Seasonal constraints on the estimation of new production from space using temperature-nitrate relationships

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[1] Inverse relationships between sea surface temperature and concentrations of the major inorganic nutrients have recently been exploited to estimate new production from remotely sensed data. In situ surface data collected in the Irminger Basin during four successive seasons in 2001/2 allow a robust examination of the conceptual processes behind temperature-nitrate relationships. The data confirm a simple model of the seasonal variation in the temperature-nitrate relationship. A strong inverse correlation between temperature and nitrate is found in both winter data sets, but no correlation is seen in spring or summer. Furthermore, the slope of the temperature-nitrate regression is found to be different for the two winter data sets. The results have implications for using temperature-nitrate relationships to derive new production estimates at high latitudes from satellite sea surface temperature measurements. However, the data allow a simple, lower-bound estimate of the region’s new production to be made by exploiting Argo float data. INDEX TERMS: 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling; 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 4227 Oceanography: General: Diurnal, seasonal, and annual cycles; 4572 Oceanography: Physical: Upper ocean processes; KEYWORDS: temperature-nitrate relationship, seasonal variability, Irminger Basin, new production estimates. Citation: Henson, S. A., R. Sanders, J. T. Allen, I. S. Robinson, and L. Brown, Seasonal constraints on the estimation of new production from space using temperature-nitrate relationships, Geophys. Res. Lett., 30(17), 1912, doi:10.1029/2003GL017982, 2003.

1. Introduction

[2] Export production is the flux of biogenic material from surface waters to the ocean interior and is generally taken to be the fraction of production derived from the new, rather than recycled, input of nutrients to the euphotic zone. Estimating the magnitude and seasonality of this flux is vital to understanding the controls over, and strength of, the biological carbon pump and its impact on atmospheric CO2 levels [Eppley and Peterson, 1979]. Ship-based observations, such as new production measurements and changes in nutrient concentrations, all inevitably suffer from an inability to sample over wide areas or long time periods. For this reason much attention has been focused on using remote sensing techniques to estimate new production. One method is to exploit the widely reported inverse relationships between sea surface temperature (SST) and concentrations of nitrate, phosphate and silicate [e.g., Sathyendranath et al., 1991; Morin et al., 1993; Minas and Codispoti, 1993; Chavez et al., 1996; Goes et al., 2000]. The correlation reflects the mixing of cold, nutrient rich water into the euphotic zone, which is subsequently warmed through solar heating and depleted of nutrients following the onset of the phytoplankton growth season. Although the slope of the temperature-nitrate (TN) relationship varies with location and season, the apparent consistency of the correlation has enabled the determination of large-scale estimates of surface nitrate from satellite SST measurements [see Kamikowski et al., 2002 and references therein]. In turn estimates of the f-ratio, and hence new production, have been derived [Sathyendranath et al., 1991; Dugdale et al., 1997; Alvarez-Salgado et al., 2002].

[3] Determining the parameters of the TN regression for a particular location necessarily requires a large number of in situ measurements. Previous authors have tended to aggregate all available cruise data from a region, irrespective of season. Although the possible effects of seasonal and interannual variability on the TN relationship have been acknowledged [Pastuszak et al., 1982; Sathyendranath et al., 1991; Minas and Minas, 1992; Gong et al., 1995], little attention has been paid to the causes and consequences of such variability. In this study a unique data set from four consecutive cruises to the same region (including a repeat winter survey) is used to explore the seasonal and interannual variability in the TN relationship in a high latitude area of the North Atlantic where export production is thought to be high [e.g., Laws et al., 2000].

2. Measurements

[4] The objective of the Marine Productivity program was to study the physical factors controlling zooplankton distribution (http://www.nerc.ac.uk/marprod). As part of the program four consecutive cruises to the Irminger Basin were undertaken: two early winter cruises (November–December 2001 and 2002), a pre-bloom spring cruise (April–May 2002) and a post-bloom summer cruise (July–August 2002). Figure 1 shows the location of the study region and data points. It should be noted that several data points fall outside the Irminger Basin, defined as west of the Reykjanes Ridge. Removing these data points had little effect on the results and they were therefore included in the analysis. This study uses nutrient data from the surface bottle of each CTD cast and, with the exception of the winter 2001 cruise, surface nutrient samples taken every four hours from the RRS Discovery’s
continuous thermosalinograph outflow at a depth of 5 m. The concentration of nitrate was determined via conventional colorimetric methods (cadmium reduction) using a Skalar San Plus autoanalyser [Kirkwood, 1995]. Continuous underway SST data were recorded by the ship’s Surfmet system. Protocols for collecting and analyzing samples were the same for all four cruises [Pollard et al., 2002; Richards et al., 2002; Brierley et al., 2003; Allen et al., 2003]. A total of 480 good quality temperature/nitrate pairs were used.

3. Results and Discussion

A linear fit to a TN plot containing data from all four cruises had an $r^2$ of 0.71; TN relationships reported in the literature typically have $r^2 > 0.85$. In an attempt to understand the reasons for this somewhat disappointing result the biophysical processes underlying the TN relationship were considered.

Although a strong inverse relationship between nitrate and temperature has been observed any correlation between the two properties arises indirectly. Models of the annual cycle in nutrient and chlorophyll concentrations all display a strong seasonality at high latitudes, characterized by a short lived burst of phytoplankton growth during the spring bloom. In the classic model of the annual nutrient cycle winter wind-driven cooling and deep convective mixing results in low surface temperatures but high surface nutrient levels at the end of winter. Biological utilization of nitrate is minimal due to low light levels and continual mixing until, in spring, increasing light levels and re-stratification due to increased surface heating and reduced wind stress result in the onset of renewed biological production and rapid consumption of nutrients. In post-bloom summer nutrients have been stripped by phytoplankton from surface waters and the SST is at its peak. As solar heating declines through autumn and early winter overturning commences and cold nutrient-rich water is brought to the surface but phytoplankton are not able to utilize it. Therefore this is the only time of the year when nitrate and temperature are conserved and a linear TN relationship can be expected. At all other times of the year biological consumption of nutrients invalidates the assumption that SST varies linearly with surface nitrate.

This conceptual model of the annual cycle in the TN relationship is represented in Figure 2 (expanding on Minas and Minas [1992]). Point A represents post-bloom summer, with high temperatures and low nitrate concentrations. Point B is the late winter/pre-bloom spring before large-scale nutrient uptake begins and is associated with low temperatures and high nitrate concentrations. Points A and B represent the end-members of the mixing due to convective overturning that takes place during autumn and early winter. The return path from point B to A takes place during the growth season and can follow one of two routes. If biological utilization of nitrate occurs at a faster rate than an increase in SST through solar heating, path 1 is taken. This situation would be typical of a fast-growing spring bloom in high latitudes. Alternatively, if the increase in SST occurs more rapidly than biological uptake of nitrate, path 2 will be followed. This situation could occur in regions of rapid heating, such as the North-west Indian Ocean.

To investigate the seasonality in the data, TN plots were produced for each season and a linear regression was carried out individually on the four data sets (Figure 3). The spring and summer cruise TN plots display almost no correlation, as shown by the $r^2$ values (0.07 and 0.22 respectively). Both winter data sets however display a strong inverse correlation between temperature and nitrate ($r^2 = 0.82$ and 0.84, for winter 2001 and 2002 respectively). Data from the successive winter 2001, spring 2002 and summer 2002 cruises are displayed together in Figure 4. The solid line AB is the winter mixing line for the winter 2001 cruise data set. The dotted line represents the return path from point B to A. The late summer and early spring data lie around points A and B respectively. The majority of the scatter lies below the winter line suggesting that the spring bloom in 2002 followed path 1. Therefore in the Irminger Basin biological utilization

![Figure 1. Study area and location of data points.](image1)

![Figure 2. Idealised representation of the annual temperature-nitrate cycle. Point A represents post-bloom summer and Point B pre-bloom spring. Two alternative spring bloom scenarios are represented by Paths 1 and 2. See text for further explanation.](image2)
was mixed into surface waters. The winter mixed layer was shallower and therefore less nitrate than winter 2001 implying that the 2002 early spring bloom had different slopes (Figure 3). Winter 2002 has a shallower TN relationship. The two winter data sets do however not necessarily coincide with reduced (enhanced) end-of-winter nitrate concentrations. Alternatively the difference in surface nitrate concentrations may reflect changes in the composition of sub-mixed layer water masses.

It may be that the variability in the TN relationship for the Irminger Basin reflects a seasonal cycle that is more pronounced in high latitudes than in the lower latitudes for which TN regressions have generally been performed. The seasonal and interannual variability in the TN relationship in this region sounds a note of caution in aggregating data compiled from several different seasons and years in order to calculate new production estimates from satellite SST. More positively, we have defined the seasonal time range during which a mechanistic link exists between temperature and nitrate and therefore when TN relationships are expected to be linear and can be used with confidence to derive primary production from satellite SST data.

Although the Irminger Basin may not be suitable for estimating seasonal primary production from space using the TN relationship, a lower-bound estimate of the region’s new production can still be made. The calculation of new production from changes in nitrate concentration requires an estimate of the total nitrate removed from the water column over one annual cycle. Although satellites are only able to sense the sea surface the MLD can be determined either via regressions with SST [Goes et al., 2000] or via Argo floats. Goes et al. [2000] assume that all removal of nitrate in primary production takes place by phytoplankton growth within the mixed layer and that the nitrate consumed is equal to the seasonal change in nitrate multiplied by the depth of the nitracline at the end of summer.

Typically, the MLD in a region will shoal from winter to summer. Thus, calculating new production following Goes et al. [2000] using the MLD at the end of summer will leave some of the nitrate utilized in new production unaccounted for. Instead integrating the nitrate concentration difference over the mean MLD for the productive season provides a first order approximation of the nitrate consumed. The nitrate consumed during the growth season is then

\[ \Delta N = \left( N_B - N_A \right) \left( \frac{ZD(spr) + ZD(sum)}{2} \right), \]

where \( N_B \) and \( N_A \) are the concentrations of nitrate (\( \mu mol/l \)) in winter and at the end of summer respectively and \( ZD(spr) \) and \( ZD(sum) \) are the MLD in spring at the onset of biological activity and summer respectively. New production can then be calculated as

\[ P_N = R \Delta N, \]

where \( R \) is the Redfield Ratio of carbon to nitrogen in phytoplankton.

**Figure 3.** Temperature-nitrate plots for (a) Winter 2001 N = 23.71 – 1.53(T), \( r^2 = 0.82 \); (b) Spring 2002 and (c) Summer 2002 regression lines not shown because statistically insignificant; and (d) Winter 2002 N = 16.27 – 0.84(T), \( r^2 = 0.84 \).

**Figure 4.** Data from winter 2001 (circles), spring 2002 (squares) and summer 2002 (triangles). The straight line is the winter 2001 mixing line and the dotted line is the return path from point B to A.
layer depth data from Argo floats was introduced. Estimating a lower bound on new production using mixed variability contains information on the underlying rather than being a hindrance to formulating TN relationships estimation of new production from satellite data. However, raising concern over the validity of using this approach for the variability in physical forcing. It may be that a TN relationship different for the two winters as a consequence of interannual data sets. In addition the slope of the TN regression was rise in the mixed layer or associated with transient events production in winter, new production that takes place beneath the mixed layer or associated with transient events such as storms or eddies. Interannual variability is also ignored in this calculation and, as we have demonstrated, this may not be insignificant.

4. Conclusion

Data from four successive seasons (including a repeat winter survey) allow a unique insight into the seasonal and interannual variability in biophysical processes that underlie a relationship between temperature and nitrate in the surface waters of the Irminger Basin. The in situ data confirmed a simple model of the seasonal variability in the TN relationship. Strong linear relationships were found in both winter data sets. In addition the slope of the TN regression was different for the two winters as a consequence of interannual variability in physical forcing. It may be that a TN relationship is valid only for a specific location, season and even year, raising concern over the validity of using this approach for the estimation of new production from satellite data. However, rather than being a hindrance to formulating TN relationships the variability itself contains information on the underlying biological and physical processes. A simple method of estimating a lower bound on new production using mixed layer depth data from Argo floats was introduced.

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References


