Estimating ocean production from satellite-derived chlorophyll: insights from the Eastropac data set

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ABSTRACT

The Eastropac expedition took place in 1967-1968 in the Eastern tropical Pacific Ocean. Primary production was related to near-surface chlorophyll in these data. Much of the variability in the relation was due to the light-history of the phytoplankton and its photoadaptive state. This was due to changes in the depth of mixing of the surface waters more than changes in insolation. Accurate estimates of production from satellite chlorophyll measurements may require knowledge of the temporal and spatial variation in mixing of this region.


RÉSUMÉ

Estimation de la production oceanique par téledetection de la chlorophylle : un aperçu des données « Eastropac »

Dans les données de la campagne Eastropac, qui s’est déroulée en 1967-1968 dans l’Est du Pacifique tropical, la production primaire est reliée aux concentrations superficielles en chlorophylle. Une grande partie de la variabilité de cette relation est le fait de l’exposition antérieure du phytoplancton à la lumière et de sa photo-adaptation, et ce conditionnement dépend davantage de la profondeur de la couche de mélange que des variations de l’insolation. L’estimation précise de la production primaire à partir de mesures satellitaires de la chlorophylle peut donc requérir, dans une telle région, la connaissance des variations spatio-temporelles de l’intensité du mélange vertical.


INTRODUCTION

The coastal Zone Color Scanner (CZCS) aboard the Nimbus 7 satellite has for the first time provided large-scale views of near-surface chlorophyll-like pigments (Gordon et al., 1983; Hovis et al., 1980), particularly of the coastal regions of North America. Within a few years satellite images of chlorophyll may be available for many regions of the ocean and hopefully for the global ocean (National Academy of Sciences, 1984). A second generation instrument to replace the CZCS is not yet funded as of this writing.
The Eastropac expedition consisted of seven 2-month cruise periods from February, 1967 through April, 1968. The cruises covered an area between 20°N and 20°S and from the coast of America to 119°W. We have limited our analysis to the offshore area bounded by 93°W on the east, 119°W on the west, and 300 km offshore on the north in order to emphasize the equatorial upwelling region (Fig. 1). The Eastropac data have been published in the form of atlases (Love, 1970-1977) which contain detailed cruise tracks and data in chart form. Primary production was measured with the 14C method in noon to sunset, simulated in situ incubations (Owen, Zeitzschel, 1970 a,b). Samples from each of seven depths in the euphotic zone were incubated under neutral density screens at the temperature of surface seawater. The resulting rates were integrated over depth to express water column primary production mgC m−2 d−1. This quantity is hereafter called Pi (Bannister, 1974). Chlorophyll and phaeopigments were measured using a fluorometer (Owen, Zeitzschel, 1970 a). Insolation was measured on the ships with pyrheliometers (Owen, unpublished). The stepwise linear regression program we used, number P2R, is from BMDP-83 (Dixon, 1983).

To estimate the chlorophyll-like pigments expected to be registered by the Coastal Zone Color Scanner and its successors, we calculated the average value of chlorophyll plus phaeopigment for the upper two sampling depths, mg m−3. This value is called Ck (Smith, Baker, 1978). We calculated the diffuse attenuation coefficient for light, Kt, by assuming the irradiance at the bottom of the euphotic zone equaled one percent of the surface value.

It is assumed that the 14C method of measuring primary production, as used in the Eastropac expeditions and elsewhere since 1952, provides an accurate measure of primary production during the incubation period. Thus the discrepancies between results with this method and those that integrate over larger space and time scales are due to an inadequate scale of sampling, a problem that may be overcome using satellite information.

METHODS

The Eastropac expedition consisted of seven 2-month cruise periods from February, 1967 through April, 1968. The cruises covered an area between 20°N and 20°S and from the coast of America to 119°W. We have
RESULTS

Multiple regression model

Since present or future satellite data may include sea surface temperature, insolation, and winds from which the depth of mixing might be estimated, we used these variables (except winds) in stepwise multiple linear regression models of \( P_i \). In the absence of wind data we used mixed layer depth, inferred from temperature profiles. The results were not impressive and at most only 34% of the variability in \( P_i \) could be explained (Tab. 1). The second equation of Table 1 includes a parameter, \( I_c \) (a concept introduced by Myers and Graham, 1959), an estimate of the average irradiance experienced by a phytoplankter in the euphotic zone. It combines insolation, \( K_t \) and mixed layer depth in an analytical expression that has proved useful in studies of photosynthesis and growth of algal cultures (Tab. 1).

Table 1
Stepwise multiple linear regression equations for \( P_i \) (primary production, mg C m\(^{-2}\) d\(^{-1}\)), \( C_k \) (near-surface chlorophyll-like pigments, mg m\(^{-3}\)), \( I_c \) (irradiance, watt m\(^{-2}\)) \( K_t \) (diffuse attenuation coefficient, m\(^{-1}\)), MLD (mixed layer depth, m), and \( I_c \) (mean irradiance experienced by the phytoplankton) \( F = \) (IcKtMLD) (1-exp-KtMLD). Values in parenthesis represent the variance explained by the parameter.

\[
\begin{align*}
\ln P_i &= 6.90 + 0.722 \ln C_k + 0.0010 \ln I_c - 8.59 \ln K_t + 0.0043 \ln \text{MLD} \\
\ln P_i &= 5.07 + 0.580 \ln C_k + 0.255 \ln \text{Ic} + 0.047 \\
\text{Total } r^2 &= 0.336 \\
\text{Total } r^2 &= 0.316
\end{align*}
\]

The \( C_k \) was the most important variable in these equations (Tab. 1). \( I_c \) explained about 5% of the variability, only a bit more that insolation alone. Regression equations without the log transformation of variables explained less of the variability in \( P_i \) than those shown.

Analytical model

Bannister (1974) and Smith and Baker (1978) developed a simple model relating \( P_i \) and \( C_k \) to the photoadaptive state of nutrient-sufficient phytoplankton:

\[
P_i = 2.3 \frac{P_{\text{max}}}{C_k K_t},
\]

where \( P_{\text{max}} \) is the highest rate of photosynthesis per weight of chlorophyll observed at some discrete depth in the water column. Figure 2 shows the result in the form of the identity \( P_i/C_k = F = 2.3 P_{\text{max}}/K_t \). The slope of the least squares regression line is 2.3, as predicted, and about 70% of the variation in \( P_i \) is accounted for in the regression. We can draw two conclusions from Figure 2. First, variations in \( F \) are probably due to photoadaptation. The photoadaptive state of the plankton reflects its recent light history, that is whether the plankton grew in bright or dim light. Photoadaptation depends upon irradiance, day-length and the depth of mixing of the surface waters as those are the factors which determine the parameters of the photosynthesis-light curves of the plankton. They are expected to be correlated with \( F \) (Smith, 1978). Second, the fit implies that most of the light attenuation is due to plankton.

Variations between current systems

Blackburn et al. (1970) described the spatial and temporal variation in chlorophyll and Owen and Zeititschel (1970) the corresponding variations in primary production before the stations could be assigned to discrete currents; the geostrophic currents were described later (Tsuchiya, 1974). Table 2 shows

Table 2
Data from the Eastropac expedition, 1967-1968: \( P_i \) (primary production mg C m\(^{-2}\) d\(^{-1}\)); \( C_k \) (near-surface chlorophyll-like pigments mg m\(^{-3}\)) and the ratio \( P_i/C_k \); mean (and standard deviation) for stations in discrete currents.

<table>
<thead>
<tr>
<th>Current</th>
<th>No. of stations</th>
<th>( P_i )</th>
<th>( C_k )</th>
<th>( F = P_i/C_k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEC</td>
<td>31</td>
<td>240</td>
<td>136</td>
<td>0.16 ± 0.09</td>
</tr>
<tr>
<td>NECC</td>
<td>21</td>
<td>194</td>
<td>133</td>
<td>0.16 ± 0.07</td>
</tr>
<tr>
<td>SEC</td>
<td>54</td>
<td>205</td>
<td>105</td>
<td>0.20 ± 0.09</td>
</tr>
<tr>
<td>Equator</td>
<td>20</td>
<td>307</td>
<td>156</td>
<td>0.25 ± 0.07</td>
</tr>
</tbody>
</table>

NEC = North Equatorial Current, NECC = North Equatorial Counter current, SEC = South Equatorial Current.

the variation in \( F \) between the North Equatorial Current (NEC), North Equatorial Counter Current (NECC), and South Equatorial Current (SEC). The mean value of \( F \) was higher and the variability was greatest in the NECC and NEC. Both regions were outside the upwelling area as judged by the absence of nitrate at 10 m depth. Within the SEC, and at stations within about 1.5° latitude of the Equator, where no geostrophic flow could be assigned, \( F \) was about 1.200 (Tab. 2). Nitrate was present at all these stations.
Equatorial stations with uniform chlorophyll over depth, and therefore with well mixed waters, showed the lowest values of \( F \) (about 600; the lower limit value of \( F \) is about 100; Eppley et al., 1985) while higher values, up to 2,400, were found in stratified waters with subsurface chlorophyll maxima. Stations in both the NEC and NECC showed a larger range in the variance of chlorophyll over depth, implying greater chlorophyll stratification, than in the SEC.

**DISCUSSION**

Highest values of \( F \) and greatest variability in \( Pi \) and \( Ck \) were found in the NEC and NECC where the waters were both oligotrophic, judged by the absence of nitrate at 10 m depth, and stratified. Conversely \( F \) was lowest in the nutrient-rich SEC. There, nutrients were in excess and were not likely to limit primary production. Rather, changes in primary production resulted from changes in stability and mixing; production was reduced by a poverty of light rather than nutrients (Barber et al., 1983; Menshutkin, Finenko, 1975 — cited in Vinogradov, 1981). The reduction in primary production during the 1982 El Niño event was due to a greatly increased mixing depth, rather than a lack of nutrients (Barber et al., 1983).

The variability in the depth distribution of chlorophyll near the Equator and in the SEC generally suggests that even in the nutrient-rich equatorial waters of the eastern Pacific the intensity of vertical mixing must be patchy, as reported earlier from both biological (Vinogradov, 1981) and physical observations (Knox, Anderson, 1985 and references therein).

Improved models for estimating the intensity of mixing using satellite wind data may be possible. At present only about 34% of the variability in \( Pi \) could be explained using our stepwise multiple linear regression model. Better estimates would require either in situ measurements of the intensity of mixing or of photosynthetic parameters such as \( P_{\text{max}} \). It is interesting that a goal of the TROPIC HEAT program is "...to parameterize the turbulence in terms of larger scale quantities which are both easier to monitor and resolvable in model studies" (Ertelken, 1985). Attainment of this goal would also facilitate estimating primary production from satellite chlorophyll in the eastern tropical Pacific. Also, more extensive studies of primary production and chlorophyll variability in relation to hydrography have taken place in the tropical Atlantic. Variability has been examined on time scales from 24 hour (Le Bouteiller, Herblad, 1982), to several days (Herblad, Le Bouteiller, 1982) and seasons (Herblad et al., 1983). Analysis of this data set is expected to increase significantly our understanding of the use of satellite data to estimate primary productivity in equatorial waters.

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