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Basin scale estimates of Sea Surface Nitrate and New Production from remotely sensed Sea Surface Temperature and Chlorophyll

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Abstract. The highly variable nature of T-N relationships in oceanic waters has restricted nitrate (N) measurements from remotely sensed sea surface temperature (SST) to small time and space domains. Here we show that if changes in T-N relationships resulting from phytoplankton (chlorophyll *a*) are taken into account, remote sensing can be exploited to provide high resolution maps of sea surface nitrate (SSN) that are valid over much larger scales than has been previously possible. We illustrate the potential of the method for monitoring basin scale, interannual variations in SSN in the north Pacific Ocean using co-registered imagery of SST and chl *a* and demonstrate the usefulness of such data for estimating basin scale annual new production.

Introduction

The uptake of CO_2 by phytoplankton and its export out of the euphotic zone, into the deep ocean via the "biological pump", represents a potential long term sink for atmospheric CO_2 [*Eppley and Peterson,* 1979]. A major fraction of this carbon transported into the oceans' interior is associated with allochthonous nitrogen inputs, primarily nitrate (N), into the euphotic zone [*Eppley and Peterson,* 1979; *Platt et al.,* 1989]. Hence, understanding the spatial and temporal variations of N over basin and global scales in the euphotic layer is an important requirement for ocean biogeochemical and climate studies [*Platt et al.,* 1989]. Unfortunately, since N measured conventionally, has limited coverage over space and time, particularly in high latitude areas in winter, most studies rely on maps of N constructed using multi-year data sets [*Strass and Woods,* 1991; *Campbell and Aarup,* 1992; *Conkright et al.,* 1994; *Glover et al.,* 1994]. For ocean biogeochemical or climate studies, when the purpose is to monitor interannual changes, the usefulness of these maps could be limited.

Although N in seawater lacks a distinct electromagnetic signature that can be utilized for its estimation from space, satellites have for long been suggested as a promising alternative for its measurement, because N correlates well with certain remotely measurable seawater properties [*Garside and Garside,* 1995]. The relationship between N and seawater temperature (T) for instance, has consistently been found to be negative as nutrient rich waters brought up into the euphotic zone from the deep by physical processes such as upwelling or winter convective overturning are colder than the surface waters which are generally nutrient poor. Although empirical algorithms based on T-N relationships have been in existence for a while [*Kamykowski and Zentara,* 1986; *Sathyendranath et al.,* 1991; *Chavez and Service,* 1996], their application to remote sensing of N over large temporal and spatial scales, has been frustrated by their time and space varying nature. *Garside and Garside* [1995] and *Chavez and Service* [1996] have pointed out several reasons for this highly variable nature of T-N relationships. In the euphotic zone for example, the presence of phytoplankton could have a significant impact on T-N relationships. Although incident solar radiation causes seawater to warm, it also provides the light for N uptake by phytoplankton. Yet, there have been no attempts to model variations in N as a function of both T and phytoplankton. In this study, we show that N estimates from space could be improved considerably, if, in addition to seawater temperature, changes in N concentrations resulting from the presence of phytoplankton are taken into account. We illustrate the utility of satellite derived N maps, by demonstrating their use in estimating new production in the north Pacific Ocean.

Data source and analysis

A large database of shipboard measurements made by Japanese research vessels over several years (1978 to 1996), which covered a range of water types in the Pacific Ocean including the Southern Ocean allowed us to re-examine variations in N as a function of T and chlorophyll *a* (chl *a*). In this analysis, ship data sets from different cruises were pooled together, irrespective of the seasons and regions they were drawn from. The relationship between N and its predictor variables was examined using the statistical, step-wise linear regression fitting routine of JMP®, SAS Institute. This analysis was restricted to surface water samples, but subsurface data were included whenever the difference between SST's and subsurface T values was minimal (<0.2 °C). The above temperature restriction for subsurface data ensured that all our observations were well within the mixed layer.

Results and Discussion

Estimating sea surface nitrate from space:

The inclusion of chl *a* as a predictor variable, contrasts with previous attempts to estimate SSN from space solely on the basis of hydrographic properties [*Kamykowski and Zentara,* 1986; *Dugdale et al.,* 1989; *Sathyendranath et al.,* 1991; *Garside and Garside,* 1995; *Chavez and Service,* 1996]. Exclusion of deep water data prevented the strong signatures of T and N in deeper waters from obscuring changes in T-N relationships resulting from seasonal patterns of solar radiation and/or phytoplankton uptake. Although N appeared to be controlled primarily by T, the addition of chl *a* helped improve N prediction by reducing local and regional differences in the character of T-N relationships resulting from phytoplankton N uptake. The model (Fig. 1a)

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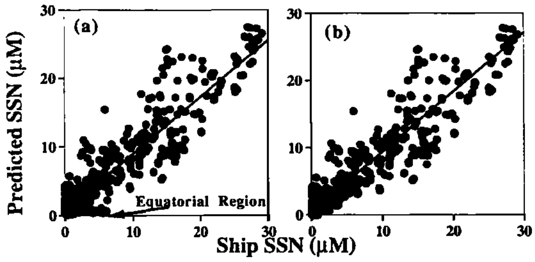


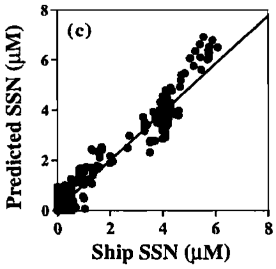


Figure 1. Relationship between measured and model predicted SSN concentrations for (a) the entire Pacific Ocean data r^2=0.83, RMSE=2.41, n=1822, (b) non-equatorial waters, r^2=0.89, RMSE=2.24, n=1231 and (c) equatorial region, r^2=0.96, RMSE=0.42, n = 531.

$$SSN = 25.22 - 1.96(T) + 0.04(T)^2 - 1.21(Chl\ a) - 0.05(Chl\ a)^2 \quad (1)$$

accounted for almost 83% of the variation in SSN, but for the equatorial region, SSN estimates were clearly lower than the shipboard values, a disparity that was the outcome of the high N source water in the equatorial region being warmer than the rest of the Pacific Ocean stations [*Chai et al.*, 1996]. When the statistical fitting procedure was applied separately to data outside the equatorial Pacific (Fig. 1b) and to the equatorial region (15 °N - 15 °S Lat.) (Fig. 1c), the precision of N prediction for each region improved considerably. Outside the equatorial Pacific Ocean, the relationship could be described by the following equation:

$$SSN = 25.68 - 1.97(T) + 0.04(T)^2 - 1.63(Chl\ a) + 0.012(Chl\ a)^2 \quad (2)$$

and in the equatorial region, by,

$$SSN = 354.47 - 23.70(T) + 0.40(T)^2 + 3.9(Chl\ a) \quad (3)$$

For individual cruise data sets, the addition of chl *a* led to an increase in the r^2 value by as high as 55% and a reduction in the RMSE by ~24%. For the entire Pacific data set, these values were 5 and 7% respectively.

Note that there are considerable differences in the absolute values of the parameters in Eqs. 2 and 3, particularly in the effect of the predictor variable chl *a* on N. These differences reflect the contrasting physical-biological interactive processes in the equatorial and non-equatorial regions [*Barber and Chavez,* 1991; *Glover et al.,* 1994]. Equation 2 shows that, any increase in chl *a* in the non-equatorial region will contribute to a decline in SSN concentrations. Outside the sub-tropical gyres, the non-equatorial region is characterized by strong seasonality of phytoplankton biomass. The increase and accumulation of phytoplankton in the euphotic water column during bloom evolution in this region results in a rapid decrease of nutrients. As a consequence, N concentrations in the euphotic zone are generally lower when chl *a* values are high [*Glover et al.,* 1994].

The equatorial region (Eq. 3) in contrast, is known for its high rates of seawater mixing [*Chai et al.,* 1996]. Additionally, N uptake and phytoplankton growth here are generally known to be low due to iron limitation and/or the high rates of zooplankton grazing [*Barber and Chavez,* 1991]. On account of these special conditions, phytoplankton seldom accumulate to form blooms here, which could contribute to a decrease in N concentrations within the euphotic water column. Due to lack of data from the eastern equatorial region and the known occurrence of phytoplankton blooms in this area [*Dugdale et al.,* 1989], we are not sure whether a similar distinction is appropriate for this region.

Although our equations account for the variations in N in the equatorial and non-equatorial regions, our partitioning of the shipboard data on the basis of latitudinal zones is simplistic in comparison to the approach of *Longhurst et al.* [1995], which takes into account the ecological and physiological differences that exist in oceanic waters to partition the Pacific Ocean into biogeochemical provinces.

To obtain N from satellite data, we applied Eqs. 2 and 3 to ver. 3 OCTS monthly SST and chl *a* imagery from Nov. 1996 to June 1997. These images have a spatial resolution of about 4 km and were processed at the Earth Observation Centre, National Space Development Agency of Japan (NASDA). For the level 3, global area coverage products (ver. 3) utilized here, the accuracies of the SST values are 0.68K [*Sakaida et al.,* 1998] and ~68% for chl *a* values less than 2 mg m^{-3} [*Shimada et al.,* 1998]. Above 2 mg m^{-3}, it is suspected that the OCTS underestimates chl *a*.

Satellite derived SSN values were compared with an independent data set of trans Pacific shipboard SSN data (Fig. 2) which were obtained during 11 trans-Pacific Ocean cruises on board MV *Skaugran*, as part of the Joint Japan-Canada Ocean Monitoring in the northern north Pacific Ocean. The shipboard data coincides with the period when ADEOS was operational. Strictly speaking, a comparison between these two sets of data is not straightforward because satellite data are based on several pixels scanned on different days in a month, whereas shipboard data are point measurements. Despite this limitation, the results (r^2=0.94, RMSE=1.74) are encouraging. Sensitivity tests of the equations to errors in satellite estimates of SST and chl *a* indicated that such a disparity between ship and satellite SSN data at high ambient SSN concentrations would result when chl *a* was underestimated by satellites [*Goes et al.,* 1999], as was the case with the OCTS [*Shimada et al.,* 1998]. Furthermore, a large number of the high SSN stations during the trans Pacific cruises were located north of 45 °N. Lat. and in winter, a region and season which were poorly represented in the shipboard data set utilized for constructing the SSN algorithm.

The monthly maps of SSN that were generated, provide a synoptic view of the spatial extent and magnitude of N injection into the surface layer due to winter convective mixing and its consumption following the onset and progress of phytoplankton growth season. Nitrate inputs into the euphotic zone were clearly the highest in March (Fig. 3) following which, a northwestward propagation of oligotrophy was discernible. In June, remnant SSN observed in the subarctic Pacific is in agreement with previous studies [*Conkright et al.,* 1994]. Our maps are spatially consistent with climatological maps of N for the north Pacific Ocean con-

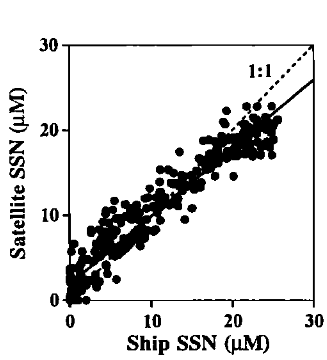


Figure 2. Relationship between shipboard and satellite estimated SSN, (r^2=0.94, RMSE = 1.74, n =337).

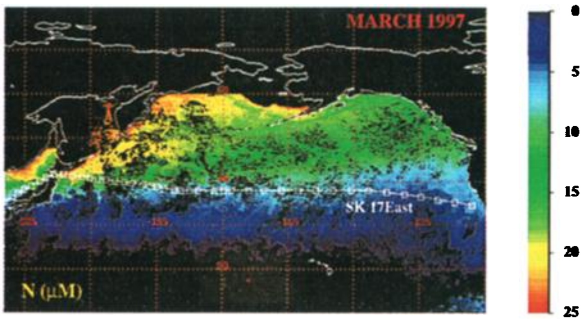


Figure 3. Distribution of SSN in the north Pacific Ocean for March 1997 using OCTS, SST and chl *a*. MV *Skaugran* (SK 17 East) cruise track and stations occupied in March 97 are shown.

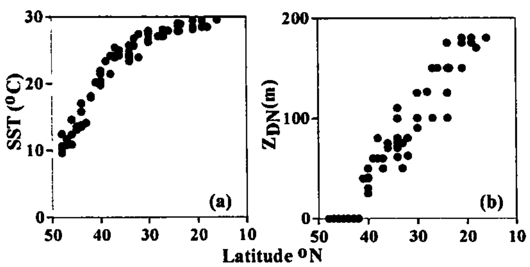
structed by pooling ship data from several years [*Glover et al.*, 1994; *Conkright et al.*, 1994]. In our N map for March, the highest concentrations of N (>22 µM) can be observed in the western North Pacific Ocean in the vicinity of the Aleutian and Kuril Island chains, a region in which intense vertical mixing and nutrient injection is known to occur [*Kono*, 1997]. These values are clearly higher than those seen in this region in the winter climatological maps, but compare well with the winter N map for 1997 [*Wong et al.*, 1999]. These differences, possibly interannual, underscore the advantages and potential of remote sensing as a tool for monitoring N from space.

This study represents the first attempt at demonstrating the usefulness of compound remote sensing for measuring elements in seawater that do not possess remotely measurable electromagnetic signals and over large spatial and temporal scales than has been possible before. The strength of this method lies in its simplicity and, the ease with which the required inputs can be measured from space. This capability is particularly important over regions and seasons where shipboard cruises are difficult to conduct and the problem of undersampling is acute. In areas close to land masses where the physical boundaries of the water masses are more diverse and dynamic to be understood from shipboard measurements alone, satellite data could be particularly invaluable. Since the method can be utilized to monitor basin-scale, annual and interannual variations in SSN distributions, it offers the potential for use in biogeochemical process studies, climate-change related studies, interpolating N coverage measured by shipboard data sets and for validating N distributions generated by coupled biological and physical models.

Application - estimating new production from space:

An estimation of new production in the North Pacific Ocean is conducted to illustrate the usefulness of the satellite derived maps of N for ocean biogeochemical and climate studies. Outside continental margins and upwelling zones, the largest input of N into the euphotic zone of the oceans takes place during winter convective mixing. This input supports the largest fraction of new production occuring annually in the world's major ocean basins [*Strass and Woods*, 1991; *Glover et al.*, 1994]. If the magnitude of winter N consumed over the growth season of phytoplankton (ΔN) can be estimated, new production (P_N) can be calculated using the relationship $P_N = R\Delta N(t)$, where R is ratio of carbon to nitrogen for phytoplankton and t is the time i.e. late summer, when the nitracline is the deepest. Here, $\Delta N = [N(o)-N(t)]Z_{DN}(t)$, where $N(o)$ and $N(t)$ are the concentrations of N (g N m^{-3}) in winter and at the end of summer respectively, and $Z_{DN}(t)$ is the depth of the nitracline in meters at time t. Since this method does not account for P_N that could result from N inputs other than winter convective mixing [*Lewis et al.*, 1986] or for P_N that occurs after summer [*Honjo*, 1997], it represents a lower-bound estimate of P_N. In the subarctic Pacific, a sizeable fraction of N remains unconsumed at the end of summer as its uptake by phytoplankton during the growth season is constrained by environmental conditions that are particularly unique to this region [*Miller et al.*, 1991]. Since OCTS data are not available beyond June 1997, it was not possible to calculate N(*t*) and hence P_N, for 1997. We have therefore, estimated P_N for the year 1998 from N maps constructed using monthly composites of multi-channel SST data obtained from the National Oceanic and Atmospheric Administration's (NOAA), Advanced Very High Resolution Radiometer (AVHRR) and ver. 2 SeaWiFS chl *a* obtained from the Distributed Active Archive Centre (DAAC) at the Goddard Space Flight Center, USA. The SST images were obtained as weekly images and then averaged to obtain the monthly SST images. For the year 1998 also, N concentrations were highest in March and were considered as N*(o)* values. For N*(t)*, we used the seasonal minimal values of N observed during Sept. 1998.

Data collected during four Northwest Pacific Carbon Cycle Study (NOPACCS) summer cruises [*Ishizaka et al.*, 1994] provided the basis for estimating Z_{DN}. Remarkable year on year similarities in the patterns of SST (Fig. 4a) and Z_{DN} (Fig. 4b) along the NOPACCS 175°E meridional transect, enabled us to



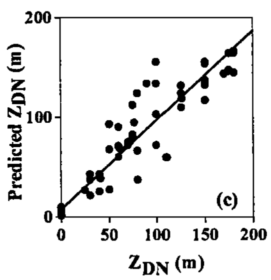


Figure 4. Variation in a) Sea surface temperature (SST) and b) Depth of the nitracline (Z_{DN}) with latitude along the Northwestern Pacific Ocean Carbon Cycling Study (NOPACCS) cruise track during the summers of 1991, 1992, 1993, (c) Relationship between measured and predicted Z_{DN} in the central Pacific Ocean using Eq. 4) $Z_{DN} = 120.62 - 18.24(SST) - 0.67(SST)^2$.

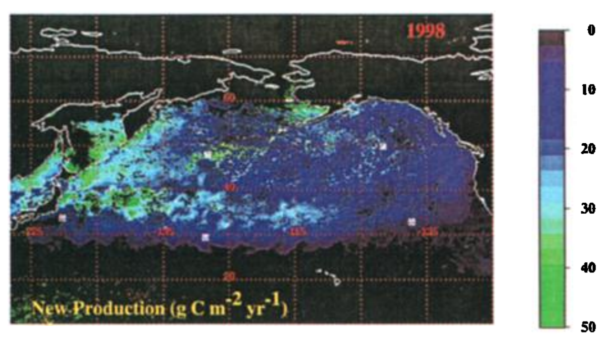


Figure 5. New production estimated using maps of N for March [N*(o)*] and Sept. [N*(t)*] 1998 and Z_{DN} for Sept. 1998. Sediment trap positions have been shown as open white squares.

Table 1. Comparison of Satellite Estimates of New Production with Sediment Trap POC Fluxes (g C m^{-2} y^{-1})

Site	Year	Measured	Satellite Trap Flux	Reference Estimated
50° N 145° W (PAPA)	1982-1983	18.1*	23	27
48° N 175° E (NOPACCS)	1993-1994	37.4*	36	26
34° N 142° E (JAPAN TRENCH)	1989-1990	12.6*	7	29
33° N 139° W (VERTEX)	1981-1984	12.95†	8	28
30° N 175° E (NOPACCS)	1993-1994	6.48†	11	26

* Referenced to 100 m using formulation of Martin *et al.*, 1987
† Referenced to 150 m using formulation of Martin *et al.*, 1987

model Z_{DN} with a high degree of precision (r^2=0.90) solely on the basis of SST (Fig. 4c). On the assumption that this relationship is valid for other longitudes also, we applied Eq. 4. to a monthly composite of AVHRR SST image for the month of Sept. 1998, in order to obtain Z_{DN} values at the end of the growth season in the north Pacific Ocean. In the region north of 40 °N where the SST was below 19 °C, the NOPACCS data set revealed that N was uniformly present in the upper 25 m. Here the Z_{DN} was set to 25 m.

New production estimates (Fig. 5) appear encouraging when compared with sediment trap carbon export flux data (Table 1). The highest values of P_N(30 to 50 g C m^{-2} y^{-1}), were in the western north Pacific where N inputs were the highest, highlighting the importance of this region for ocean biogeochemical and climate change studies [*Honjo*, 1997]. Here export flux values in excess of 50 g C m^{-2} y^{-1} have been measured [*Noriki and Tsunogai*, 1986]. The trend of an eastward as well as southward decline in P_N is consistent with sediment trap estimates from other locations in the Pacific Ocean (Table 1). Our present approach for calculating P_N from satellite N maps is based on simple empirical equations. We are certain that the utility of our N maps would be greatly enhanced when used in conjunction with information concerning the kinetics of N uptake or with the physiological rate constants of phytoplankton photosynthesis and *f* ratios [*Dugdale et al.*, 1989; *Sathyendranath et al.*, 1991; *Platt et al.*, 1991].

One expects that as satellite based estimates continue to improve, and shipboard data sets with greater precision become available, errors in N estimates from space will be minimized and their utility immensely enhanced. Any information obtainable by satellites on basin and global scales, has several obvious benefits over conventional methods, the foremost being spatial and temporal coverage [*Sathyendranath et al.*, 1991; *Platt et al.*, 1991].

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