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Figure 1. A composite CZCS-scanner image of chlorophyll $a$ concentration from the NASA EOS page:
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Figure 2. A CZCS image of the Northeast shelf, from
(http://seawifs.gsfc.nasa.gov/SEAWIFS/IMAGES/dumping1.gif). The warm and cold core rings are large
mesoscale eddies created from meanders in the Gulf Stream. Cold core rings affect the nutrient dynamics of the
North Atlantic gyre. As these rings decay, the flux of nitrate is increased into the euphotic zone. ............... 29

Figure 3. An AVHRR image of Cape Cod on September 30, 2000. This image for temperature is updated every few
hours at the Rutgers University IMCS web site. There are also daily images of Chl $a$. The page (URL:
http://marine.rutgers.edu/mrs/newevery.fye.html) contains the following note: Remember! This image has
been automatically moved from the satellite receiver to this homepage. There has been no human intervention.
Therefore, some of the images will not be perfectly navigated with the coastline overlaid on them. ............ 30

Assignment

TOPIC

How can phytoplankton standing stock and production be estimated from space?

REQUIRED PAPERS


concentration. Limnol. Oceanogr. 42: 1-20. [Lit review of $^{14}$C production estimates from the MARMAP program
used to derive productivity model to improve on Platt & Sathyendranath (1988). A new parameter $P_{opt}^A$ is
proposed. The paper is available for free at the ASLO web site
http://www.aslo.org/lo/toc/vol_42/issue_1/0001.pdf]

SUPPLEMENTAL

physiology from space. Global Biogeochemical Cycles 19: [They estimate the physiological status of
phytoplankton cells, to determine the effects of nutrient stress on C:Chl $a$ ratios. New algorithms are used,
producing estimates of specific growth rates and production. Preprint available here:
http://web.science.oregonstate.edu/ocean.productivity/references/GBC%20paper.pdf]

Campbell, J. W. and J. E. O'Reilly. 1988. Role of satellites in estimating primary productivity on the northwest Atlantic
continental shelf. Cont. Shelf Res. 8: 179-204. [Uses the NE Shelf MARMAP data to evaluate methods to
estimate production from Chl $a$ in the upper optical depth]

chlorophyll. Introduction to regional differences and statistics for the Southern California Bight. Journal of
Plankton Research 7: 57-70.
SOME KEY QUESTIONS FROM THE READINGS

1. How is Chl $a$ estimated from space?
2. To what depth is Chl $a$ measured?
3. What is the significance of the hinge wavelength at 550 nm?
4. How can primary production be estimated from estimates of surface Chl $a$ concentration?
5. How are the satellite estimations of primary production using the Platt & Sathyendranath (1988) or Eppley et al. (1985) regional regression approaches affected by the Great Debate (see Peterson 1980) over the $^{14}$C technique?

SOME KEY ISSUES

The distinction between Chl $a$ concentration and primary production is fundamental. Production is production and standing stock is standing stock and never the `twain shall meet. However, life may be simpler than we thought twenty-five years ago. Twenty years ago, the goal of estimating water-column production from space might have seemed unattainable. Platt & Sathyendranath (1988) showed how this goal could be accomplished, but their satellite-derived estimates had a relatively low precision. Platt et al. (1988, p. 873) estimated that the relative error on water column production to be $\pm 42\%$. Using their P vs. I approach, and the uncertainty associated with estimating model parameters, specifically their $\alpha^i$, the error rises to $\pm 60\%$. The latest algorithm for estimating primary production from space was described by Behrenfeld & Falkowski (1997).
ESTIMATING CHL A CONCENTRATION FROM THE UPPER OPTICAL DEPTH

Mary Jane Perry (1986) briefly describes the algorithms used to estimate Chl a concentrations from space using the sea-surface reflectance of light at 5 wavelength bands. There were only 5 wavelength bands in the original coastal zone color scanner (CZCS) sensor on the Nimbus-7 satellite. The basic Chl a algorithms used in the latest generation of sensors, SeaWiFS and MODIS, are based on the same principles, but these satellites can detect over 30 different wavelength bands. Two algorithms are used: an oceanic or Type I or Case I algorithm which computes Chl a as being inversely related to the ratio of reflected light at 440:550 nm and the neritic or Type II or Case II (or high Chl a) algorithm that uses the ratio of reflected light at 520:550 nm. The case II algorithm must be used when there is a high concentration of Chl a because little 440-nm light can be detected by the satellite. Most of the 440 nm light would be absorbed by the photosynthetic pigments in the water column.

Most biological oceanographers assume that these algorithms give relatively precise estimates of surface Chl a concentrations (to one optical depth [optical depth = light attenuation depth = 1/k, where k is the absorption coefficient for PAR]). Gordon & McCluney (1975) showed that 90% of the satellite-detected water-column signal comes from the upper light attenuation depth.

The distinction between Case 1 and Case 2 waters (sometimes called Type I and II) was proposed by Morel and Prieur (1977). Carder et al. (1997) state that Chl a dominates optical properties of seawater in Case 1 waters, and the CZCS is reasonably accurate in estimating sea-surface Chl a (±40%, Gordon et al. 1983). In Case 2 waters, suspended sediments, coccolithophores, gelbstoff (colored dissolved organic matter), detritus and bacteria also contribute to the optical signal, leading to inaccuracies as high as 133%. Carder et al. (1997) describe new highly accurate algorithms for Case 2 waters that will utilize the additional receiving wavelengths that are available on the new MODIS sensors.

Perry (1986) reviews some of the assumptions needed to estimate Chl a from space. A few studies have questioned the methods used in computing the original equations used in estimating Chl a with CZCS data (Gordon et al. 1980). These algorithms worked well in Type I waters, but often broke down in Type II or high Chl a and high turbidity nearshore waters. Some of the major problems are that in Type II waters, dissolved colored organic matter and suspended particulate matter absorb light, and coccolithophores reflect light. The new MODIS satellite will have 37 bandwidths available and new algorithms have been developed to estimate Chl a concentrations in coastal waters. In offshore waters, primary production can often be dominated by cyanobacteria, which have pigments that absorb light at the crucial hinge wavelength (550 nm). The MODIS satellite will be able to estimate the concentrations of phycoerythrin directly.

PRIMARY PRODUCTION FROM SPACE

Empirical approach

Smith et al. (1982) provided one of the first attempts to estimate primary production from space. They used a relatively straightforward regression equation. The coefficient of determination between observed and estimated production was low (r^2=0.6). Eppley et al. (1985) expanded on this regression approach and argued that regional regression equations were needed to estimate primary production. The r^2 of roughly 0.6 might have been an upper limit. Though these r^2 values were low, the satellites did allow a synoptic picture of relative primary production that was impossible using shipboard sampling procedures.
Analytical approach

**Platt (1986)** changed utterly the view of coupling between primary production and Chl a standing stock. He reviewed the literature and found that \( \Psi (Psi) \), a parameter related to the initial slope or \( a \) in models of the \( P \) vs. \( I \) relationship. \( \Psi \) exhibited little variation from region to region. The phytoplankton populations which dominate biomass at any one point in time appear to exhibit \( P \) vs. \( I \) parameters which are very high relative to the known thermodynamic efficiency for photosynthesis.

**Platt’s (1986)** new algorithm for remote sensing conflicts with the `bottom-up' modeling view of ecosystems which would reduce the value of \( a \) (i.e., the slope of the \( P \) vs. \( I \) curve) drastically to account for nutrient limitation. **Platt’s (1986)** relationship appears to indicate that, in general, the bulk of phytoplankton standing stock in the water column at a given point in time exhibit little apparent nutrient stress. **Harrison & Platt (1986)** showed that the estimated parameters of the Jassby-Platt \( P \) vs. \( I \) model from polar waters was not a function of external nutrient concentration. **Cole & Cloern (1987)** and **Kelly & Doering (1997)** have used the **Platt (1986)** relationship to justify their finding that estuarine production can be predicted from a knowledge of light intensity and depth-integrated Chl a concentrations [nutrients not needed]. Obviously, **Platt’s (1986)** algorithm is consistent with the Goldman-McCarthy and G.P. Harris view of that those phytoplankton species which dominate the standing stock in a water column are growing at a high relative specific growth rate and don't exhibit the symptoms of nutrient stress (e.g., low initial slope in \( P \) vs. \( I \) curves or high C:N ratios).

**Platt and Sathyendranath (1988)** expand on the **Harrison et al. (1985)** \( P \) vs. \( I \) modeling approach, which estimated primary production on a regional scale, to estimates of primary production on a global scale. To estimate primary production from satellite data, one needs regional estimates of the \( P \) vs. \( I \) curves, generalized depth distribution of Chl a concentration, and light intensity as a function of depth. Platt and Sathyendranath argue that there is large-scale regional and seasonal consistency in the \( P \) vs. \( I \) and generalized depth profiles. If their speculation is correct, estimation of primary production from satellite is relatively straightforward. Platt and Sathyendranath divide the Atlantic Ocean from 20°S to 50°N into 5 regions, assign \( P \) vs. \( I \) parameters and generalized pigment depth profiles to each region, and estimate primary production. They advocate that oceanographers focus their field sampling on estimating vertical pigment structure and the determination of regional and temporal variation in \( P \) vs. \( I \) parameters.

For many applications (e.g., the biological pump of DIC to the deep sea), estimates of total primary production are less important than estimates of new production. Oceanographers therefore should obtain estimates of the ratio of new:total production in different geographic regions.

In order to apply **Platt & Sathyendranath’s (1988)** approach, the spatial and temporal correlation among Chl a and primary production model parameters must be assessed. **Yoder et al. (1987)** applied Kriging to the analysis of spatial autocorrelation among satellite-derived Chl a measurements. Kriging is a method for performing data interpolation, taking into account the spatial variance structure of the data. Clouds pose a major problem for satellite images; Kriging is one of several methods that can be used to infer the Chl a concentration from areas that are blocked out from clouds. The spatial gradients in Chl a are not isotropic, that is, Chl a concentration exhibits different rates of change in one direction than another. The offshore gradients in Chl a concentrations are often very steep relative to the alongshore gradients, and the latitudinal gradients are often stronger than the meridional gradients. To apply the Platt and Sathyendranath approach would require that the multivariate spatial autocorrelation among variables be determined. If the spatial and temporal autocorrelation among model parameters is low, the Platt and Sathyendranath approach will still work, but the precision will be low.
Platt’s analytical approach is the one that will be used to estimate primary production using the MODIS data, beginning in 1998. In addition to sea surface Chl a, the MODIS satellite will collect data sufficient to estimate instaneous PAR, absorbed photosynthetically available radiation. Algorithms are under development to estimate the mixed-layer depth as well.

The MODIS satellite will also be able to detect upwelled fluorescent light (at 683 nm). When the CZCS satellite was developed, it was thought that little 680 nm wavelength light would leave the sea surface, since that is the peak absorption wavelength for Chl a and seawater absorbs strongly at this wavelength. The CZCS scanner was able to detect upwelled radiance at 680 nm, and this light was attributed to solar-induced fluorescence. With the MODIS satellite, solar induced fluorescence will be used as another method to estimate sea-surface production.

I don't like ending on a pessimistic note, but... Campbell and O'Reilly (1988) describe the role of satellites in assessing primary production without using any satellite data. The covariance of extant shipboard NMFS cruise data on Chl a concentration and primary production were analyzed to assess the anticipated precision of satellite-derived estimates of primary production. Campbell and O'Reilly (1988) concluded that estimates of primary production on the New England continental shelf can be made, but that the precision will be low ($r^2=0.62$) unless new methods for estimating the light field are developed.

**Web resources**

There is a tremendous amount of material on satellite remote sensing on the web. Table 1 provides the URL’s and a brief description of these web pages. I’ve included a 1 to 4 star ranking as well.

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<td>NASA Earth Science Enterprise</td>
<td><a href="http://www.earth.nasa.gov">http://www.earth.nasa.gov</a></td>
<td>Overview of ESE with links to other NASA web pages ⭐⭐</td>
</tr>
<tr>
<td>NASA MODIS satellite</td>
<td><a href="http://modis.gsfc.nasa.gov/">http://modis.gsfc.nasa.gov/</a></td>
<td>MODIS will be the key ocean color satellite after 1998. This page links to a bibliography of publications sponsored by the Modis program ⭐⭐</td>
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SeaWiFS and MODIS Filled Level-3 Rolling 32-Day Composites

This month’s chl a picture

NASA Goddard Space Center: Primary Productivity Research

Brief overview of meetings and activities, including Behrenfeld-Falkowsky & Howard-Yoder MODIS productivity maps.

NOAA National Geophysical Data Center

Sea surface topography from space based on gravity anomalies - great pictures

Rutgers IMCS Remote Sensing LAB

TOPEX Sea surface temperatures for the E. Coast, updated daily

US Global Change Research Project

Links to US Global Change Research

Terms & Concepts

**AVHRR**  Advanced Very High Resolution Radiometer. Used for sea-surface temperature - see Rutgers IMCS page for daily East Coast ocean temperature images.

**CZCS**  Coastal Zone Color Scanner. On the Nimbus-7 satellite

**EOS**  Earth Observing System. A fleet of satellites, part of NASA’s mission to planet earth, to be launched over the next two decades. MODIS will be launched aboard EOS AM-1 in 1998.

**FLI**  Fluorescence line imager. An aircraft sensor to detect upwelled fluorescent light, centered at 683 nm (Gower & Borstad 1990)

**GOES**  Geosynchronous observing environmental satellite.

**MODIS**  Moderate Resolution Imaging Spectroradiometer. There are two MODIS satellites. The first, called Terra, was launched on the EOS AM-1 satellite on 12/18/99. The second, called Aqua, was launched on 4/4/02. MODIS will view the entire earth surface every 1 to 2 days MODIS contains a much more extensive array of receiving bands than the CZCS scanner (36 spectral bands, including: λ =412, 443, 488, 531, 551, 665.1, 676.7, 746.3 nm). MODIS measures radiance in the visible, near IR, and thermal IR bands. Algorithms have been developed to estimate Chl a concentration in Case 1 and Case 2 waters, instantaneous photosynthetically available radiation (IPAR), absorbed radiation by phytoplankton (ARP, total number of quanta absorbed by phytoplankton in the top attenuation depth measured at 685 nm, z_{top}), chlorophyll fluorescence (Sun-stimulated fluorescence can be used to estimate primary production). Satellites can detect upwelled light at 683 nm, produced by Chl a fluorescence, Abbott & Letelier 1997) and phycoerythrin (Hoge 1996).


**TOPEX/Poseidon**[http://topex-www.jpl.nasa.gov/mission/mission.html]  Launched: August 10, 1992 TOPEX/Poseidon data has revolutionized the way the global ocean is studied. For the first time, the seasonal cycle and other temporal variabilities of the ocean have been determined globally with high accuracy, yielding fundamentally important information for testing ocean circulation models. Major observations were

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made using TOPEX/Poseidon data on Oceanic circulation including details on the movement of Rossby and Kelvin waves, Oceanic and coastal tides, El Niño, La Niña, and the Pacific Decadal Oscillation, El Niño-like circulation in the Atlantic Ocean, Oceanic seasons in the Mediterranean, Ocean floor topography from surface data used to refine the geoid model.

Outlines of papers

Assigned

I. Introduction  
A. 95% of marine photosynthesis is due to phytoplankton  
B. The magnitude and variability of oceanic primary production is uncertain  
   1. The ratio of marine to total global photosynthesis = 10% to 50%  
   2. magnitude from 20 x 10^{15} g carbon per year to 55 x 10^{15} g carbon per year  
   3. little is known about inter-annual variance in primary production in 332 million km^2 of open ocean.  
C. Why is our knowledge so poor?  
   1. limits on sampling by ship, mooring and drifter  
   2. temporal and spatial variation  
   3. Existing estimates of primary production based on pre-1970's data  
II. Satellite remote sensing of sea-surface Chl a can fill the gaps  
A. CZCS demonstrated the potential for satellites to estimate Chl a  
B. goal is to provide primary production estimates.  
III. Deriving phytoplankton biomass form ocean color  
A. Aircraft observations set the stage for satellite remote sensing  
B. CZCS launched in October 1978 on the Nimbus-7 satellite  
C. Features of CZCS  
   1. 1-km pixel resolution  
   2. 1600-km wide swath  
   3. repeat coverage every 5-6 d  
D. Principles of remote sensing:  
   1. differential absorption and reflectance.  
   2. photo pigments  
      a. high absorbance of blue, blue-green and red  
      b. low absorbance for green-yellow  
   3. Five operational channels (20 nm bandwidth):  
      a. 440 nm  
      b. 520 nm  
      c. 550 nm (the hinge wavelength)  
      d. 670 nm (used to estimate atmospheric backscatter)  
      e. 100 nm wide 750 nm bandwidth  
   4. The chlorophyll algorithm:  
      a. The ratio of reflectance from the sea surface in the 440 to 550 nm channels is inversely proportional to chlorophyll a.  
      b. 520:550 nm used for waters with higher Chl a concentration (>1.5 mg Chl a m^-3)  
      c. atmospheric correction  
         (1) 90% of reflectance is due to atmospheric backscatter  
         (2) aerosol backscatter is removed by signal received at 670 nm, a wavelength band at which the ocean is assumed to reflect no light.  
      d. 90% of the radiance leaving the water originates in the upper attenuation length, or the upper 20-30% of the photic zone.  
      e. The algorithm underestimates water column Chl a in regions with a subsurface chlorophyll maximum.
Assumptions in deriving biomass:

A. Absorption at 550 nm is minimal
   1. Phycobiliproteins (Cyanobacteria) can cause problems "...cyanobacterial species such as *Synechococcus* spp. are often more abundant and pigmented at depth" [This is often not the case]
   2. Often more pigmented at depth.
   3. Degradation pigments covary with Chl *a* in most ocean waters.

B. No red light (670 nm) is emitted from ocean

C. The refractive index is the same for all species.

D. Problems
   1. Contribution of phaeopigments and Gelbstoffe absorb more strongly around 400 nm than 440 nm, thus their contribution to the Chl *a* signal is reduced during bloom conditions.
   2. High quantities of red light can be generated by Chl *a* fluorescence, biasing the aerosol correction.
   3. Coccolithophorids have high refractive indices.
   4. Sun glint
   5. Differential degradation of sensor channels

Phytoplankton patchiness:

A. Patchiness evident even in the open ocean.

B. Squirts and filaments off the WA-OR-CA coast (Fig. 1)

C. Patterns in sea surface temperature and chl *a* related.

Extracting primary productivity from CZCS images.

A. Implicit or assumed relationship between production and fisheries
   1. Satellite images distributed to fishermen.
   2. Albacore catches higher around fronts.

B. *Abbott and Zion* (1985) calculated phytoplankton growth rates in upwelling region.
   1. Estimated time water had traveled from 2 points
   2. They assumed that the difference in Chl *a* was due to phytoplankton growth
   3. Calculated growth of 0.8 d

C. Regional production measurements.
      a. Divided bight intro regions of high, low and intermediate chlorophyll
      b. Computed spatially averaged productivity to be 403 mg C m⁻² d⁻¹.
   2. *Brown et al.* (1985) calculated production during the North Atlantic bloom
      a. 4 regions: shelf, slope, Gulf stream and Gulf Stream warm core ring
      b. Estimated regional production with high precision.
      a. Productivity varied within and between geographical regions
      b. The productivity per unit Chl *a* tended to decrease as Chl *a* concentration increased.
   4. Factors controlling primary production
      a. Instantaneous light intensity
      b. Past light intensity
      c. Nutrient availability
   5. Light can be measured using GOES geostationary satellite imagery.

Supplemental

G. Fig. 8. PAR and SST
H. IP/C*s (mg Chl a m^(-3)) accounts for only 42% of the variation in cruise data.

V. Covariance analysis among and within cruises
A. C*s (mg Chl a m^(-3)) is the only variable correlated with within cruise variance, r^2 = 62%
B. SST and PAR not correlated to \( \pi \) (mg C m^(-2) d^(-1)) within cruises

VI. Theoretical models
A. Bannister's (1974) quantum yield
B. quantum yield = \( \Theta = \) ratio of carbon mixed (as moles or mg C) per mole photons (Ein) of light absorbed by the phytoplankton. The theoretical max \( \Theta = 0.125 \text{ mol C Ein}^{-1} \) (1500 mg C Ein^{-1}). A practical upper limit is probably closer to 0.1 mol C Ein^{-1} (1200 mg C Ein^{-1})

C. Platt (1986) argued that \( \Psi = \Psi(\Psi; k_c) = <\Theta> / 4.6 \), where \( k_c \) is chl-specific diffuse attenuation coefficient for PAR, is a stable quantity equal to 0.5 mg C (mg chl a)^(-1) m^2 Ein^{-1}. (range from 0.3 to 0.7)

D. To apply Platt's algorithm need:
1. IC from C*s (mg Chl a m^(-3))
2. ability to estimate I_c from space
3. knowledge of \( \Psi(\Psi; k_c) \)
   - or more generally \(<\Theta>\) and \( k_c \)

E. Estimates of Platt parameters
1. C*s (mg Chl a m^(-3)) and IC (mean euphotic chl) correlated r^2=0.93
2. Stability of \( \Psi(\Psi; k_c) \), no linear relationship evident
3. water column utilization index. \( \Psi = \text{IP/(IC*I)} \)
   - higher than Platt's value 1.23 mg C (mg chl a)^(-1) m^2 Ein^{-1}, 2 order of magnitude variation.

VII. Discussion:
A. Disagrees with Platt, \( \Psi \) is higher and more variable than Platt had indicated.
B. Yoder found similarly high values
C. variability due to oceanographic extent and diverse nature of the Northeast Atlantic.
D. Variability in \( \Theta \) and \( k_c \)
E. The satellite algorithm (Equation 7)
\[
\text{IP} = <\Theta> / 4.6 \quad (7)
\]
1. thermodynamic efficiency is 0.4*\( \Theta_{max} \), Platt assumed 0.1.
2. the predictability of \( Q \) is difficult, where \( Q(z) \) is the rate of absorption of light by phytoplankton at depth \( z \).
   - to account for \( Q \) will require the capability to account for optical variability of phytoplankton resulting from variability in species assemblages as well as variability due to substances other than phytoplankton.

VIII. Conclusions;
A. Variance in \( \pi \) (mg C m^(-2) d^(-1)) due to
   1. variations in rate of light absorption
   2. Seasonal changes in the efficiency of light utilization with maximal quantum yield in the lower part of the euphotic zone.

B. \( \pi \) estimated from chl concentration
C. \( \psi \) (mg C m^(-2) d^(-1)) = \( C_s \) (mg m^(-3)) * F
D. large variance in F.
   1. part regional
   2. F is proportional to insolation

II. Introduction
A. attractive idea
B. no one expects much precision in estimates
   - CZCS only measures upper 1/5 of euphotic zone.
C. primary production controlled by:
1. temp
2. light
3. nutrients
4. species and their chemical composition

III. Methods
A. many cruises in the SC bight
B. definition of terms
1. $\pi$ (mg C m$^{-2}$ d$^{-1}$) = water column production
2. $C_i$ (chl-like pigments) and $C_s$ (phaeopigment).
3. $C_s$ (mg m$^{-3}$) averaged over the upper attenuation length
4. $C_i$ (mg m$^{-3}$) refers to surface pigment
5. $C_i$ (mg m$^{-3}$) chl integrated over the euphotic zone.
6. $K_T$ (m$^{-1}$) defined using a submersed quantumeter
7. Upper attenuation length = $K_T^{-1}$ (m$^{-1}$), 4.6 attenuation lengths in the euphotic zone.
8. $F$ is proportionality between $\pi$ (mg C m$^{-2}$ d$^{-1}$)/$C_i$ (mg m$^{-3}$)

C. Statistical methods.
1. Marquardt algorithm used
2. stepwise multiple regression
3. data divided into 2 sets: estimating and testing.
4. PTA = departure in temp from a long-term 54 year mean value, 7-day running ave.

IV. Results:
A. Regional differences in the relation between $\pi$ (mg C m$^{-2}$ d$^{-1}$) and $C_i$ (mg m$^{-3}$)
1. non-linear relationship -0.5 power function
2. seasonal differences
3. Conclusions
   a. precision is improved by knowing the location of the satellite image
   b. accuracy improved by knowing the time of year.
B. SC Bight
1. $\pi$ (mg C m$^{-2}$ d$^{-1}$)/$C_i$ (mg m$^{-3}$) shows an annual variability (due to light!)
2. onshore-offshore increase in the ratio:
   a. increasing depth of the euphotic zone
   b. decreasing average chl
   c. decreasing average production m$^{-3}$
   d. increasing depth of the nitracline
   e. decreases in other measures of phytoplankton standing stock
      (POC, PON, ATP)
C. Seasonality in the data
   seasonal variation makes up only 9% of total variation (fit data to a trigonometric function of time)
D. Production and environmental variables.
1. PTA is a useful variable
2. 3 environmental variables survived multiple regression
   $C_i$ (mg m$^{-3}$), PTA, and daylength

V. Discussion
A. Regional variation in F
1. decreasing F with increasing $C_i$ (mg m$^{-3}$)
2. differences in regional estimates of F due to differential absorption by phytoplankton and water (turbidity)
B. Variability of $\pi$ (mg C m$^{-2}$ d$^{-1}$) in the SCBS cruises
1. most of the variability due to $C_i$ (mg m$^{-3}$)
2. other problems
   a. $C_i$ (mg m$^{-3}$) is only a small part of phytoplankton
   b. misses subsurface chl max
   c. all info on vertical structure lost
3. Fronts could be important
C. Different equations needed for different ocean regions.
1. Introduction
2. Remote sensing of pigment concentration
   a. Satellite sensors
   b. Atmospheric correction
   c. Cloud cover
   d. Conversion of water-leaving radiance into pigment
   e. Case II waters
   f. Sub-surface chlorophyll maxima
3. Estimation of primary production from pigment concentration
   a. Empirical models
   b. Semi-analytical models
   c. Consideration of errors
4. The Celtic Sea and English Channel as a case study: estimation of annual phytoplankton production
   a. Seasonal changes in ocean colour
   b. Chlorophyll concentration in the Celtic Sea and western English Channel
   c. Estimation of annual production: comparison with previous estimates for the Celtic Sea and western English Channel
5. The additional potential of satellite remote sensing
   a. New production and limits to productivity
   b. Estimation of other biogeochemical parameters
6. Future developments

i. calculation of downwelling irradiance

ii. Equations 2-5 calculate $I_d$

e. The primary production model

i. Equations 6-9 calculate the $P$ vs. $I$ curve

ii. $\alpha(\lambda)$ is the photosynthetic action spectrum.

iii. $\Pi(z)=\int (\alpha(z,\lambda)I_d(z,\lambda)\sec\theta + 1.20 I_s(z,\lambda))d\lambda$  \hspace{1cm} (9)

where $\lambda =$ wavelength

$\alpha(\lambda) =$ photosynthetic action spectrum

$I_d =$ direct component of sunlight

$I_s =$ diffuse (sky) component of sunlight.

iv. $\alpha(\lambda)$ appears to have a common shape in a variety of oceanographic regions.

Fig. 1. Nearly a perfect correlation using Equation (9) between estimated and observed primary production.

f. The biomass profiles.

i. satellites don't measure vertical structure.

ii. DCM is widespread (Cullen review)

iii. Generalized biomass profile from Platt et al. 1988:

$$B(z) = B_o + \left[ \frac{h}{(\sigma 2\pi)^{0.5}} \right] \exp \left[ -\frac{(z-z_m)^2}{2 \sigma^2} \right]$$  \hspace{1cm} (10)

where, $B_o =$ background or baseline pigment

$z_m =$ the depth of chl. maximum

$\sigma =$ defines breadth of peak

$$\frac{h}{m^2} = \text{total biomass above background.}$$

iv. calculated $P$ vs. $I$ curves

v. Error analysis: the errors can be considerable if the chlorophyll maximum lies near the surface of the euphotic zone! (p. 1615)

Fig. 2. Relative error in the estimation of primary production when satellite estimated chl concentration is assumed to extend throughout the euphotic zone.

4. Extension of the Local production to Large Horizontal scale.

a. 2 parameters needed to describe the $P$ vs. $I$ relationship and 4 parameters for the biomass algorithm

b. Local algorithm can be modified such that only 3 properties of the biomass profile need to be specified.

c. Assume constant vertical profiles: Typical Tropical structure (see Endnote 31)

Fig. 3. The generalized Chl $a$ profile.

d. The procedure would be similar to the partitioning of the continents or oceans into biogeographic provinces according to taxonomic criteria, except that the boundaries of the regions and the magnitudes of the characteristic parameters in the regions could change with season. We might call this partition a "dynamic biogeography".

5. Recommended protocol:


b. Primary production calculated for 3800 grid points

Fig. 4. Estimation of water column primary production 4b ocean divided into grids. 4d estimated primary production.

6. New Production: $P_n$ is the force behind the biological pump but it is difficult to measure by satellite.

7. Second order factors

a. Nitrate as measured by chemiluminescence has revolutionized view of effects of N pulses

b. species composition important

8. Alternatives for the Local Algorithms

a. Empirical regression models

b. Linearized models: Relationship to Platt '86:
i. $\Psi$ has the same dimensions as $\alpha$
ii. $\Psi$ directly proportional to $\alpha$ and relatively constant
iii. Linearized models could be used where $B(z)$ is unknown

c. Fluorescence
i. emission peak is at 685 nm, at which wavelength seawater is strongly absorbing.
ii. solar induced fluorescence can be detected to 80 m
iii. Fluorescence Line Imager (FLI), aircraft can monitor surface chl
iv. evidence that $\alpha$ is related to fluorescence intensity

9. Discussion of Errors:
   a. $^{14}$C still a problem
   b. clouds affect light quality
   c. Precision
   d. new production

10. Implications for oceanographic programs:
   a. establish biomass profile and seasonal variation
   b. analyze optical properties and wavelength dependence
   c. measure frequency distributions of photosynthesis parameters and their seasonal variation.
   d. calculate f ratio if new: total production needed.
   e. more detail on vertical structure: rely on satellites for horizontal structure.
   f. model primary production of the water column.


1. Abstract
   a. refinements to the linear theory in Platt (1986)
   b. evidence for the stability of surface light and biomass-normalized primary production
   c. sensitivity analysis on a generalized biomass profile

2. Introduction
   a. Challenge of estimating production from standing stock
   b. empirical vs. physiological models.
   c. Platt (1986) assumed
      i. linear photosynthesis-light model
      ii. uniform distribution of photosynthetic biomass with depth.

3. Sketch of the earlier theory
   a. $\Lambda$ = normalized integrated production (integrated over the photic zone)
      i. $\Lambda$ is a linear function of $I$, with slope $\Psi$
      ii. $\Psi$ is proportional to $\alpha^a$ of the $P$ vs. $I$ curve.
   b. errors expressible in terms of $I = I_0/I$, where $I_0$ is derived from the $P$ vs. $I$ curve.
      i. $I = P \alpha^a / \alpha^b$, where $P_{\alpha} \alpha$ is the assimilation number.
      ii. errors relatively slight and could be calculated, given $I_0$

4. Further empirical evidence:
   a. Jacques and Minas (1981); Collos and Slawyk (1986)
   c. Cole and Cloern (1987)
      i. Regression vs. $B_zI_0$
      ii. Their procedure is exactly equivalent to the one followed by Platt (1986)
      iii. The product $B_z$ simply euphotic zone biomass. Equivalent to a regression of $\Lambda$ on $I_0$ as in Platt (1986)
      iv. Regression slopes are higher than those in Platt (1986) for reasons not yet understood.
   d. Platt and Irwin (1972)
   e. Irwin et al., (1986)
   f. Platt and Irwin (1971)
   g. Platt, Irwin and Subba Rao (1973)
   h. Platt unpublished
   i. Pooled Bedford Basin data

Fig. 1. Biomass-normalized water column production vs. surface light intensity. Pooled data for Bedford Basin

5. Departure from linearity at low light.
6. Integral from of photosynthesis-light models: general properties
   a. Platt et al. (1988) Formal relationship between $a^n$ and quantum yield
      \[ a^n = \Phi \kappa \]  \hspace{1cm} (8)
      where, $\kappa$ is the chl-specific attenuation coefficient
   b. Kiefer & Mitchell (1983) model:
      \[ \mu = k \rho \Phi \]  \hspace{1cm} (9)
      where, $\rho$ is carbon:chl ratio, $\Phi$ is a function expressing decrease in quantum yield as light level increases
      \[ \Phi = \Phi_\kappa (K_\kappa / (K_\kappa + I)) \]  \hspace{1cm} (10)
      where, $K_\kappa$ is a fitting parameter
   c. The Kiefer-Mitchell model is merely a Michaelis-Menten model:
      \[ P = \frac{P \# I}{I_k + I} \]  \hspace{1cm} (13)

d. Formulations of relationship between plankton photosynthesis and available light in terms of quantum yield are equivalent to those in terms of $a$

7. Error in estimation of areal production arising from non-uniform biomass profile
   a. Generalized pigment profile:
      \[ B(z) = B_\sigma + \left( \frac{h}{\sigma \sqrt{2\pi}} \right) \exp \left[ \frac{-(z-z_\sigma)^2}{2 \sigma^2} \right] \]  \hspace{1cm} (14)
   b. Non-linear fit to field data
   c. Daily integrated production
   d. Summary of sensitivity analysis: critical dimensionless factors
      i. depth of DCM relative to euphotic depth, $z_m / z_e$
      ii. width of peak relative to euphotic depth $\sigma / z_e$
      iii. ratio of peak height to background h/(hB_\sigma)
      iv. ratio of background to phytoplankton absorption, $(K_a + K_c) / (k \cdot <B>)$, where $<B>$ is mean biomass for water column

   a. Protocol
      i. Estimate $\Lambda = \Psi_\# L = (a^n / 4.6)I_\#$
      ii. Estimate integral from o to $z_\sigma$ of $B(z)dz$ from weighted surface-layer value, $B_\sigma$, given by satellite-borne ocean color sensor.
      iii. Estimate integral of $P(z)dz = \Lambda \text{ Integral } B(z)dz = (a^n / 4.6)I_\# \text{ Integral } B(z)dz$.
   b. Platt et al. (1988, p. 873) estimate that the relative error on water column production to be ±42%.
      Using their $P$ vs $I$ approach, and the uncertainty associated with $a^n$, the error rises to ±60%


10. Concluding remarks
    - range in variation of $\Psi$ is small, ranging from 0.29 to 0.52 g C(g Chl a)^{-1} m^{-2} (E)^{-1}.
References

SATELLITE REMOTE SENSING OF CHL A AND PRODUCTION


Baker, D. J. and W. S. Wilson. 1986. Spaceborne observations in support of earth sciences. Oceanus 29: 76. [The Nimbus-7, containing the CZCS was launched in 1978, the ocean color imager is scheduled for a mid-1990's launch]


Carder, K. L, R. G. Steward, J. H. Paul and G. A. Vargo. 1986. Relationships between chlorophyll and ocean color constituents as they affect remote-sensing reflectance models. Limnol. Oceanogr. 31: 403-413. [The algorithms for determining Chl a by satellite are reviewed and tested in several oceanic areas, including an area dominated by red tide]

Case 2 Chlorophyll a (ATBD-MOD-9). Available on the MODIS web page — see above.


Guan, F., J. Pelaezm and R. H. Stewart. 1985. The atmospheric correction and measurement of chlorophyll concentration using the coastal zone color scanner. Limnol. Oceanogr. 30: 273-285. [80-90% of the light detected by the CZCS comes from the atmosphere. A new atmospheric correction is introduced here: The method described here removes the influence of air light from the CZCS images without need of external information. The new correction scheme is based on the analysis of the error distribution.]


de LaFontaine, Y. and R. H. Peters. 1986. Empirical relationship for marine primary production to the effect of environmental variables. Oceanologica Acta 9: 65-72. [Multiple regression analysis is applied to 225 observations from 15 studies. Chl a is a relatively poor predictor of primary production. The depth of the mixed layer, surface temperature and mean light level within the mixed layer significantly contribute in reducing the variability of the production-chlorophyll relationship. The conclusions of this paper are strikingly at odds with those of Platt (1986).]


Morel, A. 1997. Consequences of a Synechococcus bloom upon the optical properties of oceanic (case 1) waters. Limnol. Oceanogr. 42: 1746-1754. [This bloom would have been difficult to detect using current algorithms, because of light absorption by accessory pigments]


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Platt, T. and S. Sathyendranath. 1988. Oceanic primary production: estimation by remote sensing at local and regional scales. Science 241: 1613-1619. [If the parameters of the P vs. I curve can be estimated, and the shape of the Chl a vs. Depth curve can be estimated, then primary production can be estimated from satellite estimates of sea-surface Chl a and light intensity.]


Smith, R. C., R. W. Eppley, and K. S. Baker. 1982. Correlation of primary production as measured aboard ship in Southern California coastal waters and as estimated from satellite chlorophyll images. Marine Biology 66: 281-288. [The difference in Chl a concentration among images in a parcel of water tracked by drogue used, with a C:Chl a ratio to estimate production.]


Yoder, J. A., S. E. Schollaert, and J. E. O'Reilly. 2002. Climatological phytoplankton chlorophyll and sea surface temperature patterns in continental shelf and slope waters off the northeastern U. S. coast. Limnol. Oceanogr. 47: 672-682.[EOF analysis of CZCS and SeaWifs data shows that the peak Chl a in the Gulf of Maine is out of phase with the mid-Atlantic bight. No major long-term changes evident] [?]Satellite remote sensing of Chl a and Production


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Figure 1. A composite CZCS-scanner image of chlorophyll $a$ concentration from the NASA EOS page: http://eospso.gsfc.nasa.gov/
Figure 2. A CZCS image of the Northeast shelf, from (http://seawifs.gsfc.nasa.gov/SEAWIFS/IMAGES/dumping1.gif). The warm and cold core rings are large mesoscale eddies created from meanders in the Gulf Stream. Cold core rings affect the nutrient dynamics of the North Atlantic gyre. As these rings decay, the flux of nitrate is increased into the euphotic zone.
Figure 3 An AVHRR image of Cape Cod on September 30, 2000. This image for temperature is updated every few hours at the Rutgers University IMCS web site. There are also daily images of Chl \( a \). The page (URL: \texttt{http://marine.rutgers.edu/mrs/newevery.fyc.html}) contains the following note: Remember! This image has been automatically moved from the satellite receiver to this homepage. There has been no human intervention. Therefore, some of the images will not be perfectly navigated with the coastline overlaid on them.
Figure 4. A map of seafloor topography based on sea-surface height (altimetry), and includes known depths to the seafloor. This image is available on the NOAA National geophysics data center web page: http://www.ngdc.noaa.gov/mgg/announcements/announce_predict.html