IMPROVING THE ESTIMATION OF NORTH SEA PRIMARY PRODUCTION: MERIS CHL AND K_D IN VGPM

Marieke A. Eleveld [(1)], **Hans J. van der Woerd** [(1)], **Hylke Beck** [(2)]

[(1)] Institute for Environmental Studies (IVM) / [(2)] Hydrology and Geo-environmental Sciences,
Faculty of Earth and Life Sciences (FALW), Vrije Universiteit (VU) Amsterdam,
De Boelelaan 1087, NL 1081 HV Amsterdam, the Netherlands
e-mail: marieke.eleveld@ivm.vu.nl, hans.van.der.woerd@ivm.vu.nl; bech@falw.vu.nl

ABSTRACT

Remote sensing has several applications in the study of the carbon cycle, amongst which the estimation of marine primary production. This paper shows how to adapt the Vertically Generalised Production Model (VGPM) ─ originally developed for the open ocean by Behrenfeld and Falkowski ─ for application to the North Sea, a shallow marginal coastal sea containing Case 1 waters in the north and Case 2 waters in the south. VGPM describes a relationship between depth integrated primary production (PP_{eu}) and maximum chlorophyll-a normalized carbon fixation rate (P^B_{opt}), sea surface daily PAR (E_0), surface chlorophyll concentration derived by satellite (C_{sat}), euphotic depth (Z_{eu}) and photoperiod (D_{irr}). Input for these variables can be derived with remote sensing. PP_{eu} from VGPM is a MODIS Primary Productivity Level 4 product that has been brokered as the standard product. Results from regressions of chlorophyll derived from remote sensing (C_{sat}) and chlorophyll derived from in situ measurements (C_{is}) show the HYDROPT MERIS CHL product to perform better than the MODIS standard CHL product. In this paper we are using the VGPM model with optimal parameterisation for the North Sea: C_{sat} and Z_{eu} estimation from MERIS HYDROPT. We are currently assessing the impact on the PP_{eu} result, which might have important consequences on the perceived role of the North Sea in the carbon cycle.

1. INTRODUCTION

There is a growing concern about the present rapid increase of temperature and acidity of the North Sea and its effects on the marine ecosystem. Rates of many biological processes will severely be affected, leading to major biological changes of the North Sea in a high-CO_2 world. Notably the seasonality and spatial distribution of major bloom forming algae will change. Changes in weather patterns leading to changes in wind mixing and nutrient run-off will also affect the spatial distribution of algal blooms and the algae species involved. These changes in primary production of pelagic algae have consequences for the higher trophic levels (zooplankton, benthic fauna, fish fauna) in the North Sea [12].

An estimation of primary production (PP) from ocean colour remote sensing is relevant for the study of the carbon cycle and it's sensitivity to global change [6, 5]. To derive PP various approaches have been attempted [15, 4]. It was already shown that the oceanic primary production can be computed from satellite information of the chlorophyll pigment concentration and temperature [8]. Furthermore, satellite-based primary productivity rates can be compared with estimates of export production and vertical carbon fluxes by a global ocean circulation, biogeochemical model [9]. However, within the shallow Southern North Sea matters are complicated by suspended sediments. First, the turbid waters decrease penetration of incoming sunlight, thus allowing less photosynthesis by algae. Second, the signal of suspended sediment particles is also registered by the satellite sensor and needs to be resolved from the chlorophyll-*a* signal of the algae. In addition, waters with significant river water component and/or strong local biological activity often exhibit absorption by Coloured Dissolved Organic Matter (CDOM). Note that the contribution of coastal seas in the storage of CO_2 via a mechanism called the continental shelf pump is known to be relatively high [23]. The North Sea is well-investigated – in situ data and ecological models are available [D3, 14, respectively] – and has a well-known Case 1 and Case 2 component.

There are multiple families of daily primary production models [3], that all consider marine net primary production as the amount of carbon that is photosynthetically fixed by phytoplankton, but that differ in their level of integration over time, depth and wavelength. Intercomparison experiments for these models [8, 9] demonstrated that one of the earliest and simplest models, the VGPM type of model, delivered results that were on par with the more sophisticated depth- and wavelength-depended models. PP from Behrenfeld and Falkovski's [4] Vertically Generalised Production Model (VGPM), which comprises an estimate of chlorophyll concentrations and photosynthetic efficiencies has been used as standard MODIS products for all oceans: MODIS Primary Productivity Level 4 product brokered as P1 in MOD27W (Terra) and MYD27W (Aqua) through NASA in collaboration [R2], currently by Oregon State University [R3] and Rutgers University [R1]. Therefore, as a first approach to understand the failures and success of any satellite PP products in Case 2 waters, our research started with the implementation of a modified VGPM model, and this paper aims to show how to parameterise VGPM for the North Sea.

The model is given by:

$$PP_{eu} = 0.66125 \cdot P^B_{opt} \cdot \frac{E_0}{E_0 + 4.1} \cdot Z_{eu} \cdot C_{opt} \cdot D_{irr} \quad (1)$$

PP_{eu}	Daily C fixation integrated from the surface to Z_{eu} (mg C m^{-2})
P^B_{opt}	Maximium C fixation rate within a water column (mg C (mg CHL)$^{-1}$ h^{-1})
E_0	Daily Photosynthetically Active Radiance (PAR) (mol quanta m^{-2})
Z_{eu}	Physical depth receiving 1% of E_0 (m)
C_{opt}	Chlorophyll conc. at P^B_{opt} (mg CHL m^{-3})
D_{irr}	Photoperiod (decimal h)

In this paper we aim to parameterise this model entirely with model and satellite measurements. We used the MERIS HYDROPT approach [17] by which we implicitly couple a radiative transfer (RT) model to the model of primary production. MERIS has optimal band settings for good retrieval of chlorophyll concentrations (C_{sat}). HYDROPT, a physically-based algorithm derives several bio-physical parameters (*i.a.* C_{sat}) from reflectance spectra measured by the MERIS instrument and was calibrated and validated with apparent and inherent optical properties of the North Sea. Our approach differs from [21] because we also estimated Z_{eu} using this RT model, HYDROLIGHT. We end with comparing it with the original MODIS standard PP product

2. DATA AND METHODS

We have been performing 1) a stepwise evaluation of the principal variables (input parameters), which led to 2) parameterisation with customised MERIS products. Subsequently, 3) PP results from several parameterisations were compared. Finally, 4) our adapted final primary production product will be presented in a MapServer application on the Internet.

2.1. Data

2.1.1. Parameterisation with MODIS and validation of input parameters

First we parameterised VGPM with MODIS L3 CHL data, and Z_{eu} from [16], which is more or less the "standard" VGPM approach [R2, currently R3 and R1]. In a first customisation we applied an empirical relationship between Z_{eu} and chlorophyll and TSM from in situ measurements of the Dutch North Sea, which is probably more suitable for Case 2 waters. We validated, and made a sensitivity analysis of the input parameters for the North Sea, which stimulated us to apply MERIS parameterisation.

2.1.2. Parameterisation with MERIS and comparison with MODIS VGPM products

Subsequently, VGPM was parameterised with MERIS CHL and MERIS K_D output from a MERIS CHL algorithm (HYDROPT) that was particularly designed and validated for the North Sea (EU-REVAMP) [17]. This approach is illustrated by Fig. 1.

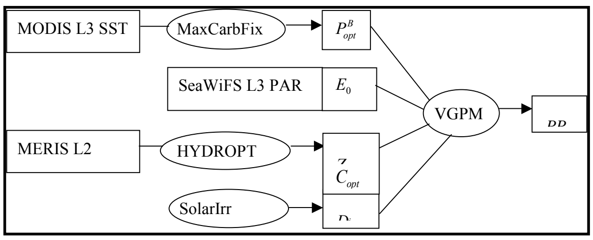

Figure 1. Flowchart showing how to derive depth integrated primary production.

Specification of datasets used:

P^B_{opt}	Modelled as a function of a MODIS Aqua Level 3 mapped 8 day (daynr 73-80 in 2007) 4 km Sea Surface Temperature (SST) composite [D1];

E_0 SeaWiFS Level 3 mapped 8 day (2007 daynr 73-80) 9 km Photosynthetically Active Radiation (PAR) data [D2];

Z_{eu} as a function of MERIS (14-21 Mar 2007) K_D derived with HYDROPT;

C_{opt} from C_{sat} in this case MERIS (14-21 Mar 2007) chlorophyll concentration derived with HYDROPT;

D_{irr} Modelled as a function of Julian day and latitude.

Data from the Ocean Productivity pages [R3] were used to see if our PP result falls within the same order of magnitude as the standard VGPM results.

2.2. Implementation

Several Matlab programs were created for automated handling and processing of the stacks of matrices (.hdf's) that we retrieved by ftp using the North Sea specific parameterisation of VGPM. For:

P_B^{opt} the latest SST composite was downloaded, the research area (62 to 48 NB, -4 WL to 12 EL converted to L3 row and column) was cut-out, conversion of scales values using slope and intercept was applied, and a polynomial [4] was used to calculate P_B^{opt} ;

E_0 PAR data were downloaded, the research area was cut out, the scaling values were converted, and the 9 km data were resampled to 4.63 km data;

Z_{eu} 13 individual MERIS L2 MEGS 7.4 / IPF 5.02 datasets were processed to K_D (for various MERIS wavelengths) with HYDROPT (see Fig.2, and [17], the results were averaged and converted to Z_{eu} by applying 4.6/ MERIS K_D (average) [11, p. 22];

C_{opt} the same 13 individual MERIS L2 MEGS 7.4 / IPF 5.02 datasets were processed to CHL with HYDROPT (see Fig 2, and [17]) and binned, mapped and resampled, to 8 day geometric mean L3 products;

D_{irr} for each cell in the research area day length (in dec. hours) was calculated as a function of latitude, longitude, date and time [11, pp 35-40].

A program converts the resulting .mat files into ASCII grid files [10], and copies those to an UMN MapServer [13]. The web application WATeRS-PP is currently (Apr 2007) being constructed, will be updated weekly, and allow open and interactive interaction by all [10].

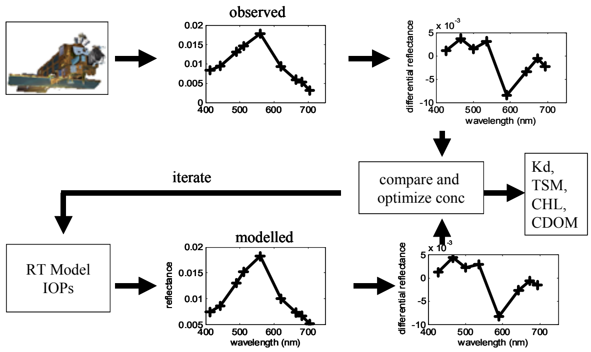

Figure 2. Flowchart illustrating retrieval of K_D and CHL with HYDROPT (after [17]).

3. RESULTS

3.1. Validation of input parameters

[8] showed that the best-performing PP model was able to reproduce ^{14}C-based in-situ measurements within a factor of 2. Therefore, input parameters were validated with in situ measurements to get a grip on uncertainty in our North Sea PP estimates and the main cause of this uncertainty (Table 1).

- P^B_{opt} in VGPM was derived from Sea Surface Temperature (SST). In situ SST measurements [D3] correlated well with the MODIS Level SST (r^2=0.97), with a minor underestimation of 6%. The net effect of the 6% underestimation of SST is a 5% underestimation of P^B_{opt} and primary production.
- Daily PAR (E_0) and photoperiod (D_{irr}) are VPGM parameters that are quite robust and have small errors for the North Sea, such as (Table 1). The SeaWiFS Level 3 PAR standard product compares well to in situ spectral irradiance measurements near the Isle of Texel [D4] r^2=0.98, although there is a 9% overestimation.
- Comparing C_{sat} from standard MODIS and customised REVAMP MERIS chlorophyll product with in situ measurements shows MERIS to perform better, which justifies parameterisation with MERIS as reported in the next section. C_{sat} from MERIS using the HYDROPT algorithm performed well in North Sea waters according to validation for 19 stations in Dutch waters [D3] r^2=0.90, but underestimates concentrations by 12%.

In summer periods, when stratification occurs in the Northern part of the North Sea, the surface values can be different from the chlorophyll concentrations at the depth of maximum production in the column (C_{opt}) [24].

Table 1. Validation of input parameters

description	period	n	regres. equation	r^2	bias	RMSE	range is	range rs
Input for P^B_{opt}: MODIS Level 3 Sea Surface Temperature 8-day standard product								
Case 1 and 2	2003-2006	462	y = 1.03x - 0.812	0.97	-0.06	0.91	3.96 - 20.57	1.57 - 20.24
Case 1 only	2003-2006	46	y = 1.202x - 2.501	0.88	-0.07	1.28	6.83 - 14.37	2.72 - 15.64
Case 2 only	2003-2006	416	y = 1.025x - 0.76	0.98	-0.06	0.85	3.96 - 20.57	1.57 - 20.24
Input for E_0: SeaWiFS Level 3 daily integrated PAR 8-day standard product								
Texel (NIOZ)	Jul-Dec 2003	15	y = 0.981x + 1.775	0.98	0.09	3.15	2.67 - 55.12	3.46 - 51.39
Input for C_{opt}: C_{sat} from MODIS Level 3 sea surface chlorophyll-a 8-day standard product (geom. mean per location)								
Case 1 and 2	2003-2006	60	$y = 1.165x^{1.068}$	0.78	0.23	1.38	0.59 - 8.02	0.61 - 7.54
Case 1 only	2003-2006	47	$y = 1.389x^{1.54}$	0.67	0.13	0.13	0.59 - 0.75	0.61 - 0.95
Case 2 only	2003-2006	13	$y = 1.193x^{1.049}$	0.59	0.27	1.58	1.78 – 8.02	2.22 – 7.54
Input for C_{opt}: C_{sat} from MERIS REVAMP Level 3 sea surface chlorophyll-a 8-day (geom. mean per location)								
Case 1 and 2	2003	62	$y = 1.031x^{0.829}$	0.90	-0.12	1.13	0.7 - 8.64	0.69 - 5.21
Case 1 only	2003	49	$y = 0.934x^{0.706}$	0.81	-0.05	0.12	0.7 - 1.27	0.69 - 1.19
Case 2 only	2003	13	$y = 1.253x^{0.697}$	0.85	-0.15	1.29	1.58 - 8.64	1.81 - 5.21

3.2. Parameterisation with MERIS and comparison with MODIS VGPM products

Fig. 3 shows first results of MERIS parameterisation (top left) versus adapted North Sea MODIS parameterisation with local Z_{eu} estimate (top right) and standard VGPM for March 2006 (bottom left) and April 2006 (bottom right). Notice that in these very first results, products from different periods are being compared, but that they have similar units. (Standard products for 2007 were not yet available through the Internet.) Through incorporation of SPM, primary production in the top figures is lower than in the bottom figures. This effect is especially noticeable for known regions of high turbidity such as the Thames estuary and Flemish Banks.

4. DISCUSSION

The adapted product still can contain other sources of uncertainty or error. Is the P^B_{opt} for the Northern (Case 1) and Southern (Case 2) part of the North Sea sufficiently reproduced by the SST approximation? [4] Already stated that less than half of the variation in P^B_{opt} was explained by the temperature polynomial. Another issue is the reliability of the depth integration and use of $Z_{eu} * C_{sat}$ to represent the PP in the water column? [24] showed the importance of deep chlorophyll maxima in the Northern North Sea.

Progress in these fields, and closure in Carbon budgets attempted for oceans by [2] and for the North Sea a link to [23] is now hampered by the limited availability of validation material that is collected within the time-frame of the present ocean colour sensors (1997- now). ^{14}C measurements are not (easily) available for the North Sea. Fortunately, chlorophyll-specific photosynthesis-irradiance parameters of natural plankton for multiple areas and at different month were collected in the early 1990's [7, 19]. However, these data show that the P-I curves (P^B_{max}, α^B) in coastal waters vary widely, and are only partly related to directly available environmental parameters, such as SST. Operational use of fully automated FRRF systems [20] might be a step forward to validate our products.

In conclusion, this paper reports on a first attempt to adapt a standard PP algorithm for the North Sea. In this paper we report on the possibilities of MERIS to improve estimates of Z_{eu} and C_{sat}, particularly for the Case 2 waters, but work on quantifying the improvement is still needed. A next step could be to consider the influence of TSM and CDOM on P^B_{opt}. The link to modelling and data assimilation is needed to further quantify carbon fluxes [1, 18, 22].

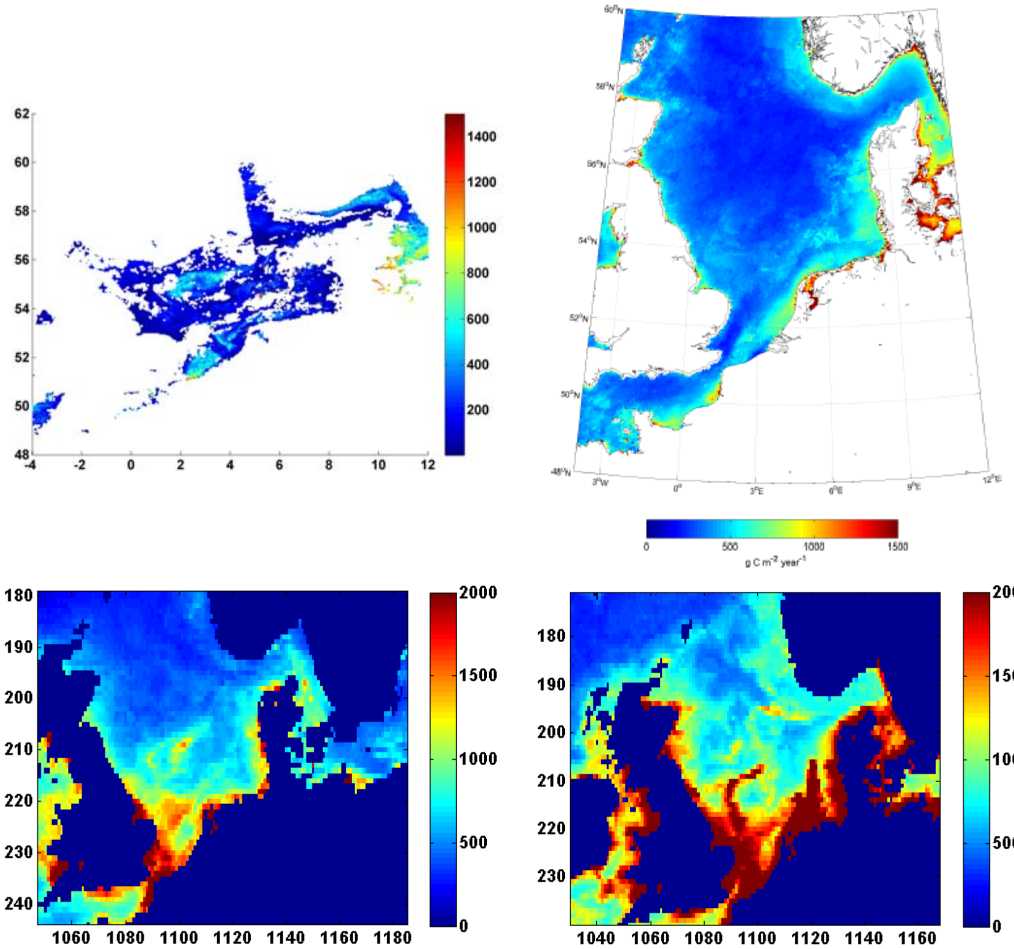

Figure 3 Primary production from MERIS 8d 14-21 Mar 2007 (mg C m^{-2} day^{-1}) (tl), adapted MODIS 2003-2005 (g C m^{-2} $year^{-1}$) (tr), standard VGPM Mar 2006 (bl), and Apr 2006 (br) (both in mg C m^{-2} day^{-1}). (Note the differences in scale bars.)

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