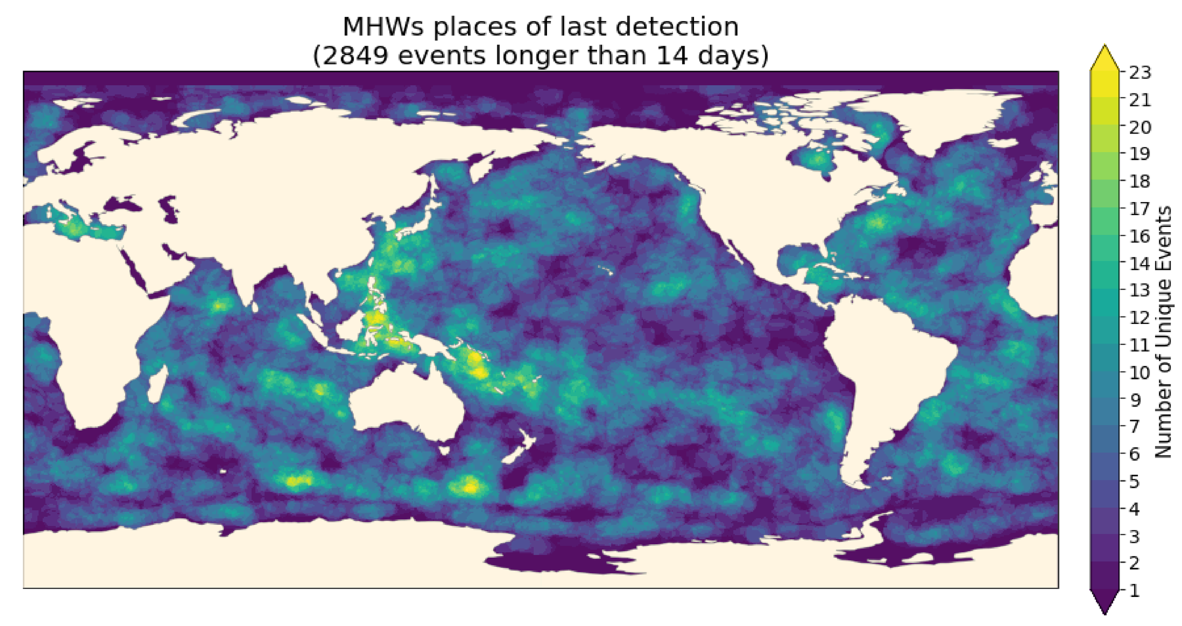
Max intensity **7.5 °C**

Mean intensity **1.2 °C**

The event lasted 36 days, propagating across the tropical Atlantic while maintaining spatial coherence. The color gradient indicates the time step index, illustrating the evolution of the event. It reached a mean size of 6,218 km², with an average intensity of 1.22 °C and a peak intensity of 7.55 °C, both relative to the seasonally adjusted, detrended 95th percentile threshold used for MHW detection.

Where do they come from, where do they go?



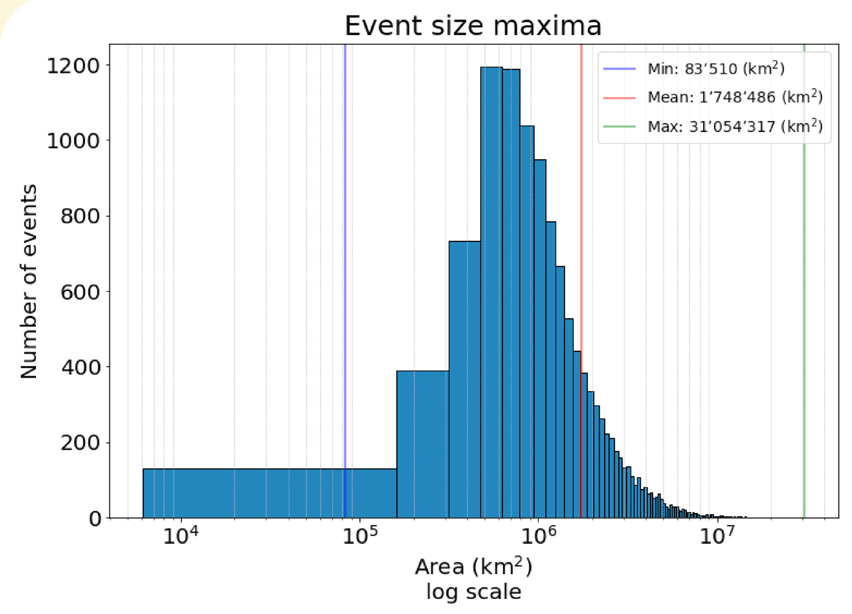


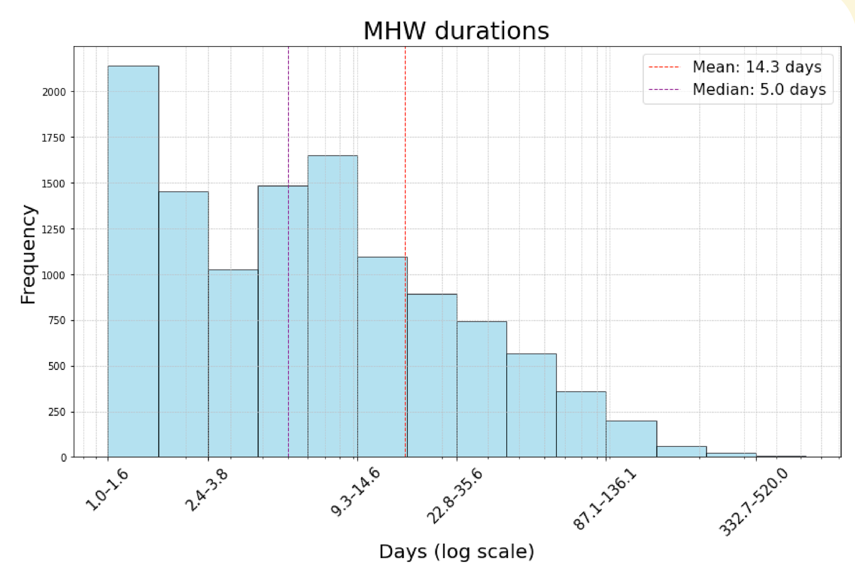
To better understand the spatial characteristics of MHW propagation, we mapped the **first** and **last** grid-cell appearances of each tracked event lasting **longer than 14 days**. Shorter events were excluded to ensure enough duration for spatial propagation, focusing on events that exhibit meaningful movement across the ocean surface.

Each map shows the **number of unique events** first detected (top) or last detected (bottom) at each location.

The two maps reveal general spatial consistency, with many MHWs first and last detected in similar regions. However, some areas act more frequently as **entry or exit points** along MHW trajectories. In particular, the **equatorial Pacific stands out for having very few first detections**, despite being a region of intense thermal variability, suggesting that MHWs tend to arrive from elsewhere rather than initiating locally. These spatial patterns provide a starting point for future work on the role of ocean currents and mesoscale transport in shaping MHW movement.

Global statistics





We analysed 11,692 tracked MHWs from ~40 years of high-resolution model data. Here we summarize their key characteristics:

- Most events last under 20 days, but some persist for over a year.
- Events maxima can reach to over 30 million km².

4 CONCLUSION

Tracking-based analysis with *marEx* reveals that MHWs are dynamic features that evolve in space and time. Many events persist and travel long distances, which is not captured by traditional methods that treat MHWs as fixed or locally confined anomalies.

We find strong spatial recurrence in where MHWs are first and last detected, suggesting persistent oceanographic conditions that favor their development. Yet, the variability in duration and extent also reflects a high sensitivity to how these events are defined and linked through time.

This approach enables a more nuanced understanding of MHW behaviour. Looking ahead, we aim to explore the influence of ocean currents and mesoscale transport on MHW trajectories and compare our model-based results to observational products, further evaluating the realism and utility of this approach.

References:

[1] A.J. Hobday et al., 2016: *A hierarchical approach to defining marine heatwaves* Progress in Oceanography, Volume 141.

[2] Scannell et al., 2021:. Ocetrac: morphological image processing for monitoring ocean temperature extremes. in Scientific Computing with Python (SciPy) 2021. SciPy

[3] D. Sun et al., 2023: Frequent marine heatwaves hidden below the surface of the global ocean, Nature Geoscience

[4] *marEx:* https://github.com/wienkers/marEx

[5] E.C.J. Oliver et al., 2021: Marine heatwaves. Annual Review of Marine Science, 13(1), 313–342.

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