Tipping Points and Abrupt Changes in Marine Ecosystems Progress Meeting
Hybrid: Plymouth Marine Laboratoray and online
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Antifragility and tipping points: Ideas on how noise connects to deterministic components of marine primary production

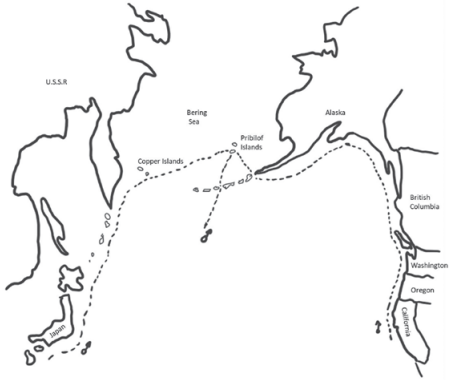
Žarko Kovač
Department of Physics, Faculty of Science, University of Split

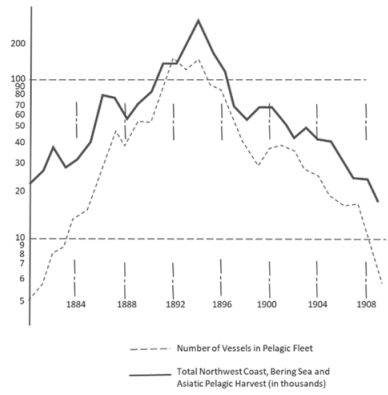
Motivation

Tragedy of the commons

The North Pacific fur seal (Callorhinus ursinus) has a life cycle that involves spending part of the year on breeding grounds (orrookeries) and the remaining part of the year at sea. This cycle has been responsible for some **hard-fought conflicts over harvesting rights** to the herd since the animals are effectively **common property during the sea period and private property while on land**.

Common Property Resources and the Dynamics of Overexploitation (Wilen, 2018)

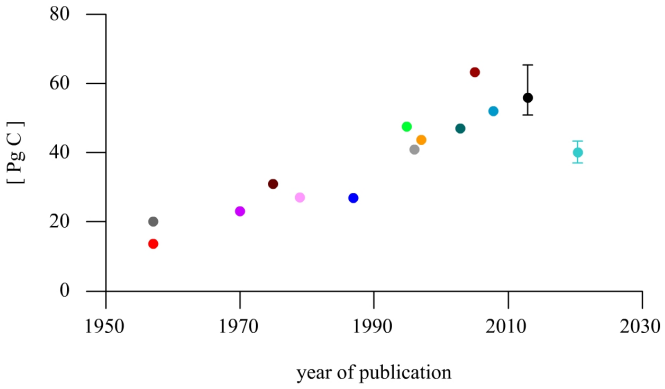




The source of the problem?

How productive is the ocean?

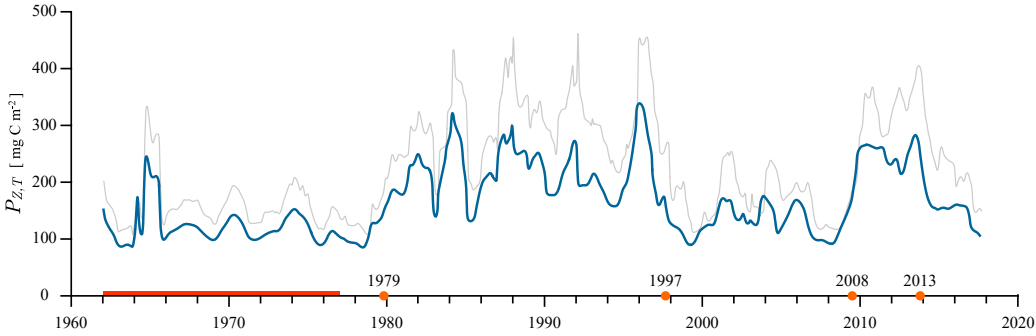
The answer from the literature



- *Steeman Nielsen & Jensen, 1957*
- *Gessner, 1957*
- *Koblenz-Mishke, 1970*
- *Platt & Subba Rao, 1975*
- *Eppley & Peterson, 1979*
- *Berger et al., 1987*
- *Longhurst et al., 1995*
- *Antoine et al., 1996*
- *Behrenfeld & Falkowski, 1997*
- *Melin, 2003*
- *Behrenfeld et al., 2005*
- *Westberry et al., 2008*
- *Buitenhuis et al., 2013*
- *Kulk et al., 2020*

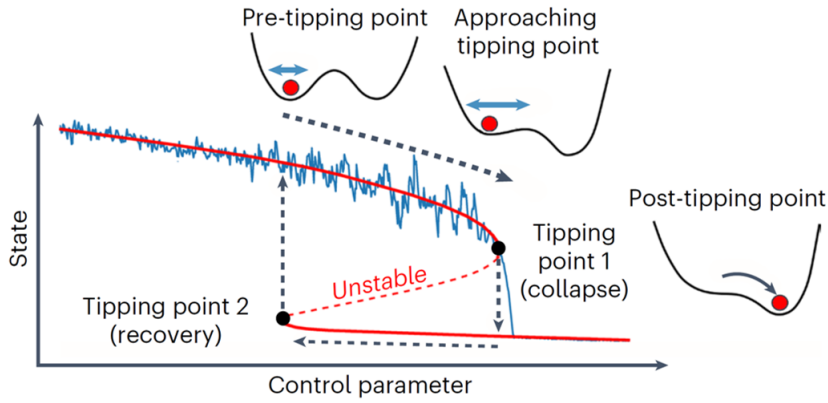
For how long will it be as productive?

A particular answer from the field

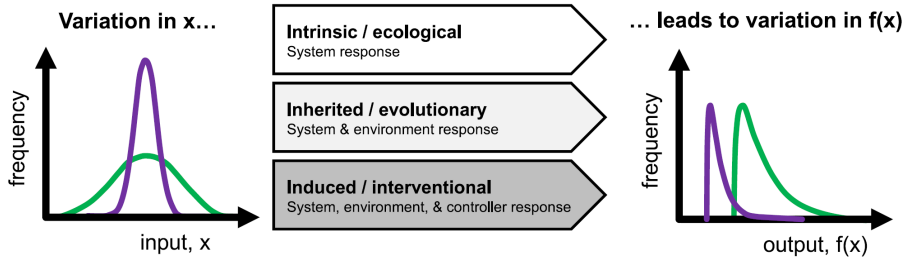


55 year long in situ time series from the Adriatic (Kovač et al., 2018)

Are we seeing evidence of tipping point dynamics? (Rietkerk et al., 2025)



Or are we seeing evidence of anti/fragility on longer time scales?



Axenie et al. (2024)

Definitions of anti/fragility for primary production (Kovač & Sathyendranath, 2022)

Marginal production

$$M_x = \frac{\partial P}{\partial x}$$

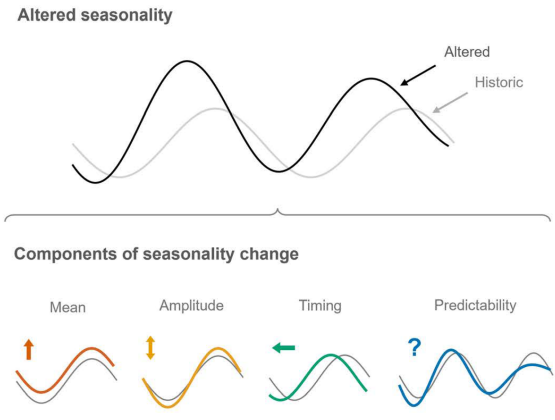
Fragility

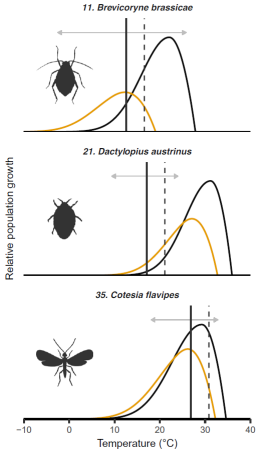
$$F_x = \frac{\partial M_x}{\partial x} = \frac{\partial^2 P}{\partial x^2}$$

x is the controlling variable, such as irradiance, nutrients, temperature, ...

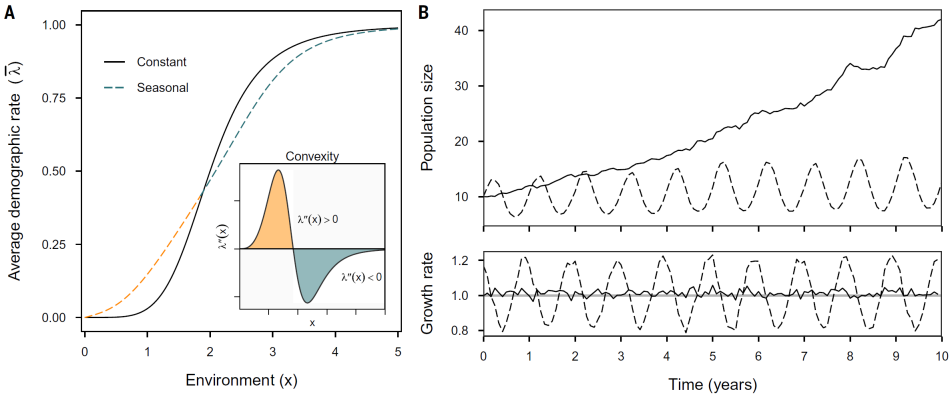
Let us focus on temperature

Changing seasonality on land (Hernández-Carrasco et al., 2025)





Effect of fluctuating growth rates on the long run population size



Hernández-Carrasco et al. (2025)

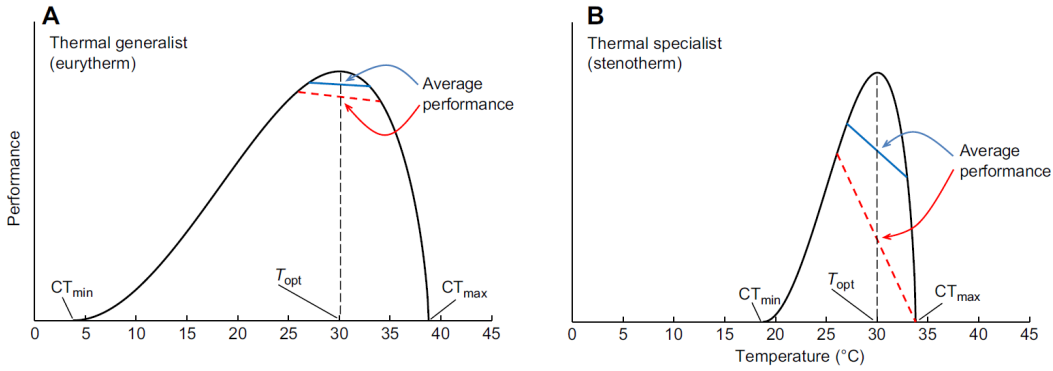
Starting with a stochastic differential equation for temperature:

$$\mathrm{d}T_t = q(T,t)\,\mathrm{d}t + \sigma\,\mathrm{d}W_t$$

Acknowledging $P = P(T)$ and applying Ito's lemma:

$$\mathrm{d}P_t = \left(q(T,t)\frac{\partial P}{\partial T} + \frac{\sigma^2}{2}\frac{\partial^2 P}{\partial T^2} \right) \mathrm{d}t + \sigma \frac{\partial P}{\partial T}\,\mathrm{d}W_t$$

Jensen's inequality illustrated on thermal performace curves (Denny, 2017)



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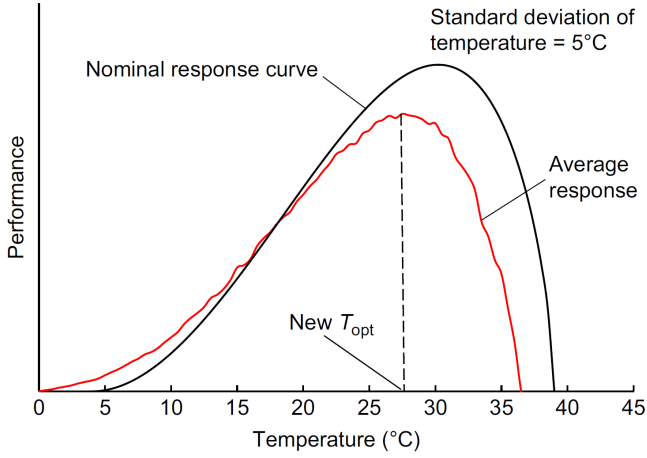
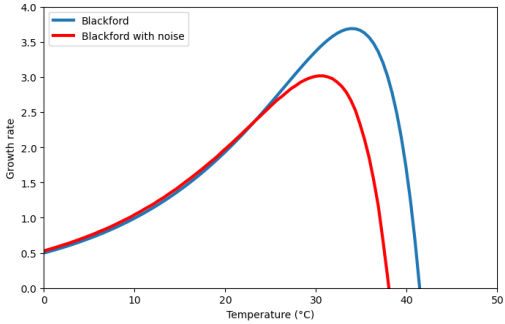
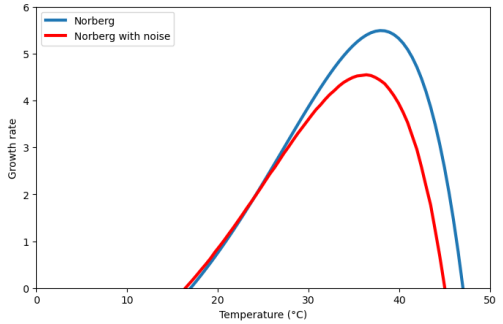




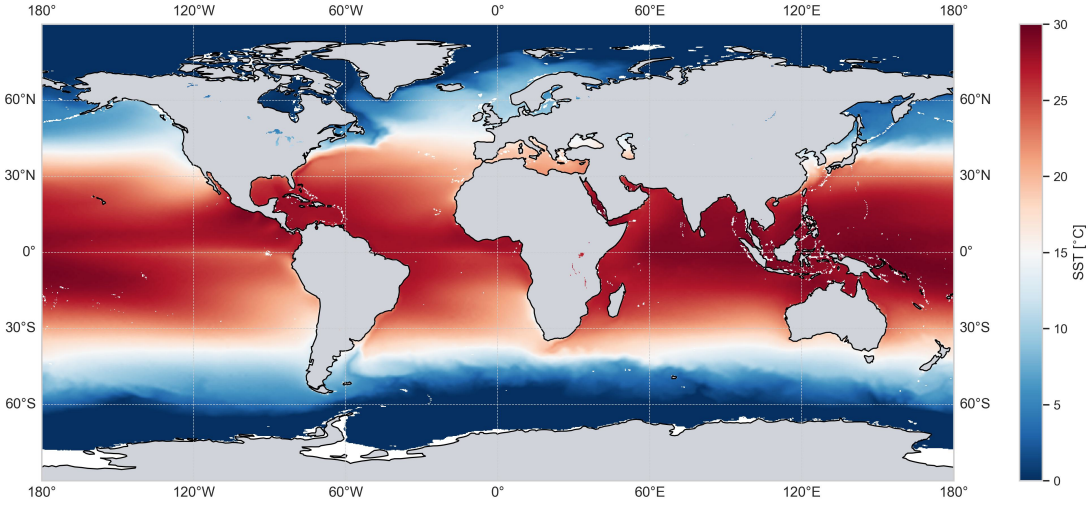


Even if temperature fluctuates symmetrically around its mean, primary production does not average symmetrically:

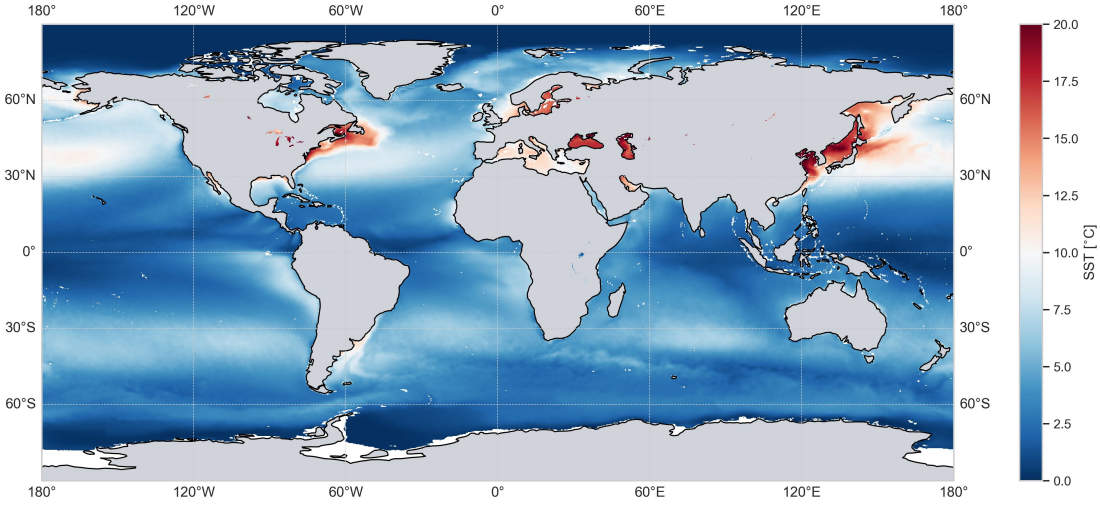
$$\mathbb{E}[P(T)] \neq P(\mathbb{E}[T])$$

Where in the ocean is this relevant?

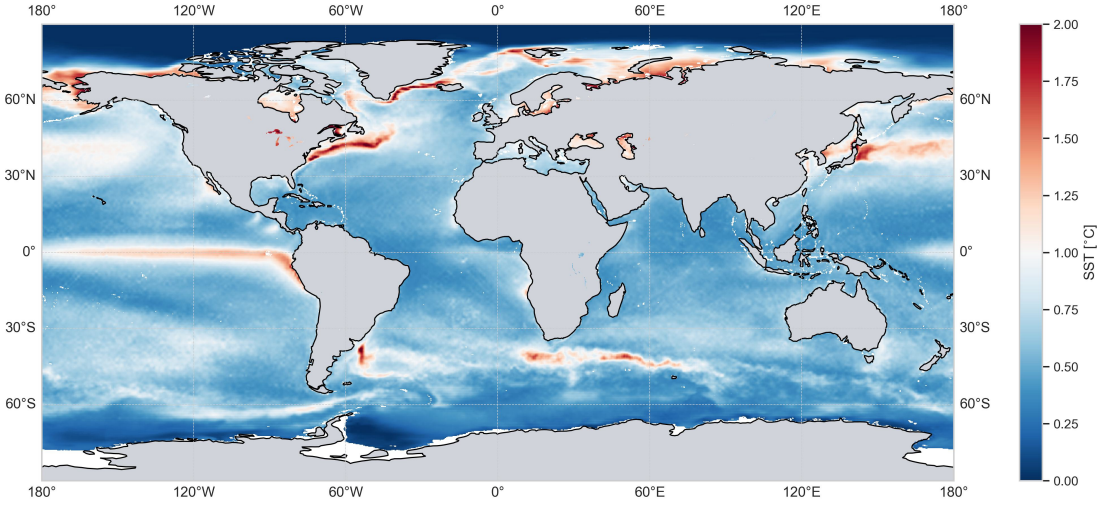
ERA 5 SST reanalysis: Mean SST (preliminary results)



ERA 5 SST reanalysis: Seasonal cycle amplitude in SST (preliminary results)



ERA 5 SST reanalysis: Standard deviation of noise in SST (preliminary results)



An example

In cold regions of the ocean we can approximate production as:

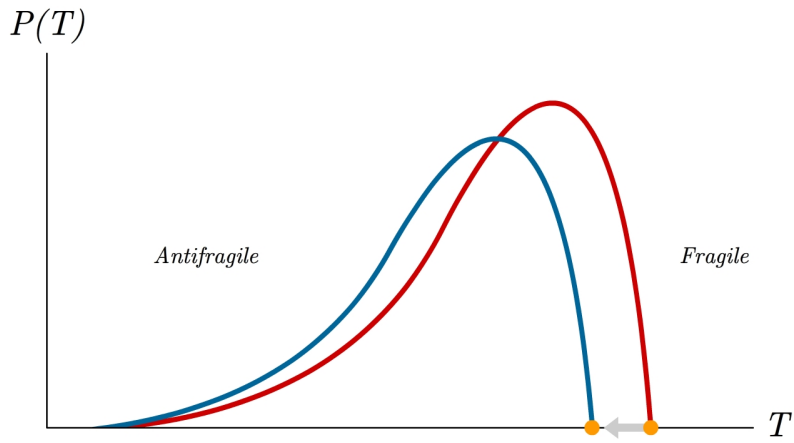
$$P(T) \approx P_0 e^{\alpha T}$$

The resulting stochastic differential equation for primary production is:

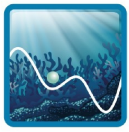
$$\mathrm{d}P_t = \left[\alpha q(T_t, t) + \frac{\sigma^2}{2}\alpha^2\right] P_t \, \mathrm{d}t + \alpha\sigma P_t \, \mathrm{d}W_t$$

Here we observe that noise enters the determinstc term (Ito drift).

Conclusion



Noise pushes the zero growth point to smaller temperatures. Sooner tipping?



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Thank you!