# Primary Production: Satellite-Based Estimates over Two Decades

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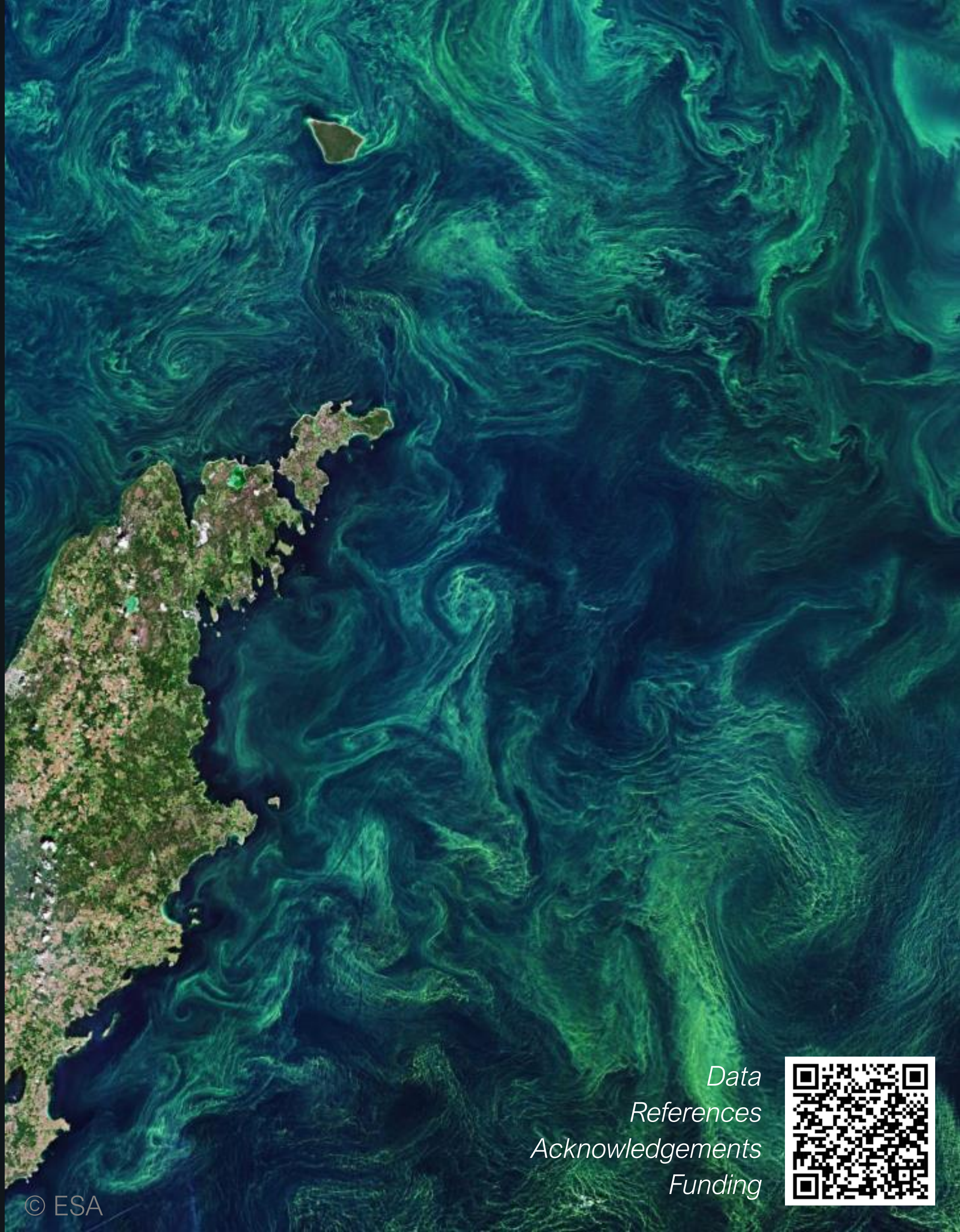
PML | Plymouth Marine Laboratory

BICEP Biological Pump and Carbon Exchange Processes

cbiomes Simons Collaboration on Computational Biogeochemical Modeling of Marine Ecosystems

esa



# Introduction

Primary production by marine phytoplankton is one of the largest fluxes of carbon on our planet. In the past few decades, considerable progress has been made in estimating global primary production at high spatial and temporal scales by combining *in situ* measurements of primary production with remote-sensing observations of phytoplankton biomass (Figure 1). One of the major challenges in this approach lies in the assignment of the appropriate model parameters that define the photosynthetic response of phytoplankton to the light field. In the present study, a global database of *in situ* measurements of photosynthesis versus irradiance (P-I) parameters and a 20-year record of climate quality satellite observations were used to assess global primary production and its variability with seasons and locations as well as between years. In addition, the sensitivity of the computed primary production to potential changes in the photosynthetic response of phytoplankton cells under changing environmental conditions was investigated.

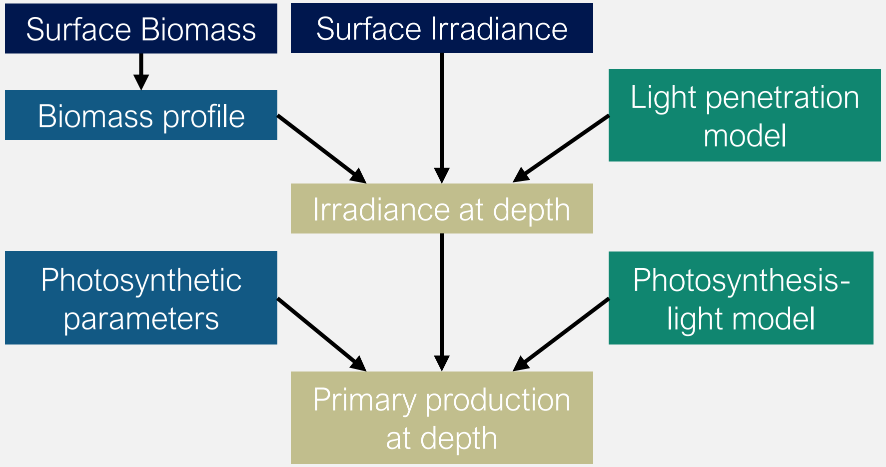



*Figure 1. Schematic diagram of the spectrally resolved and fully coupled primary production model first published by Platt & Sathyendranath (1988) with input from satellite (dark blue) and in situ (blue) observations that are used in a light penetration and light-photosynthesis models (green) to compute irradiance and primary production at depth (yellow). (Figure simplified from Sathyendranath et al. 2020)*

# Method

Primary production was estimated for each month between 1997-2018 using the model of Platt & Sathyendranath (1988), with recent updates (Sathyendranath et al. 2020). For this study the following improvements were included:

- A 21-year time series of surface phytoplankton biomass from the Ocean-Colour Climate Change Initiative, a multi-sensor, bias corrected, climate-quality-controlled product
- An extended database of 9,765 *in situ* measurements of photosynthesis-irradiance (P-I) parameters (Figure 2). Mean and standard deviation of each P-I parameter were assigned to 57 biogeographic provinces (Longhurst 2007) and 4 seasons; statistical methods were used to fill data gaps.

Model computations included 1) Main model run with mean P-I parameters and 2) Sensitivity analysis based on mean ±1 standard deviation P-I parameters.

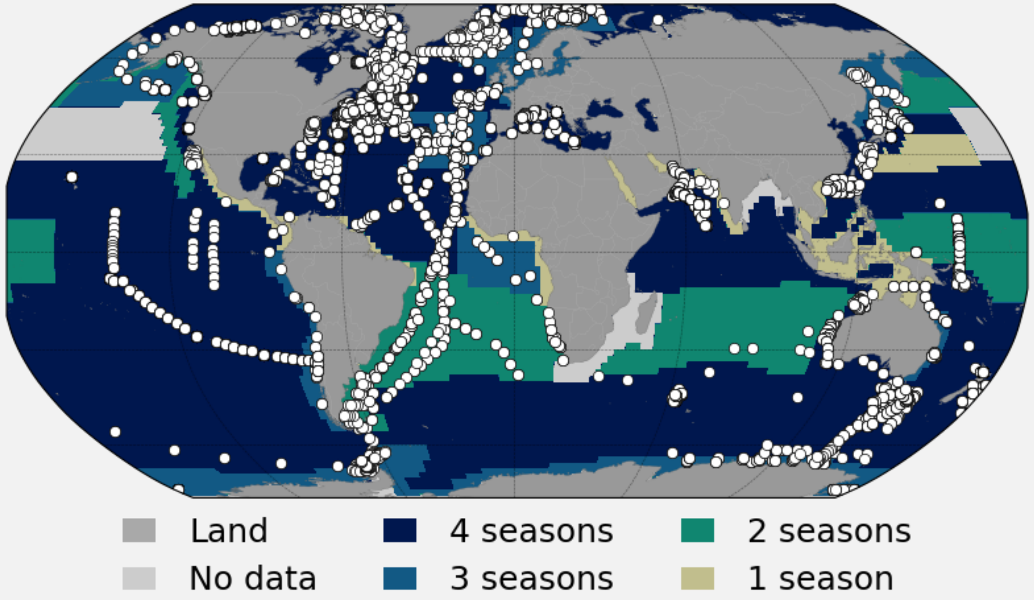


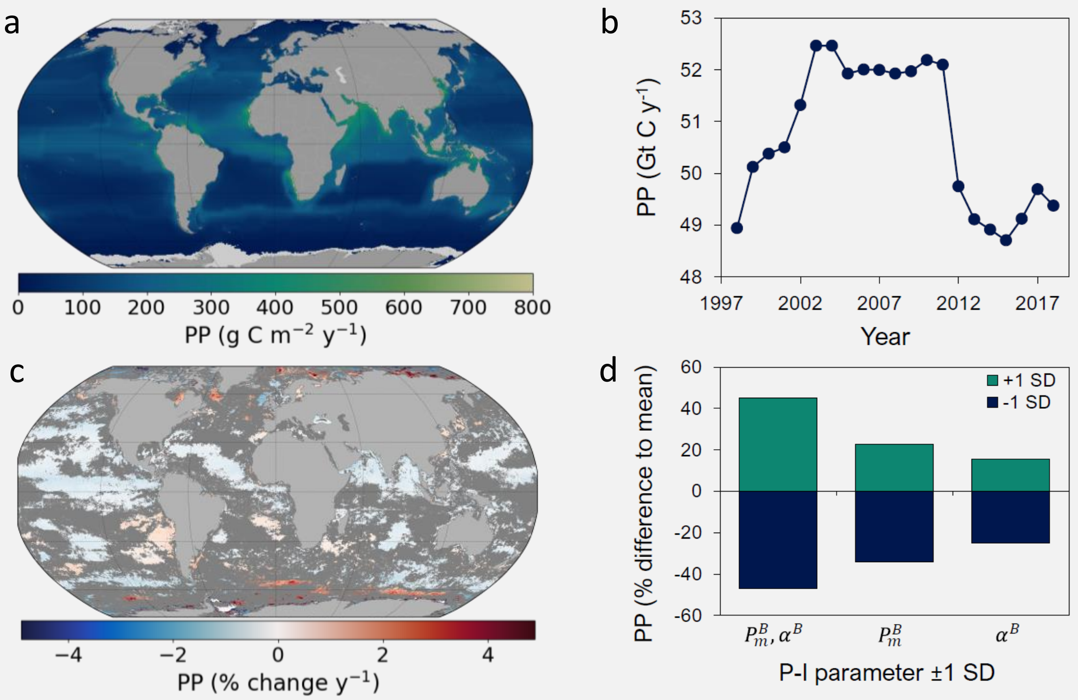

*Figure 2. Sample locations for P-I experiments obtained from databases and literature with seasonal coverage in each biogeographic province as defined by Longhurst (2007). A total of 8,676 P-I experiments were used in the present study, covering 53 biogeographic provinces and 96.6% of the world's ocean. High seasonal data coverage was obtained for 37 provinces (3-4 seasons, 79.9% coverage).*

# Results

The main model run showed that global annual primary production (PP) varied from 48.7 to 52.5 Gt C $y^{-1}$ between 1998 and 2018 (Figure 3a,b). Positive and negative linear trends in PP were observed between 1998 and 2018 (Figure 3c), but the global trend was non-linear with highest rates observed between 2003-2011 (Figure 3b). Regional variations to the global PP trend were also observed (Kulk et al. 2020).

The sensitivity analysis showed that global annual PP could increase or decrease by 45-46% when P-I parameters were changed (Figure 3d). Calculations of PP were more sensitive to changes in the assimilation number ($P_m^B$) compared with the initial slope of the P-I curve ($\alpha^B$).

Comparison between the P-I parameters and physico-chemical data available in the *in situ* database showed that variations in $\alpha^B$ were related to light, chl-a and nutrients, while variations in $P_m^B$ were related to temperature, depth, latitude and nutrients (Figure 3e).




| $\alpha^B$ | Lat | Depth | Chl-a | PAR | T | $NO_3$ | $PO_4$ | Si |
|---|---|---|---|---|---|---|---|---|
| Global | **0.12** | 0.04 | 0.04 | 0.09 | -0.09 | **0.16** | 0.05 | 0.08 |
| Antarctic | **-0.13** | **0.13** | -0.11 | -0.03 | **-0.14** | **0.30** | **0.26** | 0.14 |
| Atlantic | **0.14** | 0.00 | 0.01 | **0.15** | **-0.11** | **0.15** | 0.01 | **0.11** |
| Indian | **0.08** | 0.06 | **-0.17** | **0.40** | 0.11 | 0.00 | -0.12 | -0.15 |
| Pacific | **0.04** | **0.25** | **0.15** | 0.06 | -0.09 | **0.46** | **0.45** | 0.08 |
| Coastal | **0.13** | 0.05 | **-0.23** | **0.11** | **0.14** | **0.13** | **-0.11** | **0.13** |
| Polar | -0.02 | **0.09** | 0.03 | **0.12** | 0.06 | 0.04 | -0.03 | **-0.13** |
| Trades | **-0.13** | **0.29** | **0.27** | **0.14** | **-0.24** | 0.17 | 0.08 | 0.00 |
| Westerlies | **0.12** | 0.01 | 0.04 | **0.13** | **-0.24** | **0.18** | 0.04 | 0.08 |

| $P_m^B$ | Lat | Depth | Chl-a | PAR | T | $NO_3$ | $PO_4$ | Si |
|---|---|---|---|---|---|---|---|---|
| Global | **-0.27** | **-0.29** | -0.02 | **0.18** | **0.31** | **-0.13** | **-0.20** | **-0.17** |
| Antarctic | **-0.39** | -0.02 | -0.03 | **0.14** | **0.18** | -0.06 | **-0.17** | **-0.38** |
| Atlantic | **-0.27** | **-0.28** | **-0.10** | **0.21** | **0.33** | **-0.09** | **-0.15** | **-0.12** |
| Indian | **-0.17** | **-0.50** | -0.01 | 0.10 | **0.35** | **-0.21** | **-0.31** | **-0.21** |
| Pacific | **0.15** | **-0.54** | **0.26** | **0.10** | 0.09 | 0.04 | 0.06 | 0.01 |
| Coastal | **-0.16** | **-0.20** | **-0.19** | 0.06 | **0.42** | 0.01 | **-0.26** | -0.05 |
| Polar | **-0.39** | **-0.23** | 0.05 | **0.11** | **0.37** | **-0.18** | **-0.22** | **-0.23** |
| Trades | **0.09** | **-0.50** | -0.08 | 0.12 | 0.08 | -0.07 | -0.02 | -0.06 |
| Westerlies | 0.01 | **-0.60** | **0.19** | **0.24** | **0.14** | **-0.11** | -0.09 | -0.04 |

$\rho$: -1.00, -0.75, -0.50, -0.25, 0.00, +0.25, +0.50, +0.75, +1.00

*Figure 3. Study results with a) Climatology of PP for 1998-2018, b) Time series of global annual PP, c) Linear trends in global annual PP for 1998-2018 (dark grey colour are non-significant trends), d) Difference in PP for mean P-I parameters model run compared with computations in which P-I parameters were adjusted by ±1 standard deviation (SD), and e) Correlation coefficients (ρ) for the P-I parameters and environmental variables (p<0.05 in bold).*

# Conclusions

This is the first time that highly quality-controlled ocean-colour observations extending over two decades have been combined with increased coverage of *in situ* observations of the phytoplankton photosynthetic parameters, to compute the magnitude and variability of PP on a global scale. This has led to a more accurate assessment of global annual PP and its trends over the past 20 years. Variability in global annual PP could be related to inter-annual and multi-decadal oscillations, such that the present record of ocean-colour observations is not of sufficient length to detect trends associated with climate change. Here, we report an inter-annual variability of ±2.7% around a mean of 50.7 Gt C $y^{-1}$ between 1998-2018. The importance of accurately assigning photosynthetic parameters in global and regional calculations of PP has been illustrated by a sensitivity analysis. Methods designed to assign photosynthetic parameters based on their relationships to other variables amenable to remote-sensing, could lead to a more dynamic assignment of these parameters in the future. Sea surface temperature and phytoplankton community size structure could be suitable variables for further development of such methods for different ocean basins and biomes.