Faculty of Physics, University of Rijeka
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WORKSHOP
Light and photosynthesis in the sea

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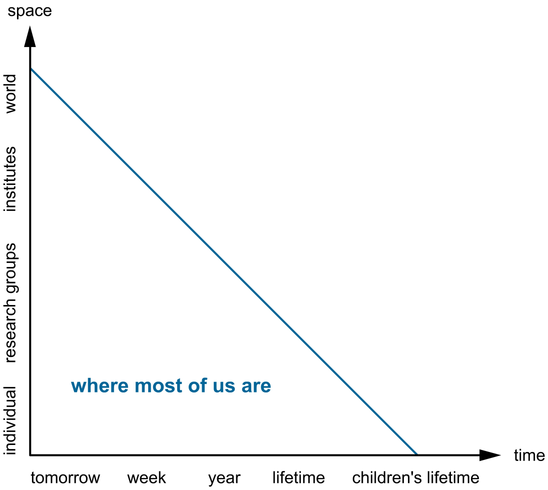
HRZZ
Croatian Science Foundation

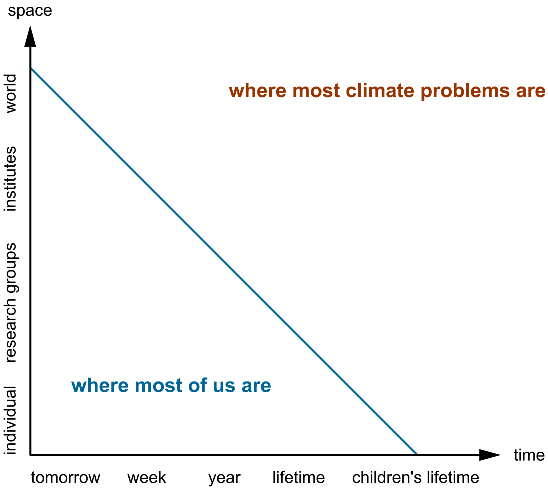
Fragility of primary production under climate change

Motivation



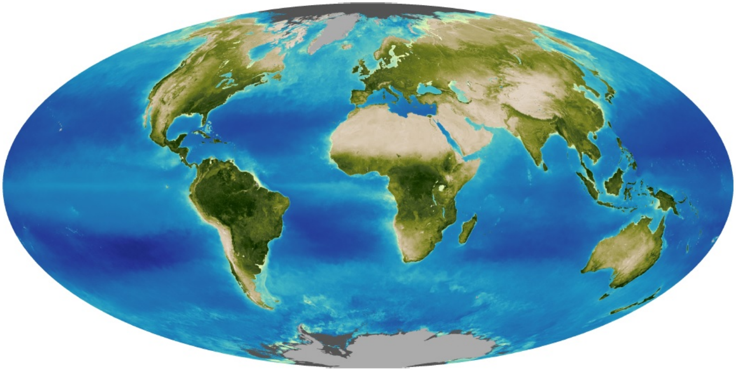
Adopted from Limits to growth (1972)

Motivation



Adopted from Limits to growth (1972)

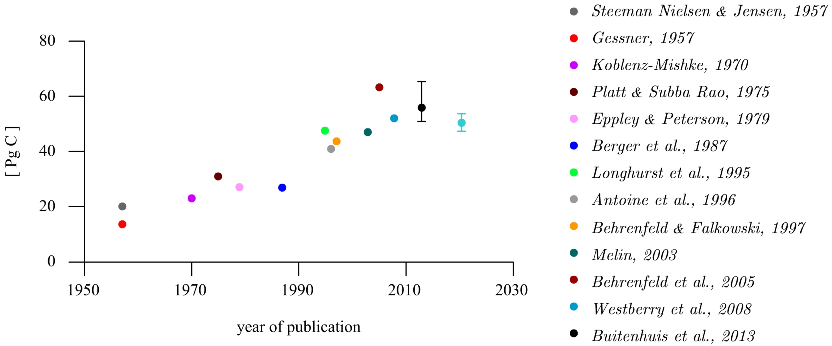
Where are we now?



Anthropogenic carbon emissions per year 10 Gt C
Carbon assimilated by the biosphere per year 100 Gt C
Carbon assimilated by phytoplankton 50% of total
Phytoplankton biomass 1% of total land biomass

How we got here

Global annual marine primary production from the literature



Adopted from Buitenhuis et al. (2013)

Where are we going?

Tragedy of the commons

If decisions about the use of renewable natural resources are based exclusively on profits, even long-term profits, **renewable natural resources will be used on a sustainable basis only if their biological growth rate is greater than the expected growth rate of alternative investments.** Because the growth rate of the world economy today is greater than the biological growth rate of most renewable resources, there are powerful economic incentives not to use renewable natural resources on a sustainable basis. **If people accept the rules of the game in a free market economy, it is rational to use renewable resources unsustainably whenever biological production fails to compete with alternative forms of investment.**

(Marnet, 2001)

The beginning for me

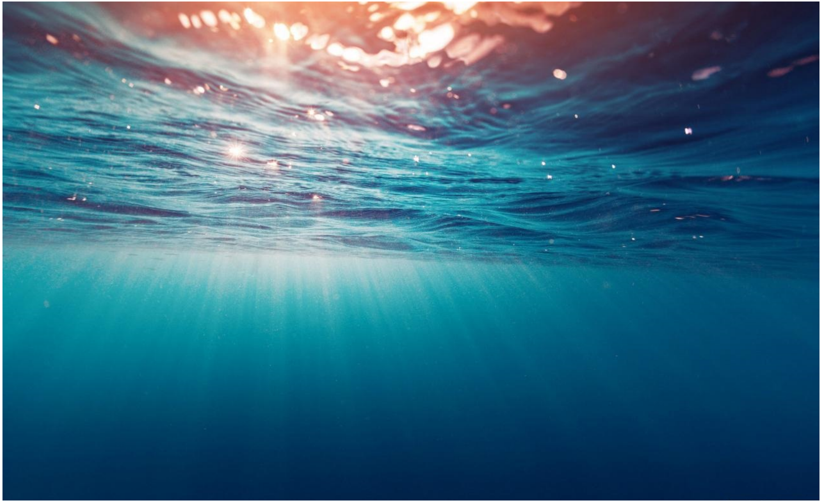
At the end of 2010 I was given teaching materials written by Trevor Platt & Shubha Sathyendranath from the Plymouth Marine Laboratory in the United Kingdom.

Here is an excerpt from those materials:

In this series of articles, we propose to develop, in a systematic and self-consistent manner, the theoretical basis for calculating primary production in aquatic systems. The material should be accessible and understandable by anyone with a working knowledge of ***elementary calculus.***

Just got my masters in Physics, so elementary calculus was not that hard ;)

What happens below the surface?



Trevor's mathematical formalism and the canonical model

$$P_{Z,T} = \int_0^\infty \int_0^D B p^B(I)\,\mathrm{d}t\,\mathrm{d}z$$

So far so good!

Trevor's exact solution (Platt et al., 1990)

$$P_{Z,T} = \frac{BP_m^B D}{K}\left(\sum_{n=1}^{\infty}\frac{2\left(I_*^m\right)^{2n-1}}{\pi\left(2n-1\right)\left(2n-1\right)!}\frac{\left(2n-2\right)!!}{\left(2n-1\right)!!} - \sum_{n=1}^{\infty}\frac{\left(I_*^m\right)^{2n}}{2n\left(2n\right)!}\frac{\left(2n-1\right)!!}{\left(2n\right)!!}\right)$$

Talk about elementary calculus! What are theses double exclamations?!

Vertical structure

Primary production

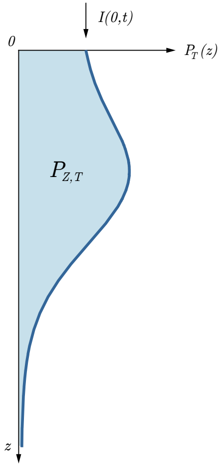
$P(z,t) \quad [\mathrm{mg\,C\,m^{-3}\,h^{-1}}]$

Daily production

$P_T\,(z) \quad [\mathrm{mg\,C\,m^{-3}}]$

Watercolumn production

$P_{Z,T} \quad [\mathrm{mg\,C\,m^{-2}}]$



Approaches to studying primary production

In situ

Incubation at sea under natural light conditions.

(Steemann Nielsen, 1952)

In vitro

Incubation under controlled light conditions.

(Platt i Jassby, 1976)

In silico

Computer implementation of primary production models.

(Gentleman, 2002)

Steemann Nielsen (1952) ICES Journal of Marine Science

The Use of Radio-active Carbon (C^{14}) for Measuring Organic Production in the Sea.

By

E. Steemann Nielsen,
Royal Danish School of Pharmacy, Copenhagen.

1. Introduction.

As on land, so in the sea autotrophic plants are the basis of all life. Sessile plants, however, live on a narrow fringe along the coasts only. If we wish to consider the amount of matter produced annually by the plants of the sea, we must therefore confine our attention to the plankton algae, which are found everywhere in the upper water-masses of the sea. It is the organic matter synthesized by the plankton algae out of purely inorganic substances by means of light which directly and indirectly serves as food for all organisms in the sea, from the smallest bacteria to the largest whale.

As the constantly increasing number of human beings on our globe requires greater and greater quantities of food, and as the food production on land can be but little increased, we must consider the sea as an important reserve.

It is therefore of great importance to be able to estimate the amount of the annual production by the plants of the sea. In recent years one has repeatedly come across figures according to which the annual production of organic matter in the sea is nearly ten times that of the production on land. These figures originate from Rabinowitch (1945), who has collected his data mainly from American sources (Riley, 1938, 1939, 1941, and Seiwell, 1935).

Whereas, according to Rabinowitch, the land annually fixes $1{\cdot}9 \times 10^{10}$ tons of carbon, a value originally calculated by Schroeder (1919), the sea is said to fix $15{\cdot}5 \times 10^{10}$ tons of carbon.

Both Riley's and Seiwell's figures for the production of organic matter in the tropical Atlantic seem incredible, even before determinations were made by the "Galathea" Expedition, and, indeed,

in what follows it will be shown that even the order of magnitude is wrong.

Before the "Galathea" Expedition put to sea in October 1950, the production of organic matter in the oceans must therefore be considered as completely unknown. Only values for the production in a few northern coastal waters had been determined by reliable methods, methods which it would normally be impossible to use on the open sea. It is therefore highly significant that the expedition was provided with equipment for determining the production of matter by phytoplankton by an entirely new method. This method, which has taken the radio-active carbon isotope C^{14} into its service, has now been used by the "Galathea" Expedition in all the oceans. It has proved applicable with equal certainty whether the productivity of the sea area was very high or extremely low. A basis has now been established for an estimate of the production of matter in the oceans, at any rate on broad lines.

2. Methods previously used for Determining the Production of Matter in the Sea.

The first attempts at determining the production of organic matter in a coastal region were made in the English Channel (Atkins, 1922, 1923). Until then scientists had had to content themselves with investigations of the magnitude of the standing crop of plants. Observations of this kind are of course of great interest in themselves. In many respects they are, however, a poor basis for a determination of the production of matter.

To take an example from the land; if immediately before the harvest we compare the quantities of matter found per square metre of surface in a cornfield and a wood, by far the greatest amount of organic matter will be found in the wood. Here the amount of matter has accumulated during a long series of years, whereas all the organic matter in the cornfield has been produced in a single season. If the production of matter in the two localities is to be determined in such a way that comparison is possible, we must determine the amount of organic matter produced in a year through photosynthesis, thus getting the gross production. If we deduct from this quantity the respiration of the plants during the year, we shall get the net production. Both the gross and the net production can be used for comparison of the productivity in the two areas.

The quantity of matter in the plankton in a sea area at a certain time cannot, of course, be compared directly with the amount of matter in the land regions mentioned above, as the matter in the sea has been produced in a very short period, often only a few days. If the production of matter by the plankton always took place at the same rate, it would of course be possible to compare the productivity of the plankton in the various areas on the basis of the amount of plankton present. However, this is not the case at all. Temperature, light, and amount of nutrient salts are of decisive importance for the rate of production.

As the constantly increasing number of human beings on our globe requires greater and greater quantities of food, and as the food production on land can be but little increased, ***we must consider the sea as an important reserve.***

Some *in situ* time series of primary production that I had access to at that time

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
Monterey Bay	1988	www.mbari.org/bog
La Coruña	1990	www.seriestemporales-ieo.com
Western Channel Observatory	1992	www.westernchannelobservatory.org.uk
Cariaco	1996	imars.marine.usf.edu/car

+ 1148 annual time series from 483 locations (Cloern et al., 2014)
+ 125 time series longer than 8 years with more than 10 measurements per year (Winder & Cloern, 2010)

Mathematical formalism

Primary production

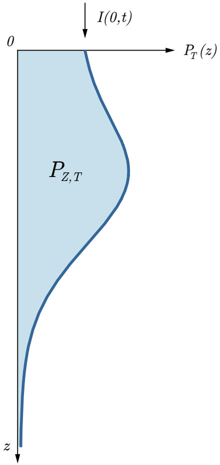
$$P(z,t) = B(z)\, p^B\Big(I(z,t)\Big)$$

Daily production

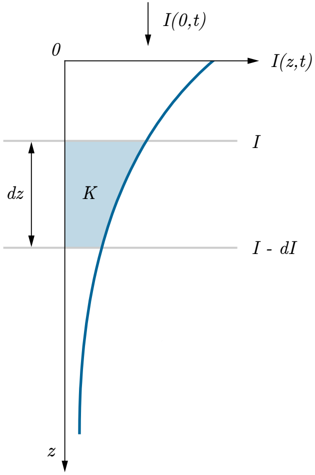
$$P_T\,(z) = \int_0^D B\,(z)\, p^B\Big(I\,(z,t)\Big)\,\mathrm{d}t$$

Watercolumn production

$$P_{Z,T} = \int_0^\infty \int_0^D B\,(z)\, p^B\Big(I\,(z,t)\Big)\,\mathrm{d}t\,\mathrm{d}z$$



Underwater light field



Surface irradiance

$I(0) = I_0$

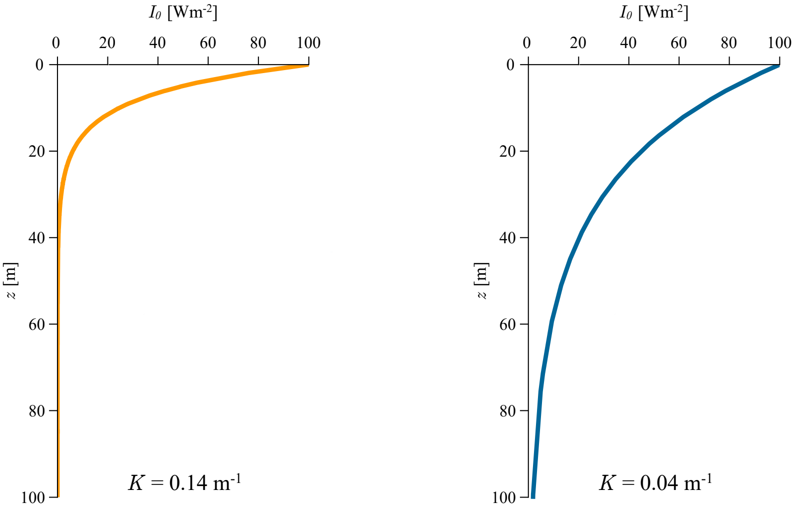
Beer-Lambert law

$$\frac{\partial I}{\partial z} = -KI$$

Irradiance at depth

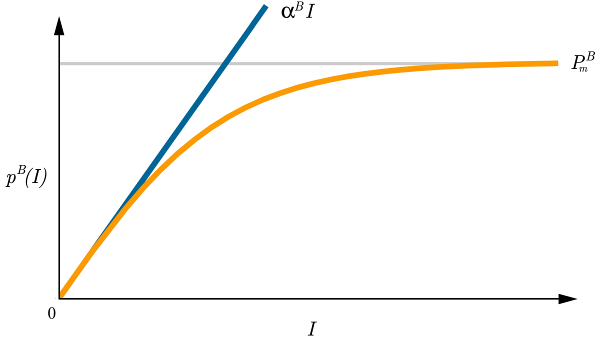
$I(z) = I_0 \exp(-Kz)$

Example



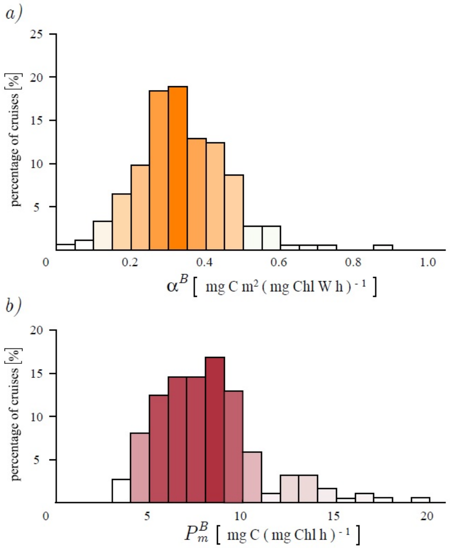
I_0 [Wm^{-2}]
0 20 40 60 80 100
z [m]
0 20 40 60 80 100
$K = 0.14$ m^{-1}
I_0 [Wm^{-2}]
0 20 40 60 80 100
z [m]
0 20 40 60 80 100
$K = 0.04$ m^{-1}

Photosynthesis irradiance function

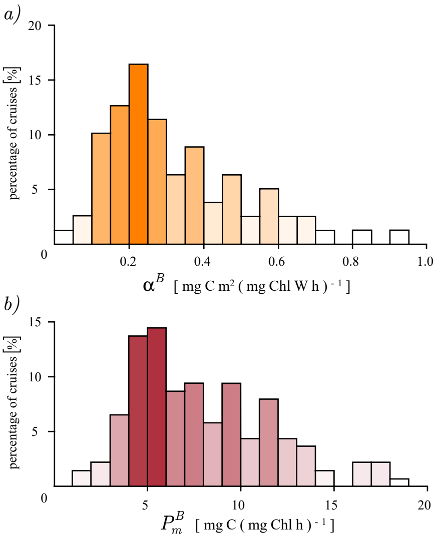


$$p^B(I) = P_m^B\left(1 - \exp\left(-\alpha^B I / P_m^B\right)\right)$$

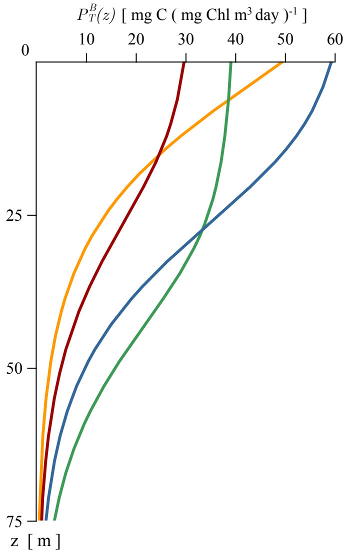
Parameters at Hawaii



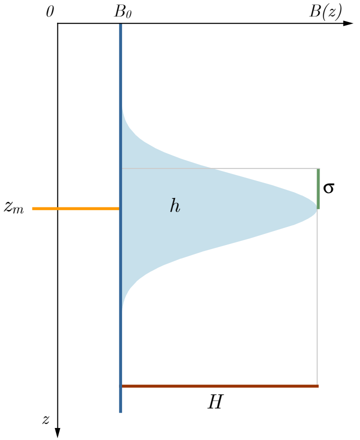
Parameters at Bermuda



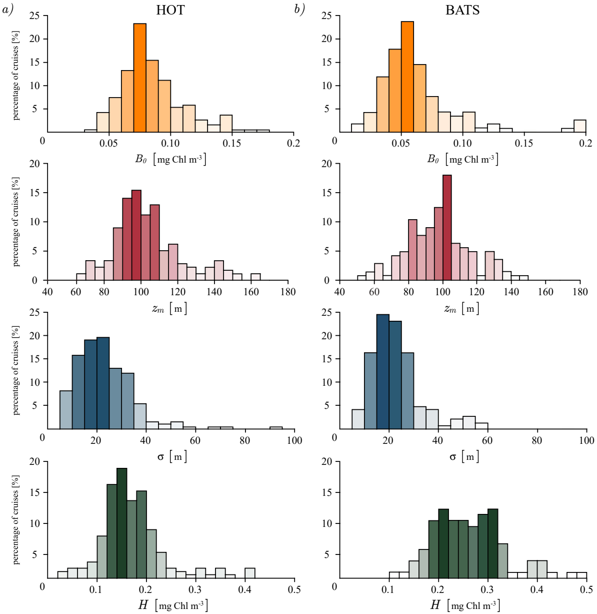
Example



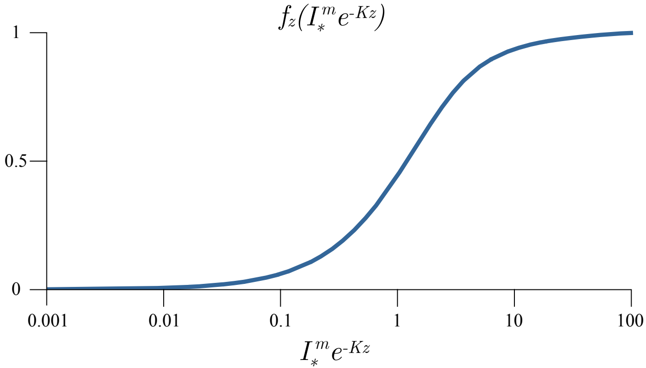
Biomass profile



$$B(z) = B_0 + \frac{h}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(z - z_m)^2}{2\sigma^2}\right)$$


a)
HOT
b)
BATS
percentage of cruises [%]
B0 [mg Chl m-3]
zm [m]
σ [m]
H [mg Chl m-3]

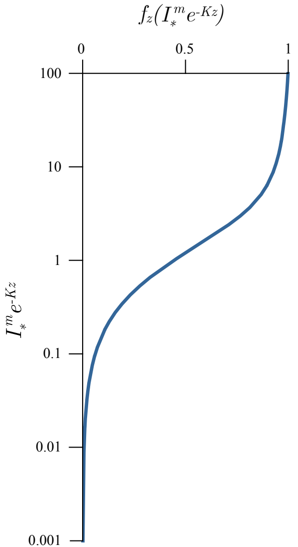
Canonical solution for daily production at depth



$$P_T(z) = B(z) P_m^B D f_z(I_m^*)$$

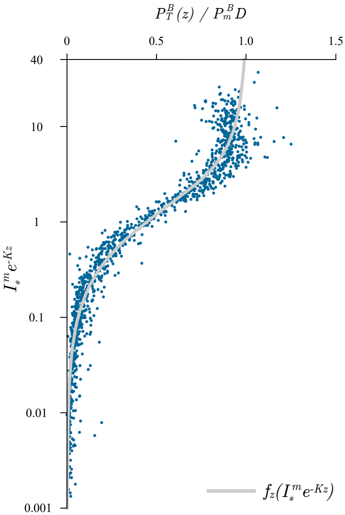
(Kovač et al., 2016)

Daily production profile

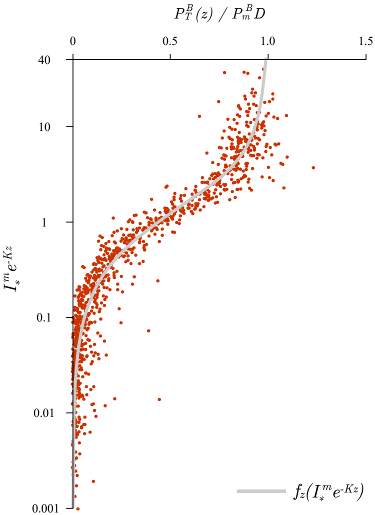


$$P_T(z) = B(z) P_m^B D f_z\left(I_*^m e^{-Kz}\right)$$

Model versus data for production at depth

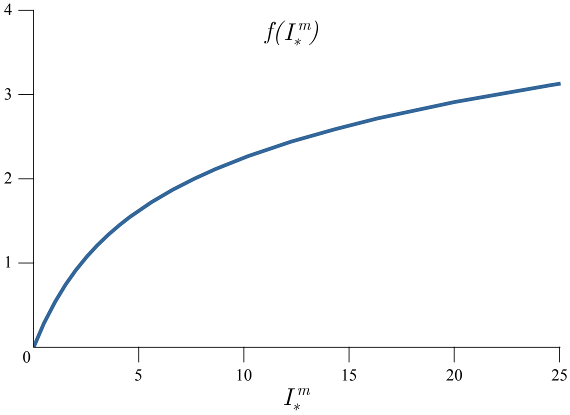


Hawaii R^2 **0.97**



Bermuda R^2 **0.95**

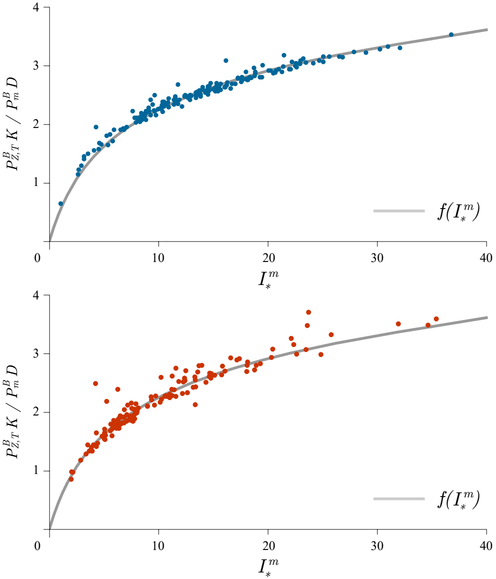
Canonical solution for daily watercolumn production



$$P_{Z,T} = \frac{B P_m^B D}{K} f(I_*^m) \qquad I_*^m = \frac{\alpha^B I_0^m}{P_m^B}$$

(Platt et al., 1990)

Model versus data for watercolumn production

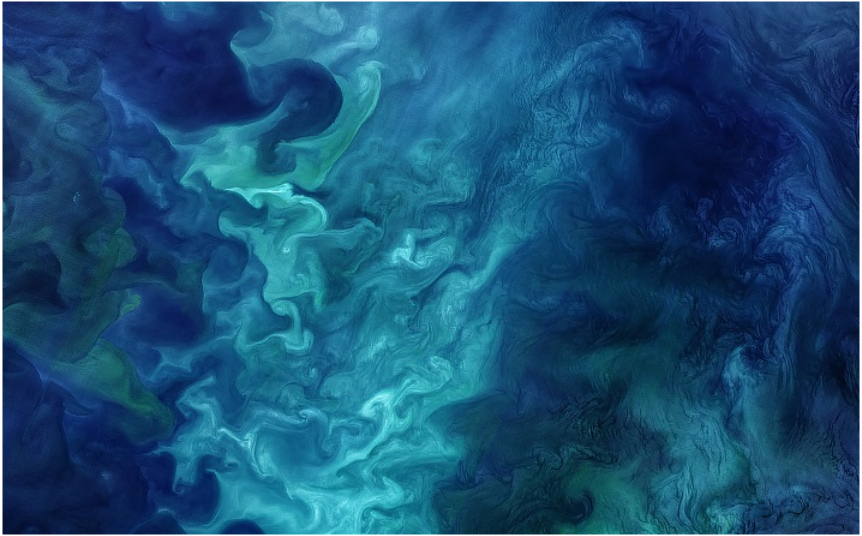


Hawaii R^2 **0.99**

Bermuda R^2 **0.97**

(Kovač et al., 2016, 2018)

Where do we use these production models?



Time evolution of phytoplankton biomass B in the ocean is modelled as:

$$\frac{\partial B}{\partial t} = P - L + advection + mixing$$

Change in biomass is a result of production, losses and transport.

How good are these models?

Time to find out by doing some coding exercises:)