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Comparison of new and primary production models using SeaWiFS data in contrasting hydrographic zones of the northern North Atlantic

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ABSTRACT

The accuracy of two satellite models of marine primary (PP) and new production (NP) were assessed against ^{14}C and ^{15}N uptake measurements taken during six research cruises in the northern North Atlantic. The wavelength resolving model (WRM) was more accurate than the Vertical General Production Model (VGPM) for computation of both PP and NP. Mean monthly satellite maps of PP and NP for both models were generated from 1997 to 2010 using SeaWiFS data for the Irminger basin and North Atlantic. Intra- and inter-annual variability of the two models was compared in six hydrographic zones. Both models exhibited similar spatio-temporal patterns: PP and NP increased from April to June and decreased by August. Higher values were associated with the East Greenland Current (EGC), Iceland Basin (ICB) and the Reykjanes Ridge (RKR) and lower values occurred in the Central Irminger Current (CIC), North Irminger Current (NIC) and Southern Irminger Current (SIC). The annual PP and NP over the SeaWiFS record was 258 and 82 gC m^{-2} yr^{-1} respectively for the VGPM and 190 and 41 gC m^{-2} yr^{-1} for the WRM. Average annual cumulative sum in the anomalies of NP for the VGPM were positively correlated with the North Atlantic Oscillation (NAO) in the EGC, CIC and SIC and negatively correlated with the multivariate ENSO index (MEI) in the ICB. By contrast, cumulative sum of the anomalies of NP for the WRM were significantly correlated with NAO only in the EGC and CIC. NP from both VGPM and WRM exhibited significant negative correlations with Arctic Oscillation (AO) in all hydrographic zones. The differences in estimates of PP and NP in these hydrographic zones arise principally from the parameterisation of the euphotic depth and the SST dependence of photo-physiological term in the VGPM, which has a greater sensitivity to variations in temperature than the WRM. In waters of 0 to 5 °C PP using the VGPM was 43% higher than WRM, from 5 to 10 °C the VGPM was 29% higher and from 10 to 15 °C the VGPM was 27% higher.

1. Introduction

Recent warming of the Global Ocean has potentially important impacts on carbon cycling in the marine ecosystem, which is hard to quantify due to the scarcity of data over both space and time. Recent advances in Earth Observation (EO) have enabled us to fill these gaps, but the accuracy of satellite models requires careful consideration if we are to employ them to quantify the carbon fluxes in an ecosystem.

Quantitative estimation of the draw-down of carbon dioxide from the atmosphere to the ocean via primary production (PP) and the exported fraction of this fixed carbon, is important for calculating the global CO_2 flux and for modeling carbon transfer through the pelagic food web to the deep sea (Azam, 1998; Falkowski, 1988; Sarmiento, Hughes, Stouffer, & Manabe, 1998). NP is that proportion of PP driven by allocthonous nutrients that are supplied to the ecosystem through physical processes, nitrogen fixation or atmospheric input (Dugdale & Goering, 1967; Yentsch, Yentsch, Phinney, Lapointe, & Yentsch, 2004). The remaining fraction, the regenerated production, is driven by nutrients produced by re-mineralisation processes which include ammonification (Dugdale & Goering, 1967) and nitrification (Yool, Martin, Fernandez, & Clark, 2007) within the euphotic zone. It is balanced by export to deep waters or higher trophic levels, and makes a direct contribution to carbon removal from the photic zone. The measurement of NP is conventionally based on the uptake of ^{15}N-labelled nitrogen (NO_3^-, NH_4^+, urea), which has undoubtedly aided our understanding of the global importance of the world's oceans in exporting carbon. In many regions, few NP measurements are available resulting in sparse spatial and temporal data coverage and a vague impression of

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phytoplankton NP dynamics. There has, therefore, been a concerted effort to derive accurate estimates of NP from satellite data to fill this gap (Falkowski, 1988; Laws, Falkowski, Smith, Ducklow, & McCarthy, 2000). These have been aided by the inverse relationship between temperature and nutrients in certain regions of the Atlantic and Pacific (Chavez, Service, & Buttrey, 1996; Goes et al., 2000; Morin, Wafar, & Lecorre, 1993; Sathyendranath, Gouveia, Shetye, Ravindran, & Platt, 1991), particularly in upwelling and tidally driven areas (Babin, Therriault, & Legendre, 1991; Dugdale, Morel, Bricaud, & Wilkerson, 1989; Morin et al., 1993; Waldron & Probyn, 1992), to enable the determination of large-scale estimates of NP from satellite Sea Surface Temperature (SST) data (Alvarez-Salgado et al., 2002; Dugdale, Davis, & Wilkerson, 1997; Kamykowski, Reed, & Kirkpatrick, 1992; Traganza, Nestor, & McDonald, 1980). The relationship between SST and nitrate breaks down however, when the water column becomes thermally stratified (Henson, Sanders, Allen, Robinson, & Brown, 2003). Under these scenarios, NP can be underestimated by >50% especially when PP exceeds ~700 mg C m^{-2} d^{-1} (Laws, 2004). Goes, Saino, Oaku, and Jiang (1999), Goes et al. (2000) thus developed an approach to derive NP for the Pacific basin that accounts for phytoplankton consumption of nitrate using a second order polynomial of SST and SeaWiFS Chlorophyll-a (Chla). The algorithm has been used accurately to study the effects of El Niño and land mass warming on NP in the Pacific (Goes, Gomes, Limsakul, Balch, & Saino, 2001) and the Arabian sea (Goes, Gomes, Limsakul, & Saino, 2004). Similarly, Laws et al. (2000) developed a food web model that can be used to predict export production from SST and PP. In this model, the ratio between NP and PP (f-ratio) is temperature-dependent and accounts for 86% of the variability in f-ratios derived from ^{15}N and ^{14}C uptake measurements. In the Pacific upwelling region, when PP is <850 mg C m^{-2} d^{-1} this method is accurate to 10–20% (Laws, 2004), but requires further validation in the Atlantic Ocean, especially at extreme northerly latitudes where few in situ data are available.

The Irminger Basin, located to the Southwest of Iceland and to the Southeast of Greenland, is an important source of export production for the North Atlantic and North Sea (deYoung et al., 2004). From satellite-derived chlorophyll concentrations, NP in the Irminger Basin is predicted to be high ~100–150 gC m^{-2} yr^{-1} (Falkowski, 1988; Laws et al., 2000) and therefore potentially important on a global scale. However, lower values of NP ~30 to 65 gC m^{-2} yr^{-1} have been predicted from in situ nutrient uptake (Henson, Sanders, Holeton, & Allen, 2006; Sanders, Brown, Henson, & Lucas, 2005; Waniek & Holliday, 2006). Recently, Henson et al. (2011) developed a model of export production based on PP and SST and their relationship with thorium (^{234}Th) derived export, which proved to be 60% lower than the e/f-ratio based estimate. Controversy therefore still exists as to the most accurate and appropriate model to estimate NP in this region, which is hampered by a lack of independent in situ observations.

Over the past two decades NASA have conducted five inter-comparisons of satellite models of PP, to determine the most accurate models and to characterise sources of error (Campbell et al., 2002; Carr et al., 2006; Friedrichs et al., 2009; Saba et al., 2010, 2011). Few inter-comparisons of satellite derived NP have been conducted (Silio-Calzada, Bricaud, Uitz, & Gentili, 2008). In a recent error analysis in computation of net PP using the vertical generalised production model (VGPM), Milutinovic and Bertino (2011) quantified the highest uncertainty to be in the northern North Atlantic (>70%) due to errors in irradiance-depth dependent and photosynthetic rate functions.

In this paper we compare the accuracy of two satellite models, the VGPM of Behrenfeld and Falkowski (1997) and a Wavelength Resolved model (WRM) of Morel (1991) at estimating PP and NP in the northern North Atlantic. Each model is used to generate a time series of PP and NP from 1997 to 2010 using SeaWiFS data for six hydrographic zones. Inter-annual differences between models are assessed and in relation to climate indices. A sensitivity analysis was performed to assess which parameters contribute most to errors in the models.

2. Methods

2.1. Study areas and sampling regimes

Integrated PP was derived from ^{14}C uptake measurements at 83 stations on six field campaigns in the Atlantic basin (D261, D264, D267, FISHES, JC011, JC037) and ^{15}N uptake NP measurements were made at 18 stations on two of these campaigns (D261, FISHES) (Fig. 1, Table 1). On all research cruises, vertical profiles of temperature, conductivity, fluorescence, oxygen and photosynthetically active radiation (PAR) were acquired using a Seabird 911+ CTD and Chelsea Instruments PAR sensor fitted to a rosette with either 24 × 20 dm^3 or 12 × 30 dm^3 Niskin-type sampling bottles to collect water samples for the determination of NP, PP, Chla, dissolved inorganic nutrients and photosynthetic parameters (described below). Euphotic depth (Z_{eu}) was determined from the CTD profiles of PAR. The field measurements were used to validate satellite models of PP and NP, which were then applied to the Irminger Sea and northern North Atlantic.

The Irminger Sea is a diverse region with influences from the subtropical thermocline via the North Atlantic Current, and from the Arctic via the dense northern overflows (Holliday et al., 2006), which in turn may influence new production. A number of major physical zones have been described where different surface mixing and re-stratification processes dominate (Holliday et al., 2006; Waniek & Holliday, 2006): The Central Irminger Current (CIC) has characteristically low temperatures and salinity (6.53–9.72 °C, 34.73–35.08) and its surface waters are dominated by cool fresh Sub-Arctic surface water that originates in the Labrador Sea and spreads across the sub-polar gyre. The Irminger Current Zone, a branch of the North Atlantic Current positioned west of the mid-Atlantic Ridge, is the warmest and most saline (7 °C, 35.00) feature of the true Irminger Sea. Two Irminger Current zones are described: The southern Irminger Current (SIC) zone extends from 54–57°N to 60°N and between 28 & 32°W. The North Irminger Current (NIC) occurs between 60 & 62°N and 28 & 32°W. The East Greenland Current Zone (EGC) dominates the western part of the Irminger Sea, including the continental shelf. The EGC is persistent along the length of the Greenland continental slope, carrying cold, fresh (<0 °C, <34.50) Arctic Polar Water and Arctic Intermediate Water (0–3 °C) from the Arctic and Nordic Seas into the sub-polar gyre (Foldvik, Aagaard, & Torresen, 1988). The Reykjanes Ridge (RKR) separates the Irminger Basin from the Iceland Basin (ICB), and is characterised by warm, saline (>8.0 °C, 35.10) water originating from the Iceland basin. The western boundary of the zone is clearly marked by a sharp front with high salinity and temperature gradients, and a distinctive change to weaker stratification and lower density compared to the adjacent Irminger Current.

2.2. Phytoplankton pigments

Chla was determined by high performance liquid chromatography (HPLC) on all field campaigns. Water samples were filtered through Whatman GF/F filters and stored in liquid nitrogen. Pigments were extracted with the aid of sonification in 90% acetone, clarified using centrifugation (5 min at 4000 r.p.m) and analysed in the laboratory, using reverse phase HPLC following the procedure outlined in Barlow, Cummings, and Gibb (1997). Pigments were separated using a 3 μm Hypersil MOS2 C8 column on a Thermo separations product HPLC, detected by absorbance at 440 nm and identified by retention time and on line diode array spectroscopy. Pigment absorption was measured against quantified standards: Chla standard was obtained from Sigma-Aldrich, and divinyl chlorophylls *a* and *b* from R. Bidigare and M. Ondrusek, University of Hawaii. Other pigment standards were purchased from the DHI Institute for Water and Environment, Denmark. Limits of detection were of the order of 0.001 mg m^{-3} (Barlow, Aiken, Moore, Holligan, & Lavender, 2004).