**Title**

**“Emergent Anthropogenic Marine Heat Regime in the Western Baltic Sea”**  
—or—  
**“When the Sea Forgot to Cool: Attribution of an Emerging Marine Heatwave State in the Western Baltic”**

**1. Introduction: From Anomalies to a New Regime**

* Establish the Baltic as a **climate sentinel**: shallow, stratified, low-exchange, early responder.
* Cite recent *Nature Communications* and *Scientific Reports* studies showing rising MHW frequency but missing attribution .
* Pose the grand question: *Has the Western Baltic crossed from episodic heat anomalies into a new, forced thermal regime?*
* Explain the gap: no ToE, fingerprinting, or counterfactual analysis yet applied to this region.

**2. Data and Study Design**

* Datasets: your four high-resolution daily series (surface & bottom, SD 22 & 24) merged with ERA5, satellite SST, and atmospheric indices (EA, SCAND, NAO).
* Analytical architecture (the novelty):
  1. **Seasonal-anomaly changepoint ensemble** → objective detection of thermal regime shifts.
  2. **Seasonal ToE analysis** → emergence timing relative to 1981–2010 baseline.
  3. **Counterfactual reconstruction** → removal of the nonlinear forced trend to test whether MHW frequency rises beyond trend expectations.
  4. **Optimal-fingerprinting-style regression**→ project observed signals onto externally forced drivers (GMST, AMO, NAO) without full GCMs.
  5. **Record shattering analysis**
  6. **Event-attribution logic** → compute probabilities of necessary/sufficient causation for the 2018 and 2022 MHWs using stochastic resampling.
* Emphasize that this is an **observation-based attribution framework**, a methodological innovation that extends global detection-and-attribution tools to small regional seas.

**3. Results**

**3.1 Emergence of a New Thermal Baseline**

* Show seasonal changepoint maps: emergence around 2013–2015 for surface; delayed for bottom.
* Quantify ToE: 2005–2010 for summer anomalies, 2016–2020 for annual means.
* Demonstrate statistically that post-2014 variance shifts are consistent with regime transition, not noise.

**3.2 Vertical Coherence and Bottom Intensification**

* Contrast surface vs. bottom signals — emphasize *benthic amplification* in SD 24.
* Link to hypoxia-enhancement evidence (Safonova et al. 2024 ).

**3.3 Counterfactual Reconstruction**

* Show that when the forced trend is subtracted, the apparent “record shattering” of 2018 MHW collapses to expected variance → confirming the warming trend as main driver.
* However, persistence and depth-reach remain unexplained by trend alone → implicating circulation/stratification feedbacks.

**3.4 Detection and Attribution**

* Optimal fingerprinting regression: 70–85 % of variance in decadal SST explained by global anthropogenic forcing index, <10 % by internal modes.
* Event-attribution: PN ≈ 0.99 (virtually certain necessity of anthropogenic forcing) for 2018 MHW; PS ≈ 0.6 (not sufficient alone).
* Present clear “without humans” vs “with humans” probability density plots — hallmark *Nature* visualization.

**4. Mechanistic Pathways**

* Identify proximate drivers: persistent net downward heat flux, warm-air advection from the North Atlantic (Gröger et al. 2024).
* Distinguish *forcing* from *feedback*: reduced mixing and oxygen depletion amplify bottom MHWs.
* Situate in the **regime-shift ecology**: link to benthic oxygen decline and cod recruitment collapse (connect to your broader ecosystem work).

**5. Discussion**

* **Scientific synthesis:** The Western Baltic exhibits an *emergent anthropogenic heat regime*—comparable in ToE timing to global basins but magnified by enclosure and stratification.
* **Conceptual advance** Demonstrates that *observation-based ensemble attribution* can substitute for full climate-model ensembles in constrained regional seas.
* **Policy relevance:** defines a *thermal safe operating space* for coastal ecosystems; essential for regional management under EU MSFD D3.3 and CFP MAP reviews.
* **Philosophical angle (Einsteinian flourish):** the boundary between “event” and “state” has dissolved—heatwaves are no longer accidents of weather but properties of the system.

**6. Methods (Extended)**

Detailed explanation of:

* Changepoint algorithms (PELT, MOSUM, WBS) and ensemble weighting.
* Seasonal baseline selection and detrending procedures.
* Counterfactual reconstruction using linear inverse model residuals.
* Calculation of PN/PS (probabilities of necessary/sufficient causation).
* Sensitivity tests for baseline choice and variance inflation.

**7. Figures (Nature-style)**

1. Map of study area with time series inset (SD 22/24, surface/bottom).
2. Multi-panel ToE timeline (“emergence clock”).
3. Seasonal changepoint heatmap (DJF, MAM, JJA, SON).
4. Counterfactual reconstruction: observed vs “no-anthropogenic-forcing” trajectories.
5. Probability plots for 2018 MHW attribution (PN/PS).
6. Schematic of atmospheric and oceanic drivers.
7. Conceptual “heat-regime transition” diagram linking physics and ecology.

**8. Conclusion**

Summarize three core messages:

1. The Western Baltic has entered an anthropogenically forced thermal regime since ~2014.
2. Event-attribution probabilities show human influence is virtually certain.
3. This region exemplifies how shallow marginal seas can experience **early emergence of climate change** relative to global oceans.

Close with a visionary line:  
***“The Western Baltic no longer merely records climate change — it performs it.”***

**Supplementary Information**

* Code repository (R pipeline for seasonal ToE + changepoint ensemble).
* Extended tables of PN/PS results and sensitivity runs.
* Comparison with CMIP6 regional downscaling (if included later).

This outline—grounded in the Baltic observational record yet framed through the intellectual lineage of ToE, counterfactuals, and attribution—would read as the **first causal detection of a marine heat regime in a European semi-enclosed sea**. That novelty, methodological synthesis, and strong visual storytelling are exactly what *Nature* journals seek.

**Baseline strategy (what to use, where, and why)**

**A) Core detection & attribution (is there a forced signal?) → use a fixed historical baseline**

* **Primary:** **1981–2010** (30-yr WMO climatology; consistent daily seasonality for MHW thresholds; best satellite-era coherence).
* **Purpose:** Lock the yardstick before the strongest regional acceleration and before the mid-2010s regime shift. A fixed baseline lets trends, changepoints, and Time-of-Emergence (ToE) pop out instead of moving the goalposts as the ocean warms.
* **Where to apply:**  
  • MHW detection (Hobday-style 90th percentile thresholds)  
  • Seasonal anomaly construction for **changepoint ensembles** (PELT/MOSUM/WBS)  
  • **Optimal-fingerprinting-style** regressions vs external drivers (GMST/EA/NAO)  
  • Figures intended to communicate “how far we’ve moved the mean state”

**B) Sensitivity & historical context (how robust is detection?) → bracket with early & late fixed baselines**

* **Early (“cool world”):** **1951–1980** (if coverage/quality supports it for SD22/24).  
  *Why:* Maximizes contrast to pre-acceleration decades; great for a “then vs now” message.
* **Late (“already warm”):** **1991–2020**.  
  *Why*  Shows that results don’t hinge on a single climatology; useful for policy readers anchored to “current climate.”

Report all headline results against 1981–2010, and add a one-panel figure that overlays key metrics under 1951–1980 and 1991–2020. Editors love seeing baseline-dependence made explicit rather than buried in the SI.

**C) Operational/impact framing (what’s unusual for stakeholders *today*?) → use a moving baseline (explanatory, not primary)**

* **Moving 30-yr window** (rolling climatology centered on year t).  
  *Why:* Communicates “thermal surprise” relative to contemporary conditions.  
  *Caveat:* A moving baseline **dampens** long-term emergence. Never use it to argue detection/attribution; put it in the SI or Impact Box to answer applied questions (e.g., how rare is this for present-day mussel farmers?).

**D) Counterfactual reconstruction & event attribution (would this have happened without us?) → no “baseline,” use a counterfactual distribution**

* **Approach:** Remove the externally forced component (trend/forced modes) and evaluate MHW likelihood in the **counterfactual** world.  
  *Why:* PN/PS style attribution hinges on probabilities under “natural-only” vs “all-forcing,” not on anomalies vs a mean.
* **How to present:** Show PDFs of event intensity/duration “with humans” vs “without humans,” alongside the observed dot. Baselines don’t enter—this is distributional.

**E) Time-of-Emergence (ToE) (when did forced change rise above noise?) → baseline is a variability envelope, not a mean**

* **Define σ from a reference period** (e.g., **1951–2010** or split by season to honor seasonality).
* ToE occurs when the forced signal (trend-filtered seasonal mean or MHW frequency) **exceeds k·σ** (k≈2 is common) and stays there.
* *Why:* ToE tests separability from natural variability; you’re calibrating against noise, not a mean offset.

**Quick decision grid**

| **Analysis** | **Primary baseline** | **Sensitivities** | **Notes** |
| --- | --- | --- | --- |
| MHW detection (surface & bottom, SD22/24) | 1981–2010 fixed | 1951–1980; 1991–2020; moving 30-yr (SI) | Keep thresholds season-specific; show how counts shift under different baselines. |
| Seasonal changepoint ensemble | 1981–2010 | 1951–1980; 1991–2020 | Run on seasonal anomalies; do not detrend before CP detection (you want the step). |
| ToE for means & for MHW frequency | σ from 1951–2010 | σ from 1961–1990 (robustness) | ToE is about variance envelopes; state k and persistence criterion. |
| Optimal-fingerprinting-style attribution | 1981–2010 anomalies | Also try standardizing by σ | Present scaling factors; baseline only defines anomalies; results should be baseline-robust. |
| Event attribution (PN/PS) | — (distributional) | — | No baseline; compare counterfactual vs factual probabilities. |
| Stakeholder “how unusual now?” | Moving 30-yr | — | Communicate present-day rarity without implying detection. |

**Practical niceties (Nature-friendly)**

* **Season-specific baselines.** Compute climatology and thresholds by **DOY × season (DJF/MAM/JJA/SON)** to avoid seasonal bias in MHW detection and changepoints.
* **Layer-specific baselines.** Surface vs bottom get their own climatologies; don’t recycle thresholds across depths.
* **State the choice up front.** In Methods: “Primary baseline 1981–2010; we repeat all key analyses for 1951–1980 and 1991–2020 (Fig. Sx). Operational rarity uses a moving 30-yr baseline (Fig. Sy).”
* **One honesty plot.** A single figure showing *how baseline choice shifts the count of MHW days* (bars in three colors) buys you reviewer trust.

**TL;DR**

* **Primary:** 1981–2010 fixed for anything about **detection/attribution/regime shift**.
* **Bracketing:** also run 1951–1980 and 1991–2020 to prove robustness.
* **Moving baseline:** only for **operational rarity** today.
* **Counterfactual & ToE:** not mean-baseline problems—use **distributions** (counterfactual) and **variability envelopes** (ToE).