DISENTANGLING WARMING EFFECTS ON PLANKTON DYNAMICS USING BAYESIAN CAUSAL INFERENCE

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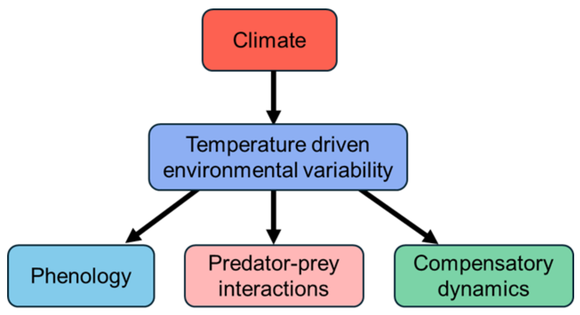
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Rationale

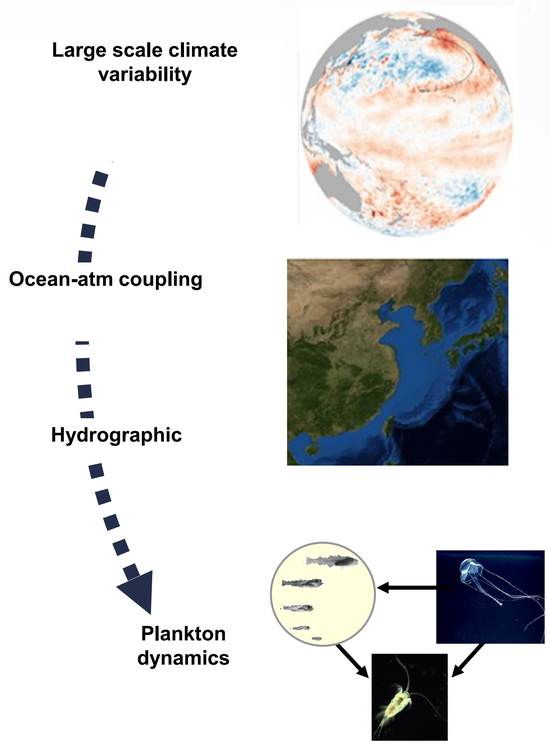
Rapid climate variability and long-term ocean warming are transforming pelagic ecosystem dynamics. Untangling their links is essential to understand how resilient pelagic systems are to shifting environmental regimes and to guide adaptive management in a changing ocean.

Using multi-decadal climate, hydrological, and zooplankton records, we apply a Bayesian causal inference framework, combining hierarchical and non-linear threshold models, to quantify how temperature regimes shape seasonal timing, trophic interactions, and community stability across pelagic ecosystems.



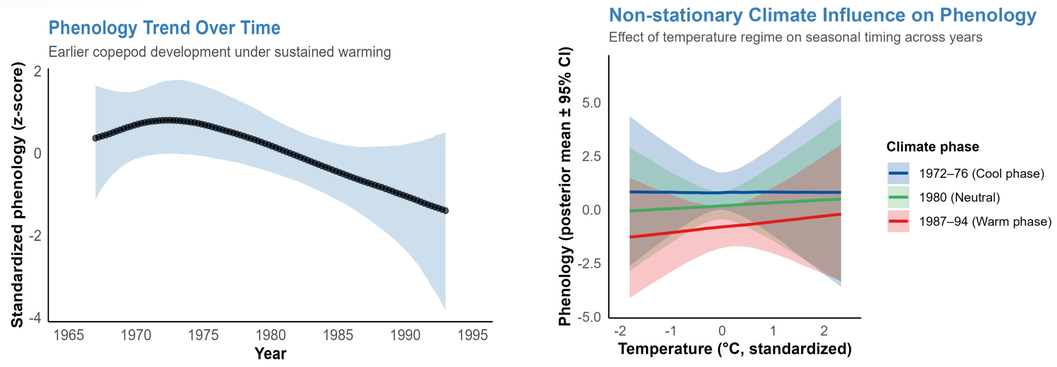
These case studies represent connected pathways through which climate forcing shapes ecosystem resilience.

Data & Methods



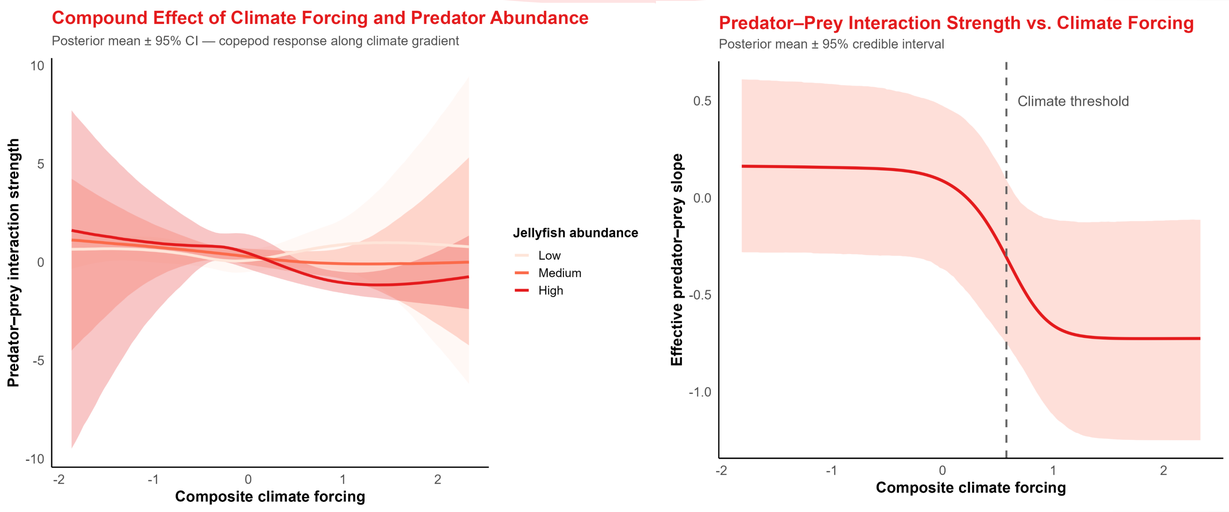
- Multi-decadal (1966–1995) time series of climate indices (North Atlantic), hydrography (0–75 m temperature), and weekly zooplankton (copepods, jellyfish) from the NW Mediterranean.
- Composite climate index (PC1) summarizing 67% of total variance from large-scale and regional thermal drivers.
- Bayesian causal models combining hierarchical smooths, non-linear thresholds, and interaction terms were used to quantify gradual, abrupt, and compensatory ecological responses.

Phenology



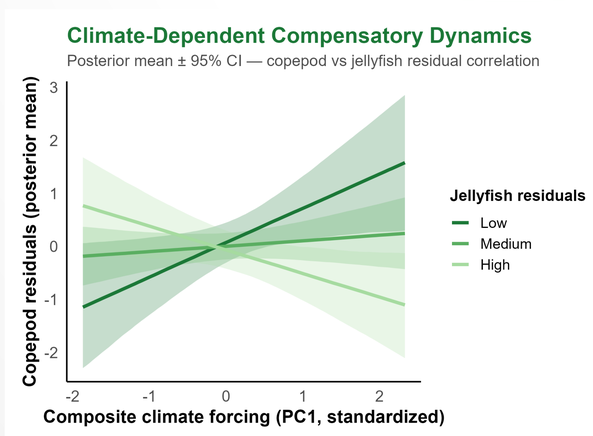
Non-stationary phenology patterns
Left panel: Long-term trend analysis shows a progressive advancement in copepod phenology. **Right panel**: The relationship between phenology and spring temperature varies across decades, indicating a non-stationary influence of climate forcing on seasonal timing.

Predator-prey dynamics



Threshold dynamics and compound climate-predator effect on copepods
The effect of climate forcing on copepod dynamics depends on jellyfish abundance. **Left panel**: Under warm regimes, predator (jellyfish) control intensifies, amplifying top-down pressure and reducing system stability. This interaction reveals non-stationary responses to climate-mediated shift enhancing top-down trophic control. **Right panel**: Bayesian threshold analysis revealed an abrupt transition driven by enhanced warming, indicating a regime shift toward jellyfish-dominated dynamics once climate forcing crosses a critical level.

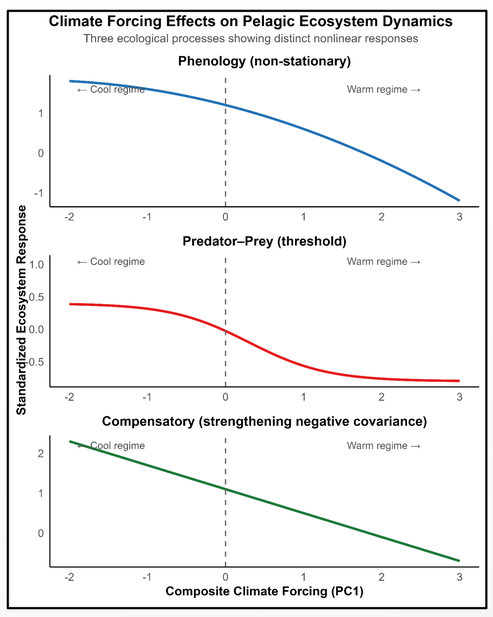
Compensatory dynamics



Climate-enhanced compensatory dynamics
Conditional effects from the Bayesian interaction model show that the negative correlation between copepod and jellyfish residuals strengthens under warm climate conditions (left panel, red line). As the climate warms, negative coupling intensifies indicating a climate-enhanced compensatory dynamics.

Model compensatory dynamics as a function of climate
The significant interaction term (β = –0.82 ± 0.32, 95% CI [–1.45, –0.18]) highlights that warming promotes compensatory fluctuations and functional replacement, signaling a loss of energy efficiency and ecosystem resilience.

Conceptual diagram



Climate Forcing Pathways Across Ecological Processes Warming shapes non-stationary responses in plankton dynamics via gradual, abrupt, and compensatory pathways.

- Secular warming erodes seasonal timing, while thresholds trigger regime transitions.
- Functional replacement among taxa under warm regime signals declining resilience.
- Bayesian causal modeling identifies early-warning indicators of non-stationary ecosystem change.

Summary

- **Warming overrides biotic control:** Persistent warm regimes can disrupt trophic balance and weaken compensatory dynamics.
- **Resilience becomes non-stationary:** Threshold-dependent responses and shifting climate regimes signal increasing uncertainty in ecosystem stability.
- **Causality informs prediction:** Bayesian causal modeling provides quantitative, predictive tools to anticipate ecosystem change and guide adaptive management in a warming ocean.

Acknowledgments:

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Further questions?