Tipping points and abrupt changes In the Marine Ecosystem
Kick off meeting 9th April 2025

Noise and primary production: Preliminary results and ideas

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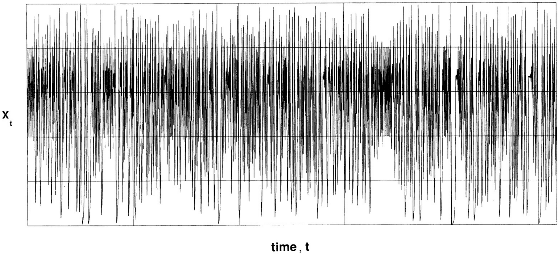
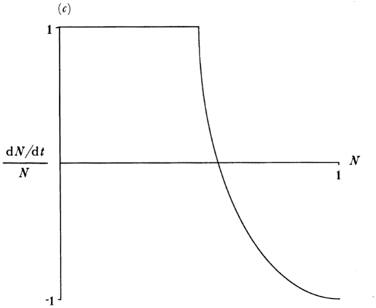
Motivation

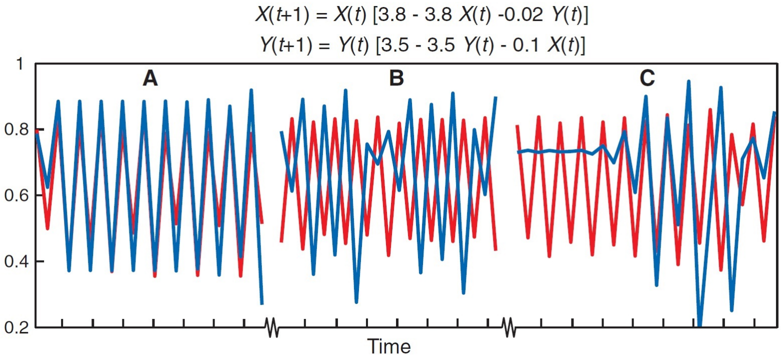
Sugihara et al. (1990) Philosophical Transactions: Biological Sciences





*Often it is thought that **environmental factors are associated with stochastic fluctuations in population density, and biological ones with deterministic regulation**. We revisit these ideas in the light of recent work on chaos and nonlinear systems. We show that **completely deterministic regulatory factors can lead to apparently random fluctuations in population density**...*

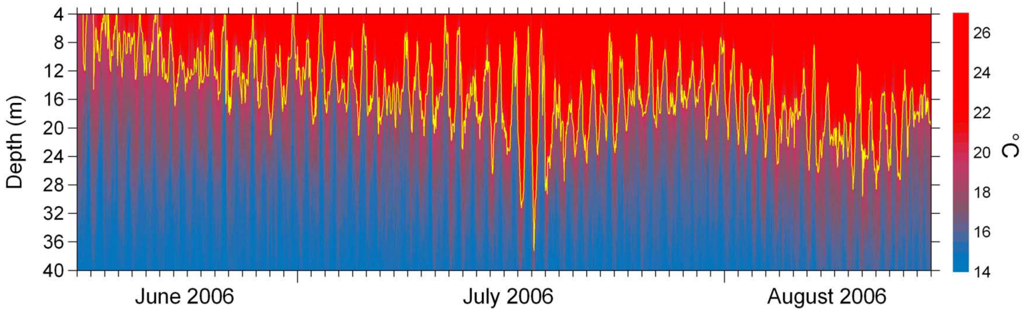
Sugihara et al. (2012) Science



Identifying causality in complex systems can be difficult. Contradictions arise in many scientific contexts where ***variables are positively coupled at some times but at other times appear unrelated*** *or even negatively coupled depending on system state.*

What about primary production and noise?

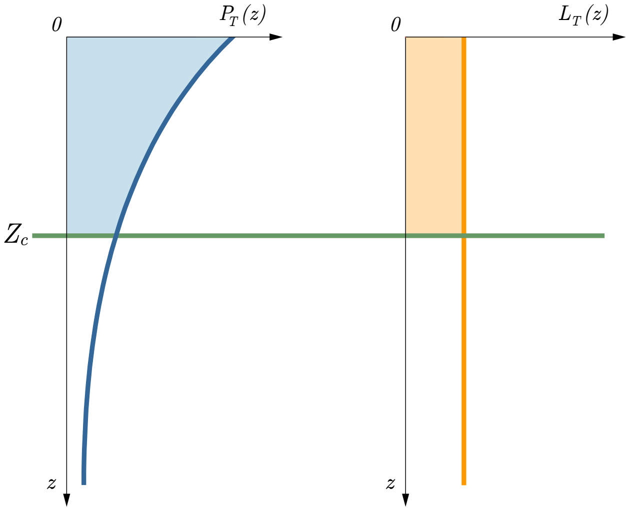
High frequency observations in the Adriatic Sea (Orlić et al., 2011)



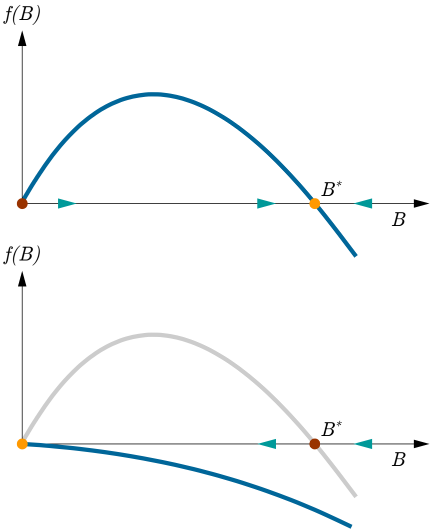
As for the productivity of coastal waters, the ***diurnal upwelling may influence the generation of phytoplankton characterized by a near-daily scale*** *and therefore may also influence the generation of zooplankton and nekton at much larger temporal scales.* ***The well-known fact that the larger areas of the islands of Lastovo and Vis are relatively productive ones in the Adriatic*** *supports the proposed mechanism and suggests that these islands represent the natural laboratories in which the generation times of various members of the food web can be studied.*

Let us first observe a simple model without noise!

The classical Critical Depth Criterion (Sverdrup, 1953)



Bio-optical bifurcation (Kovač & Sathyendranath, 2025, JGR, accepted)



Kovač et al. (2021, JMS) and Kovač & Sathyendranath (2025, JGR, accepted)

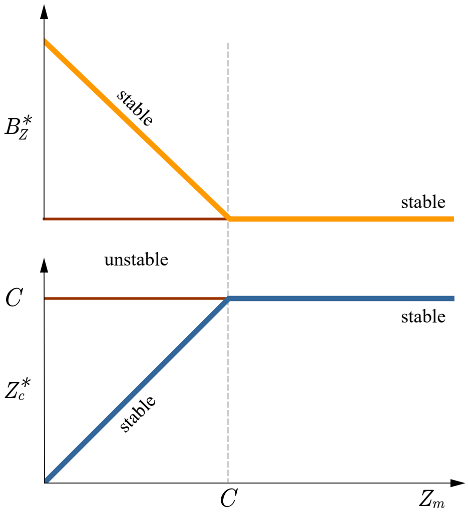
$$B^* = \frac{K_w}{k_B}\left(\frac{C}{Z_m} - 1\right)$$

$$B_Z^* = \frac{K_w}{k_B}\Big(C - Z_m\Big)$$

These simple looking solutions opened up new unexpected avenues!

For Sverdrup's model C reads: $C = \dfrac{1}{K}\Big(W_0\Big(-Ae^{-A}\Big) + A\Big)$

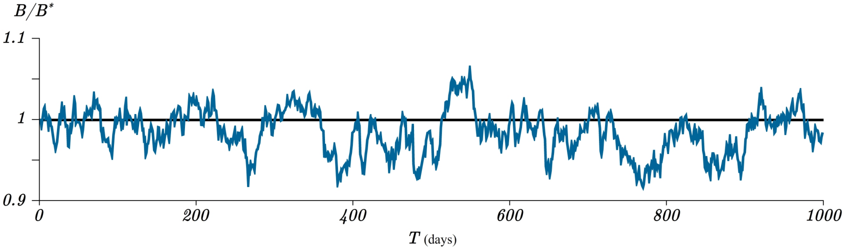
Bio-optical bifurcation (Kovač & Sathyendranath, 2025, JGR, accepted)



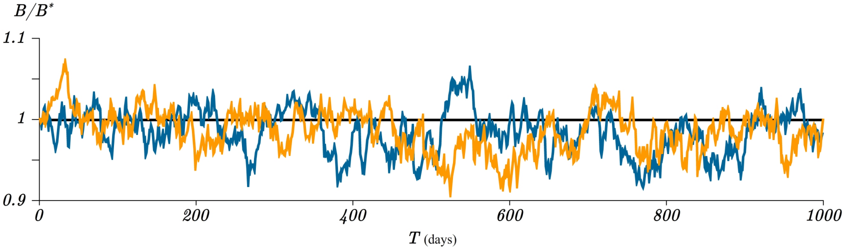
What happens when we add noise to surface irradiance?

$$I_0^m(t) = \langle I_0^m \rangle + \delta I_0^m$$

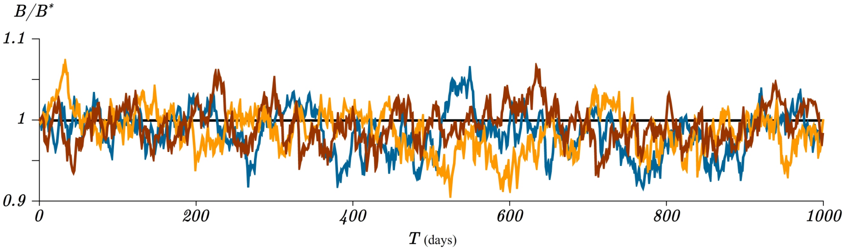
Dynamics



Dynamics



Dynamics

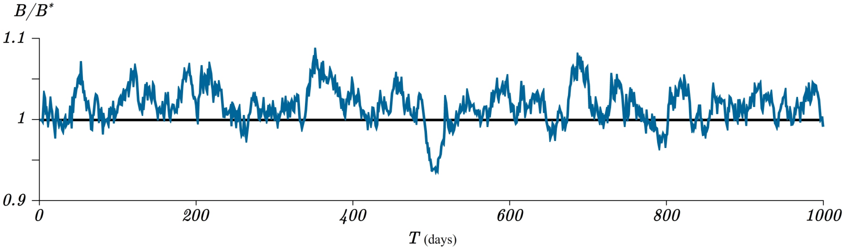


Biomass is suppressed despite having received same total energy.

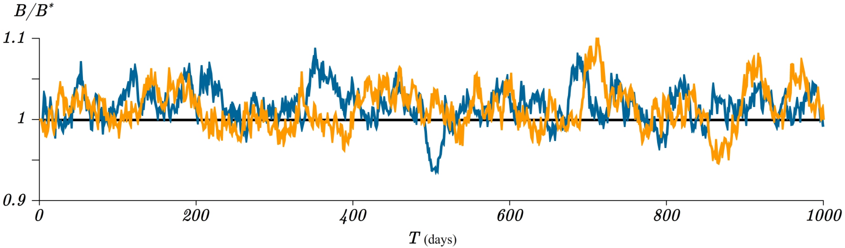
What happens when we add noise to mixed-layer depth?

$$Z_m(t) = \langle Z_m \rangle + \delta Z_m$$

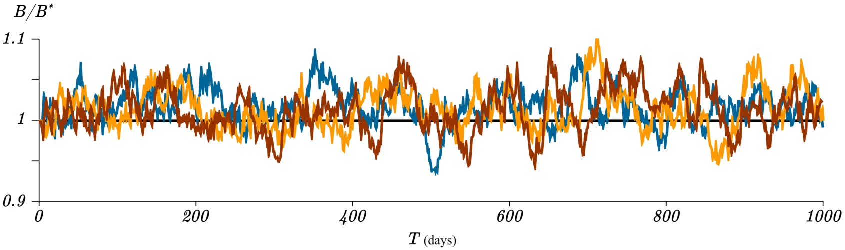
Dynamics



Dynamics



Dynamics

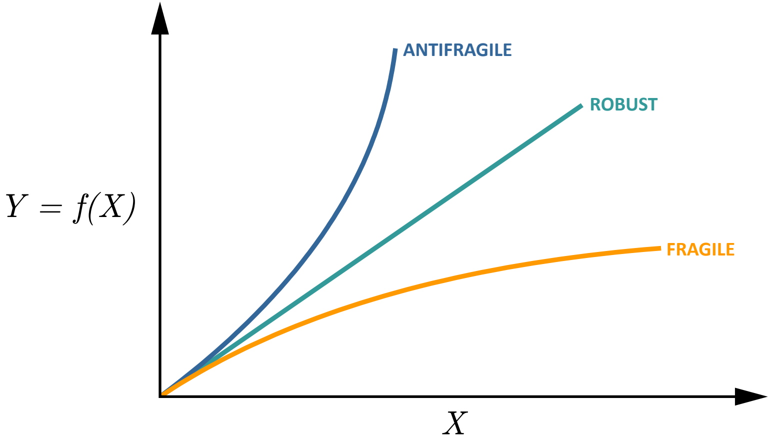


In this case the opposite holds: biomass is increased on average.

An analogy to illustrate the concept

FRAGILE	ROBUST	ANTIFRAGILE
suffers from disorder	stays the same	gains from disorder

A visual interpretation of fragility and antifrafility



A candidate definition of anti/fragility for primary production

Marginal production

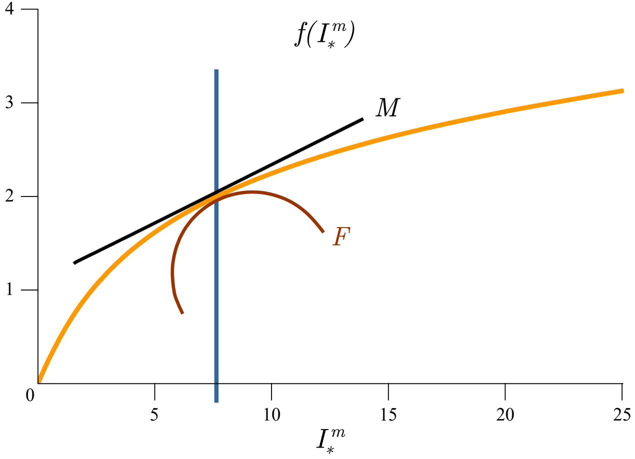
$$M_x = \frac{\partial P}{\partial x}$$

Fragility

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

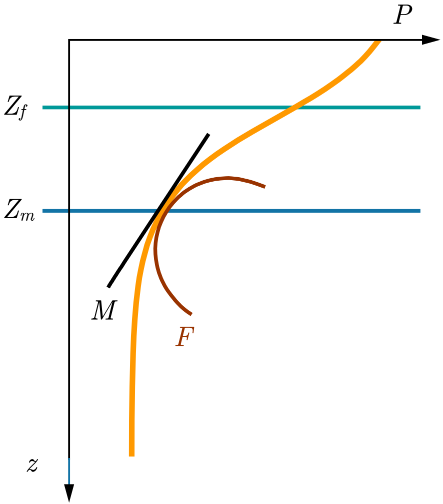
x is the controlling variable, such as irradiance, nutrients, mixed layer depth, ...

Fragility of watercolumn production with respect to irradiance



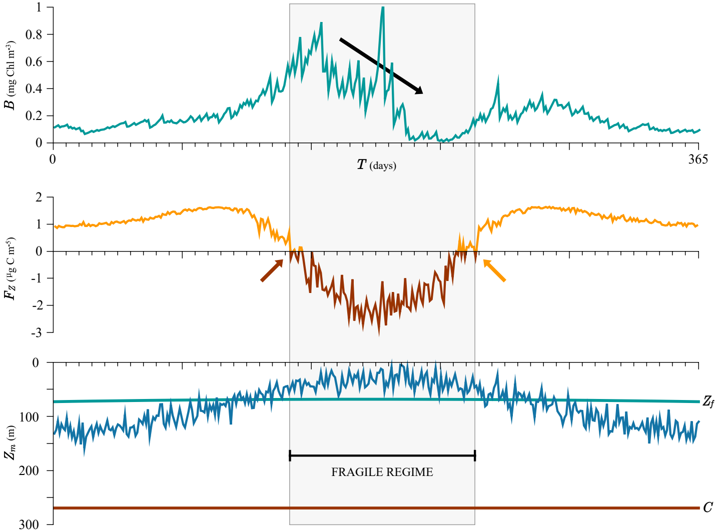
The idea of fragility comes from economics and was introduced by **Nassim Taleb**.

Antifragility of mixed layer production with respect to mixed layer depth

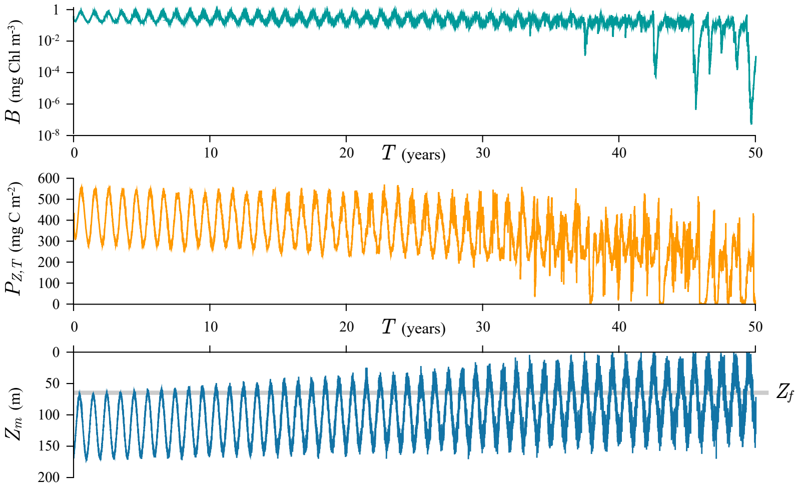


Antifragility is the opposite of fragility. Such systems gain from variability.

Looking at the seasonal cycle

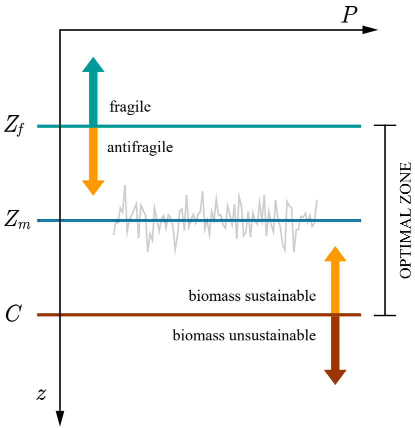


Effect of non-stationary perturbations on the seasonal cycle



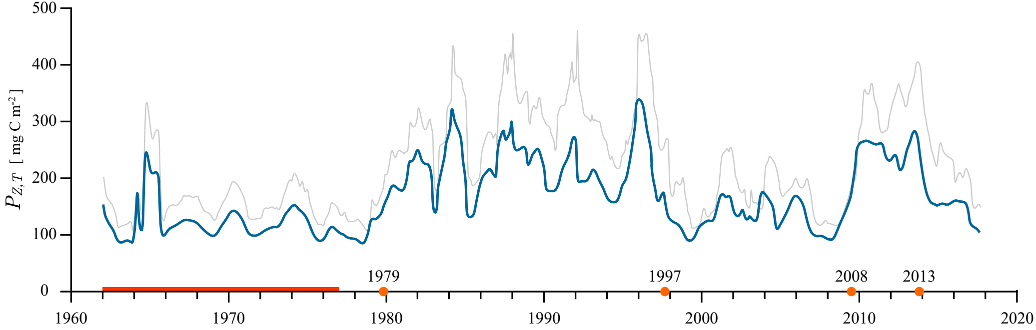
Crossing Z_f causes a decline in biomass and production due to fragility.
It also changes the seasonal cycle of biomass and production.

Interpreting the model behaviour



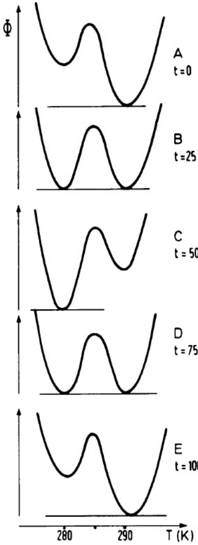
Even though the critical depth criterion is met, biomass can be suppressed due to high frequency variability. Is there an optimal zone for the phytoplankton to thrive and production to be sustained in the long run? Can we speak of tipping points in primary production?

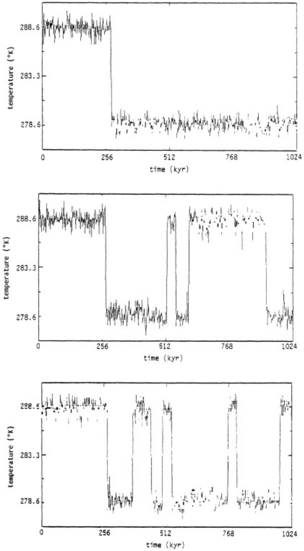
Looking at longer time scales



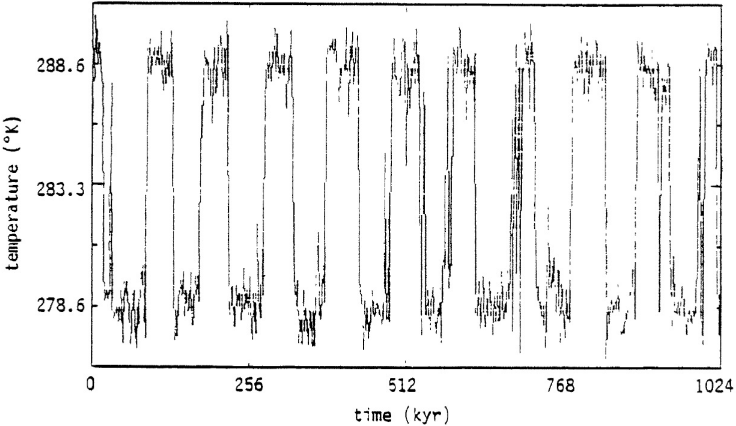
55 year long in situ time series from the Adriatic (Kovač et al., 2018)

Signs of stochastic resonance? (Benzi et al., 1981, 1982, 1983)

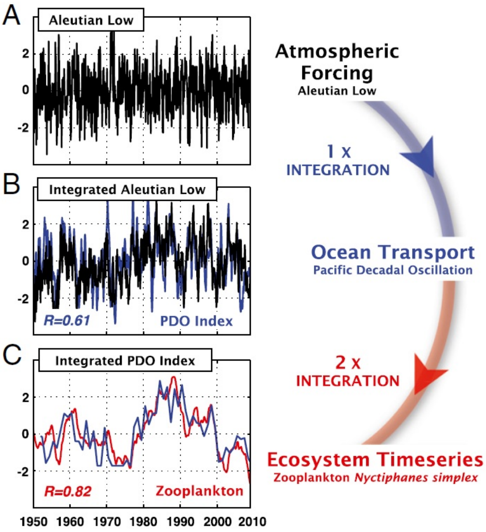




At stochastic resonance the following happens (Benzi et al., 1981, 1982, 1983)



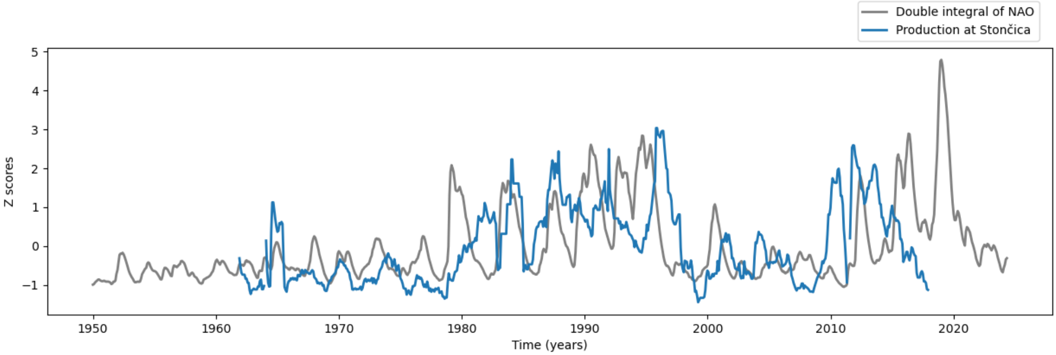
Double integration hypothesis? (Di Lorezno & Ohman, 2013, PNAS)



$$\frac{\partial \phi(t)}{\partial t} = f(t) - \frac{\partial \phi(t)}{\tau_{ocean}}$$

$$\frac{\partial \beta(t)}{\partial t} = \phi(t) - \frac{\partial \phi(t)}{\tau_{bio}}$$

Double integration hypothesis at Stončica in the Adriatic Sea



Applying the double integration technique on the NAO signal yields the above.

Herein lies the need for more time series data!

Data collection in progress

Primary production time series data acquired:

Stončica	1962	
Kaštelanski zaljev	1962	
Bermuda Atlantic Time Series	1988	bats.bios.edu
Hawaii Ocean Time Series	1988	hahana.soest.hawaii.edu/hot/hot-dogs
Cariaco	1996	imars.marine.usf.edu/car
Monterey Bay	1988	www.mbari.org/bog
La Coruña	1990	www.seriestemporales-ieo.com
Western Channel Observatory	1992	www.westernchannelobservatory.org.uk

At present we are looking into not so well known sources of data.

And the need for more theory!

Ito's lemma to model the effect of noise on primary production

If we assume the controlling variable is a stochastic process, for example:

$$\mathrm{d}X = \mu\,\mathrm{d}t + \sigma\,\mathrm{d}W$$

we need to apply **Ito's lemma** to calculate how production changes:

$$\mathrm{d}P^B = \left(\frac{\partial P^B}{\partial t} + \mu \frac{\partial P^B}{\partial x} + \frac{\sigma^2}{2}\frac{\partial^2 P^B}{\partial x^2}\right) dt + \sigma \frac{\partial P^B}{\partial x}\,\mathrm{d}W$$

Ito's lemma to model the effect of noise on primary production

Using the definitions of **marginal production** and **fragility** we get:

$$\mathrm{d}P^B = \Big(\frac{\partial P^B}{\partial t} + \mu M_x + \frac{\sigma^2}{2} F_x\Big) dt + \sigma M_x \, \mathrm{d}W$$

The effect of noise spills over to the deterministic component.

And also TIME!

Thank you!