SATELLITE REMOTE SENSING OF CHL *a* AND PRIMARY PRODUCTION

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Assignment

Topic

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

Required papers

Perry, M. J. 1986. Assessing marine primary production from space. Bioscience *36*: 461-467.

Behrenfield, M. J. and P. G. Falkowski. 1997. Photosynthetic rates derived from satellite-based chlorophyll 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^{B}_{opt} *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

Behrenfeld, M. J., E. Boss, D. A. Siegel, and D. M. Shea. 2005. Carbon-based ocean productivity and phytoplankton 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]*

Eppley, R. W., E. Stewart, M. R. Abbott, and U. Heyman. 1985. Estimating ocean primary production from satellite chlorophyll. Introduction to regional differences and statistics for the Southern California Bight. Journal of Plankton Research *7*: 57-70.

Joint, I and S. B. Groom. 2000. Estimation of phytoplankton production from space: current status and future potential of satellite remote sensing. J. Exp. Mar. Biol Ecol. *250*: 233-255. *[Review of SeaWIFS algorithms & their use in estimating production with examples from the North Sea]* (**http://www.sciencedirect.com/science/article/B6T8F-412RP6N-D/2/c1675da3510677e9db0d1bdb6a68e782**)

Platt, T. 1986. Primary production of the ocean water column as a function of surface light intensity: algorithms for remote sensing. Deep-Sea Res. *33*: 149-163.

Platt, T. *et al.* 1988. Ocean primary production and available light: further algorithms for remote sensing. Deep-Sea Research *35*: 855-879. *[Platt shows that **Cole & Cloern's (1987)** estuarine production regression is identical to his own more general **1986 algorithm**]*

Platt, T. and S. Sathyendranath. 1988. Oceanic primary production: estimation by remote sensing at local and regional scales. Science *241*: 1613-1619.

Sathyendrenath, S., L. Watts., E. Devred, T. Platt and H. Maas. 2004. Discrimination of diatoms from other phytoplankton using ocean-colour data. Mar. Ecol. Prog. Ser. *272*: 59-68. *[Differences in absorption of diatoms vs. other organisms exploited in a bioptical model to estimate diatom standing stocks in the NW Atlantic, calibrated by HPLC.]*

Comments

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 ± 42%. Using their P *vs.* I approach, and the uncertainty associated with estimating model parameters, specifically their α^B, the error rises to ± ≈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 ($r^2 \approx 0.6$). **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 Ψ (*Psi*), a parameter related to the initial slope or α in models of the P *vs.* I relationship. Ψ 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 α (*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 peforming data interpolation, taking into account the spatial variance structure of the data. Cloutds 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 far 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 photoysnthetically 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.

Table 1. Satellite remote sensing on the world wide web.

Description	URL	Comments Ranking
NASA Global Change Home Page	**http://gcmd.gsfc.nasa.gov/**	Links to other Global Change pages pages ☆☆
NASA Earth Science Enterprise	**http://www.earth.nasa.gov**	Overview of ESE with links to other NASA web pages ☆ ☆
NASA SeaWiFS Home page	**http://seawifs.gsfc.nasa.gov/SEAWIFS.html**	Links to all SeaWiFS related pages ☆ ☆ ☆ ☆
NASA MODIS satellite	**http://modis.gsfc.nasa.gov/**	MODIS will be the key ocean color satellite after 1998. This page links to a bibliography of publications sponsored by the Modis program ☆☆
NASA JSC Image collection	**http://images.jsc.nasa.gov/**	Photographs from the space shuttle ☆

SeaWiFS and MODIS Filled Level-3 Rolling 32-Day Composites	http://oceancolor.gsfc.nasa.gov/cgi/level3_filled.pl	This month's chl a picture
NASA Goddard Space Center: Primary Productivity Research	http://opp.gsfc.nasa.gov/	Brief overview of meetings and activities, including Behrenfeld-Falkowsky & Howard-Yoder MODIS productivity maps. ✰
NOAA National Geophysical Data Center	http://www.ngdc.noaa.gov/mgg/announcements/announce_predict.html	Sea surface topography from space based on gravity anomalies - great pictures ✰ ✰ ✰
Rutgers IMCS Remote Sensing LAB	http://marine.rutgers.edu/mrs/	TOPEX Sea surface temperatures for the E. Coast, updated daily ✰ ✰ ✰ ✰
US Global Change Research Project	http://www.usgcrp.gov/	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 decateds. MODIS will be launced 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_{685}.), 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**).

SeaWiFS Sea-viewing Wide Field-of-veiw Sensor. Launched in August 1997.

TOPEX/Poseiden[**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

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

Perry, M. J. 1986. Assessing marine primary production from space. Bioscience *36*: 461-467. [?]

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.

IV. Assumptions in deriving biomass:
- A. Absorption at 550 nm is minimal
  1. phycobilliproteins (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

V. 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.

VI. 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.
  3. Association between fronts and inter-annual variability in anchovies (Lasker *et al.*, 1981)
- 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^{-1}
- C. Regional production measurements.
  1. Smith *et al.* (1985):
     - 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.
  3. **Eppley *et al.*, (1985)** analyzed the use of regression analysis and observed 2 trends.
     - 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.

Behrenfield, M. J. and P. G. Falkowski. 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnol. Oceanogr. *42*: 1-20. [3, 18, 23]

I. Abstract
- A. Development of a light-dependent, depth-resolved model for carbon fixation (VGPM)
- B. P^B_{OPT}
- C. 79% of the observed variability in P_z and 86% of the variability in PP_{eu}
- D. Variability in production due to variability in P^B_{OPT}.

II. Introduction
- A. Vertically generalized production model

III. Results

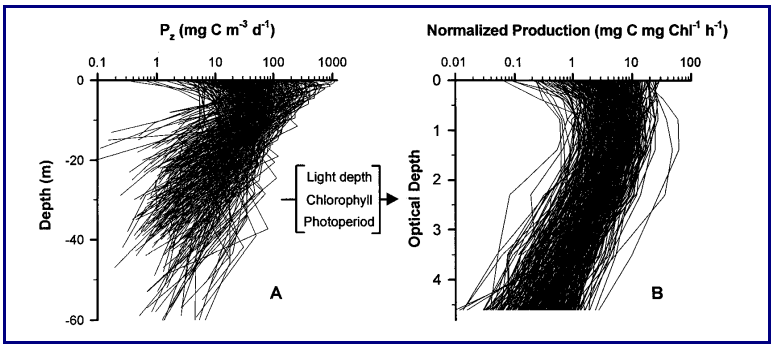


Figure 1. Normalized production vs.depth (A) and optical depth (B)

A. Ψ-type model only accounts for about 50% of the variation.

SUPPLEMENTAL

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. [?]

I. Abstract
- A. Variability in production assessed relative to environmental variables.
- B. 1057 stations from NMFS as part of MARMAP program
- C. seasonal increase in ratio of integrated productivity and surface chl., max in August, lagging insolation by 30 d.
- D. coincides with max surface water temp.
- E. surface chl correlated with
  - 1. mean euphotic chlorophyll ($r^2 = 0.93$)
  - 2. moderately correlated with productivity ($r^2 = 0.62$)
- F. improved methods of modeling photosynthetically available radiation (PAR) are needed.

II. Introduction
- A. Estimates of PP range from 20 - 55 10^9 metric tons carbon per year.
  - 1. methods may underestimate production
  - 2. shipboard observations inadequate
- B. Satellite remote sensing can alleviate problems
- C. Goals: to analyze NMFS data to assess utility of satellite chl a measures.

III. Methods
- A. 1047 stations from 41 cruises between 1977 and 1982
- B. chl a and production estimated for 2 size fractions
- C. 5-hour ^{14}C uptake experiments
- D. trapezoidal integration
- E. euphotic zone. 1% light depth.= z_e
- F. K_T (m^{-1}) = -ln [$I(z_e)/I(0)$]/z_e
- G. K_T (m^{-1}) = 4.6/z_e How did they measure z_e?
- H. C_{sat} (mg Chl *a* m^{-3}) chl a plus phaeophytin to the 37% light depth, 1 attenuation length
- I. Statistical analysis package: SAS

IV. Empirical Results:
- A. Figure 2.: chl a, C_{sat} (mg Chl *a* m^{-3}) and productivity, lognormally distributed
- B. Correlations low between C_{sat} (mg Chl *a* m^{-3}) and π (mg C m^{-2} d^{-1})
- C. Figure 5: day of the year beautiful sine wave
- D. Figure 6: C_{sat} (mg Chl *a* m^{-3}) is a variable fraction of total chlorophyll: 25% in winter 15% in summer
- E. Figure 7: π (mg C m^{-2} d^{-1}) /C_{sat} (mg Chl *a* m^{-3}) exhibits a strong seasonal pattern
- F. π (mg C m^{-2} d^{-1}) /IC a less pronounced pattern Fig. 7b.

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

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

VI. Theoretical models
A. Bannister's (1974) quantum yield
B. quantum yield = Θ = ratio of carbon mixed (as moles or mg C) per mole photons (Ein) of light absorbed by the phytoplankton. The theoretical max Θ = 0.125 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 Ψ=*Psi* = <Θ k_c>/4.6 , where k_c (z) 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_{sat} (mg Chl *a* m^{-3})
2. ability to estimate I_o from space
3. knowledge of Ψ (*Psi*)
- or more generally <Θ> and k_c
E. Estimates of Platt parameters
1. C_{sat} (mg Chl *a* m^{-3}) and IC (mean euphotic chl) correlated r^2=0.93

IC = 4.6 <C>/(K_w +k_c <C> +K_x where K_w is extinction due to water and k_x is extinction due to other substances
2. Stability of Ψ(*Psi*), no linear relationship evident
3. water column utilization index. Ψ = IP/(IC*I_o)
- 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, Ψ 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 Θ and k_c
E. The satellite algorithm (Equation 7)
IP = <Θ> <k_c>/4.6 (7)
1. thermodynamic efficiency is 0.4*$Θ_{max}$, 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;
Variance in π (mg C m^{-2} d^{-1}) due to
A. variations in rate of light absorption
B. Seasonal changes in the efficiency of light utilization with maximal quantum yield in the lower part of the euphotic zone.

Eppley, R. W., E. Stewart, M. R. Abbott, and U. Heyman. 1985. Estimating ocean primary production from satellite chlorophyll. Introduction to regional differences and statistics for the Southern California Bight. Journal of Plankton Research *7*: 57-70. (a) Abstract
B. π estimated from chl concentration
C. $_{\pi}$ (mg C m^{-2} d^{-1}) = C_k (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

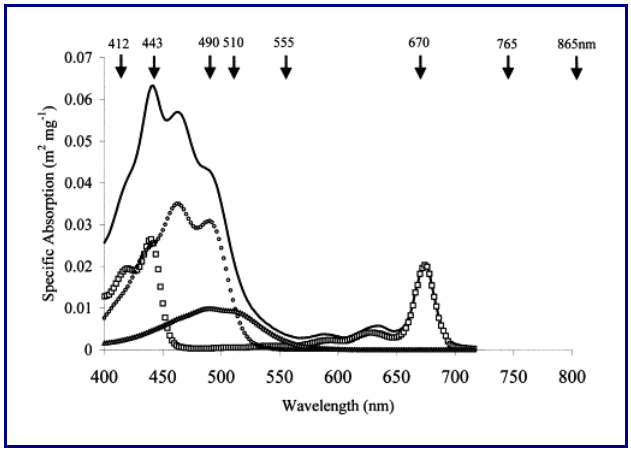
III. Methods
  A. many cruises in the SC bight
  B. definition of terms
    1. π (mg C m^{-2} d^{-1}) = water column production
    2. C_1 (chl-like pigments) and C_2 (phaeopigment.
    3. C_k (mg m^{-3}) averaged over the upper attenuation length
    4. C_0 (mg m^{-3}) refers to surface pigment
    5. C_T (mg m^{-3}) chl integrated over the euphotic zone.
    6. K_T (m^{-1}) defined using a submersed quantameter
    7. Upper attenuation length = K_T^{-1} ($m^{)}$, 4.6 attenuation lengths in the euphotic zone.
    8. F is proportionality between π (mg C m^{-2} d^{-1}) /C_k (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 π (mg C m^{-2} d^{-1}) and C_k (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. π (mg C m^{-2} d^{-1}) /C_k (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_k (mg m^{-3}) ,PTA, and daylength

V. Discussion
  A. Regional variation in F
    1. decreasing F with increasing C_k (mg m^{-3})
    2. differences in regional estimates of F due to differential absorption by phytoplankton and water (turbidity)
  B. Variability of π (mg C m^{-2} d^{-1}) in the SCBS cruises
    1. most of the variability due to C_k (mg m^{-3})
    2. other problems
      a. C_k (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.

Joint, I and S. B. Groom. 2000. Estimation of phytoplankton production from space: current status and future potential of satellite remote sensing. J. Exp. Mar. Biol Ecol. 250: 233-255. [Review of SeaWIFS algorithms & their use in estimating production] (**http://www.sciencedirect.com/science/article/B6T8F-412RP6N-D/2/c1675da3510677e9db0d1bdb6a68e782**)

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



Joint & Groom Fig. 1

Platt, T. and S. Sathyendranath. 1988. Oceanic primary production: estimation by remote sensing at local and regional scales. Science *241*: 1613-1619.[3]

1. Abstract
   a. Problem in applied plant physiology
   b. dynamic biogeography needed
2. Introduction
   a. Global production 5 x 10^{16} g Carbon/year (J. Martin 1987)
   b. Problems with conventional methodsslow cruising speeds
      i. inadequate spatial resolution
   c. CZCS
      i. synoptic sampling
      ii. Samples upper attenuation length
      iii. 2 algorithms available to convert optical signal to chl a concentration.
3. The Local algorithm for primary production.
   a. Determination of primary production at regional scales has 2 parts
      i. develop a local algorithm
      ii. extrapolate results to larger scales.
   b. Use the generalized P *vs.* I relationship:

$$P^B = p(I;\ \alpha^B\ ,\ P^B{}_m) \qquad (1)$$

   c. A complication is that the photosynthetic pigments influence the intensity and quality of the submarine light filed (Sathyendranath & Platt, In press)
   d. *The irradiance field*

i. calculation of downwelling irradiance
ii. Equations 2-5 calculate $_{Iz}$

e. *The primary production model*
i. Equations 6-9 calculate the P *vs.* I curve
ii. $\alpha(\lambda)$ is the photosynthetic action spectrum.
iii. $\Pi(z)=\text{Integral } (\alpha(z,\lambda)\{I_d(z,\lambda,\theta_d)\sec\theta_d+1.20\ I_s(z,\lambda)\}d\lambda$ (9)

where λ= 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**:

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

$$\begin{aligned} \textit{where, } B_o &= \textit{background or baseline pigment} \\ z_m &= \textit{the depth of chl. maximum} \\ \sigma &= \textit{defines breadth of peak} \\ h\left[\frac{mg\,\text{Chl}\,a}{m^2}\right] &= \textit{total biomass above background.} \end{aligned} \qquad (10)$$

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:
a. Example for 20°S to 50°N in September 1979.
b. primary production calculated for 3800 grid points

Fig. 4. Estimation of water column primary production 4b ocean divided into grids. 4 d 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. Ψ has the same dimensions as α
ii. Ψ 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 α 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.

Platt, T. *et al.* 1988. Ocean primary production and available light: further algorithms for remote sensing. Deep-Sea Research *35*: 855-879. [3]

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. Λ = normalized integrated production (integrated over the photic zone)
i. Λ is a linear function of I_o with slope Ψ
ii. Ψ is proportional to α^B of the P *vs.* I curve
b. errors expressible in terms of $I_* = I_o / I_k$, where I_k is derived from the P *vs.* I curve.
i. $I_k = P^B_m / \alpha^B$, where P^B_m is the assimilation number.
ii. errors relatively slight and could be calculated, given I_k

4. Further empirical evidence:
a. Jacques and Minas (1981); Collos and Slawyk (1986)
b. Bruno, Staker and Sharma (1980)
c. **Cole and Cloern (1987)**
i. Regression *vs.* Bz_pI_o
ii. Their procedure is exactly equivalent to the one followed by **Platt (1986)**
iii. The product Bz_p is simply euphotic zone biomass. Equivalent to a regression of Λ on I_o 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
j. Malone (1976) and Falkowski (1981)

5. Departure from linearity at low light.

6. Integral from of photosynthesis-light models: general properties
   a. Platt *et al.* (1988) Formal relationship between α^B and quantum yield

$$\alpha^B = \Phi_m k_c \quad (8)$$

   where, k_c is the chl-specific attenuation coefficient
   b. Kiefer & Mitchell (1983) model:

$$\mu = k_c \rho I \Phi \quad (9)$$

   where, ρ is carbon:chl ratio, Φ is a function expressing decrease in quantum yield as light level increases

$$\Phi = \Phi_m K_\Phi / (K_\Phi + I) \quad (10)$$

   where, K_Φ is a fitting parameter
   c. The Kiefer-Mitchell model is merely a Michaelis-Menten model:

$$P = \frac{P_m I}{I_k + I} \quad (13)$$

   d. Formulations of relationship between plankton photosynthesis and available light in terms of quantum yield are equivalent to those in terms of α
7. Error in estimation of areal production arising from non-uniform biomass profile
   a. Generalized pigment profile:

$$B(z) = B_o + \left(\frac{h}{\sigma\sqrt{2\pi}}\right) \exp\left[\frac{-(z-z_m)^2}{2\sigma^2}\right] \quad (14)$$

   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_p
      ii. width of peak relative to euphotic depth σ / z_p
      iii. ratio of peak height to background $h/(\sigma B_o)$
      iv. ratio of background to phytoplankton absorption, $(K_w + K_z)/(k_c \langle B \rangle)$, where $\langle B \rangle$ is mean biomass for water column
8. Random errors in estimation of water column production by remote sensing.
   a. Protocol
      i. Estimate $\Lambda = \Psi I_o = (\alpha^B / 4.6) I_o$
      ii. Estimate Integral from o to z_p of B(z)dz from weighted surface-layer value, B_s, given by satellite-borne ocean color sensor.
      iii. Estimate integral of P(z)dz=Λ Integral B(z)dz=$(\alpha^B / 4.6) I_o$ 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 α^B, the error rises to ± ≈60%
9. Systematic errors in estimation of primary production using satellite-weighted chlorophyll concentration.
10. Concluding remarks

-range in variation of Ψ is small, ranging from 0.29 to 0.52 g C(g Chl *a*)$^{-1}$ m^2 (E)$^{-1}$.

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SATELLITE REMOTE SENSING OF CHL A AND PRODUCTION

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MISCELLANEOUS

Behrenfeld, M. J. and P. G. Falkowski. 1997. A consumer's guide to phytoplankton productivity models. Limnol. Oceanogr. 42: 1479-1491. *[Reviews the major classes of P vs. I models for estimating production.]{**3**, **18**, **23** }*

Cole, B. E. and J. E. Cloern. 1987. An empirical model for estimating phytoplankton productivity in estuaries. Mar. Ecol. Prog. Ser. *36*: 299-305. *[Primary production is proportional to Chl a conc, euphotic zone depth, and light intensity.]* {**3**, **5**, **15**, **20**, **25**, **26**}

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Harrison, W. G. and T. Platt. 1986. Photosynthesis-irradiance relationships in polar and temperate phytoplankton populations. Polar Biology *5*: 153-164. *[P* vs. *I parameters from dozens of studies compiled and regressed against environmental variables. Assimilation number increases with temperature. Little correlation between photosynthetic rate parameters and external nutrient concentration]* {?}

Kelly, J. R. and P. H. Doering. 1997. Monitoring and modeling primary production in coastal waters: studies in Massachusetts Bay 1992-1994. Mar. Ecol. Prog. Ser. *148*: 155-168. *[Three years of monitoring data are described and fit to the **Cole & Cloern (1987)** BZI model]{?}*

Peterson, B. 1980. Aquatic primary productivity and the ^{14}C-CO_2 method: a history of the productivity problem. Ann. Rev. Ecol. Syst. *11*: 359-385. *[Reviews the great debate in biological oceanography: Does the ^{14}C method underestimate production, especially in the gyres?]* {3}

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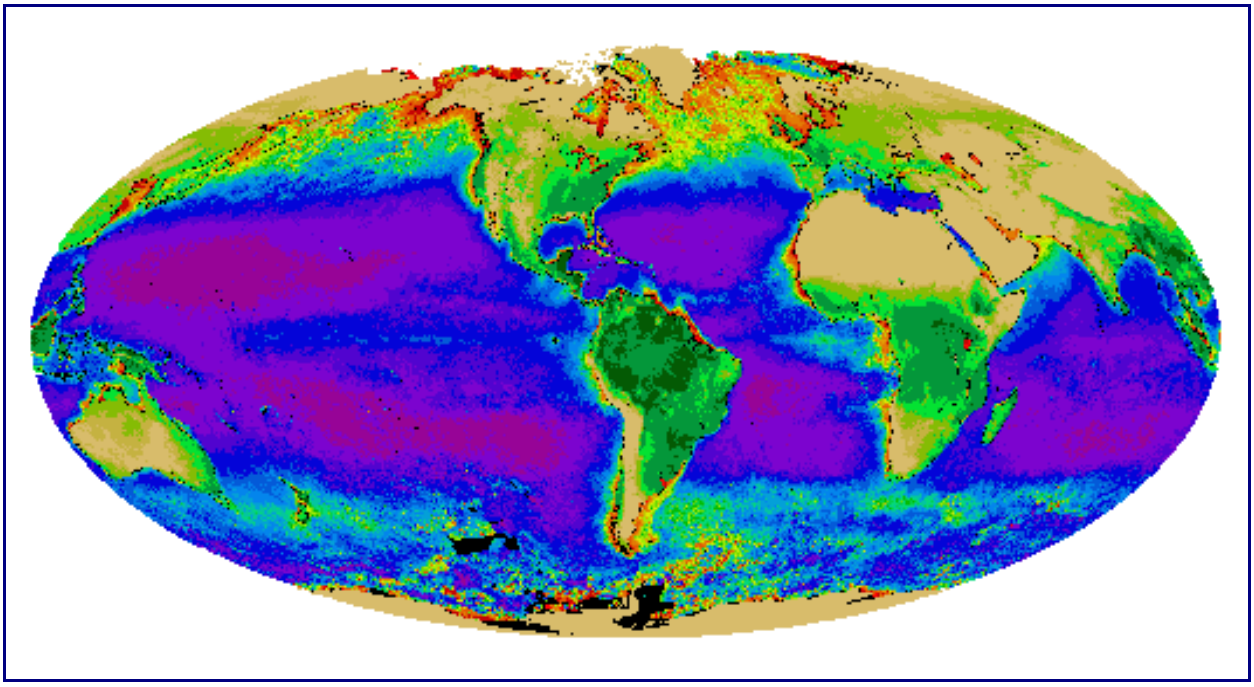

Figure 1. A composite CZCS-scanner image of chlorophyll *a* concentration from the NASA EOS page: **http://eospso.gsfc.nasa.gov/**

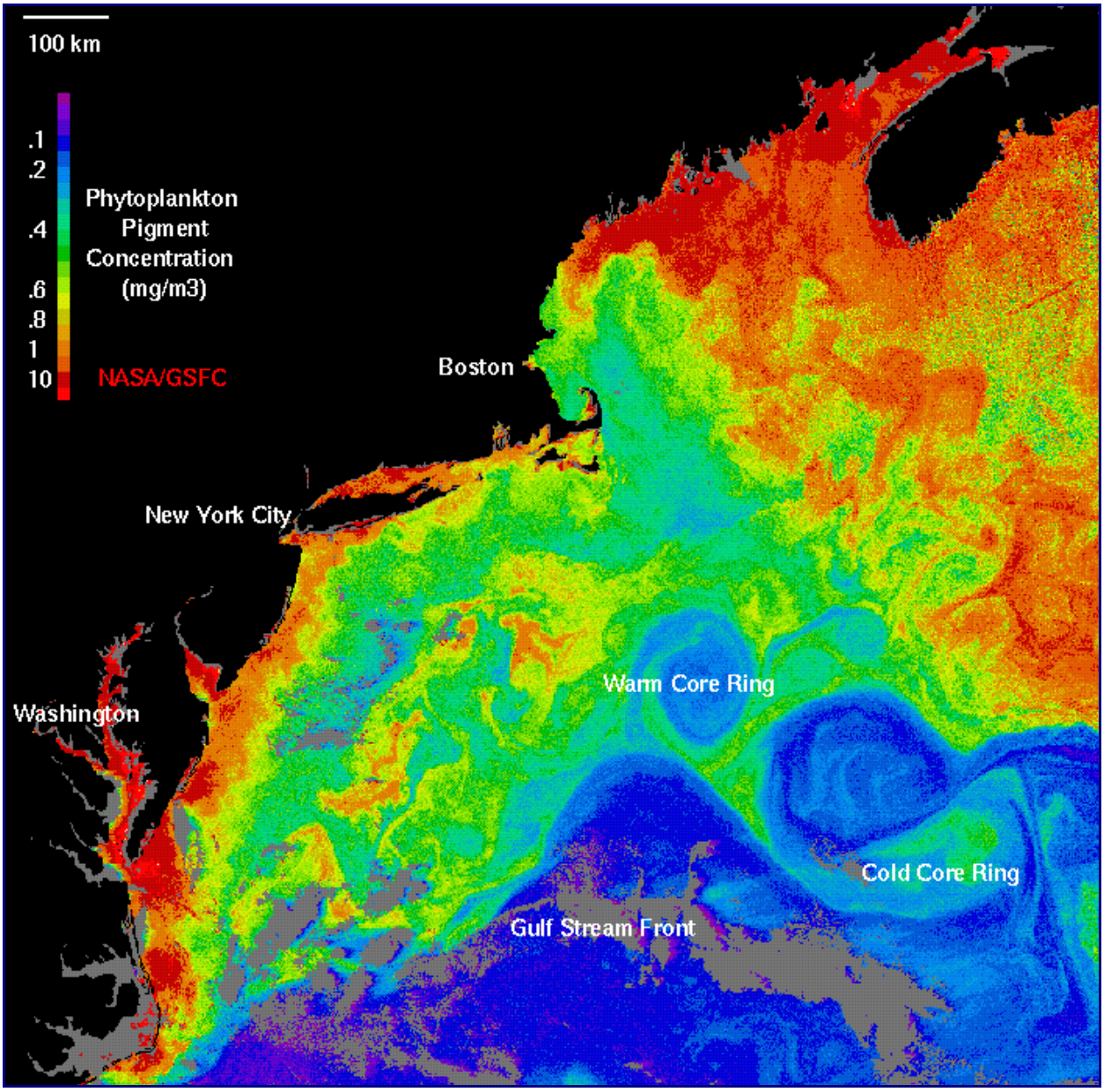

Figure 2. A CZCS image of the Northeast shelf, from (**http://seawifs.gsfc.nasa.gov/SEAWIFS/IMAGES/dumping1.gif**). The warm and cold core rings are large mesoscale eddies created from meanders in the Gulf Stream. Cold core rings affect the nutrient dynamics of the North Atlantic gyre. As these rings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

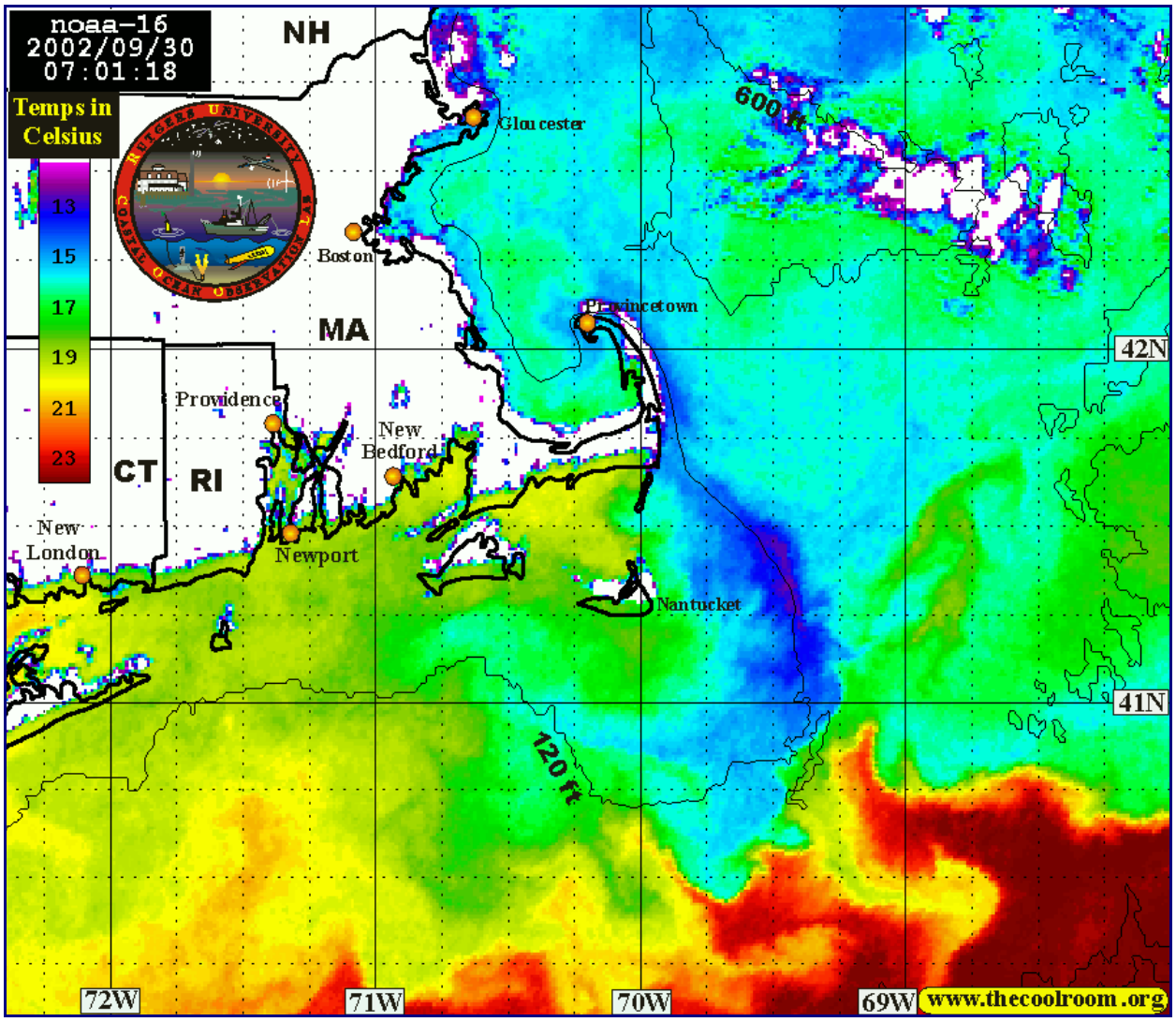

Figure 3 An **AVHRR** image of Cape Cod on September 30, 2000. This image for temperature is updated every few hours at the Rutgers University IMCS web site. There are also daily images of Chl *a*. The page (URL: **http://marine.rutgers.edu/mrs/newevery.fyc.html**) contains the following note: Remember! 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.

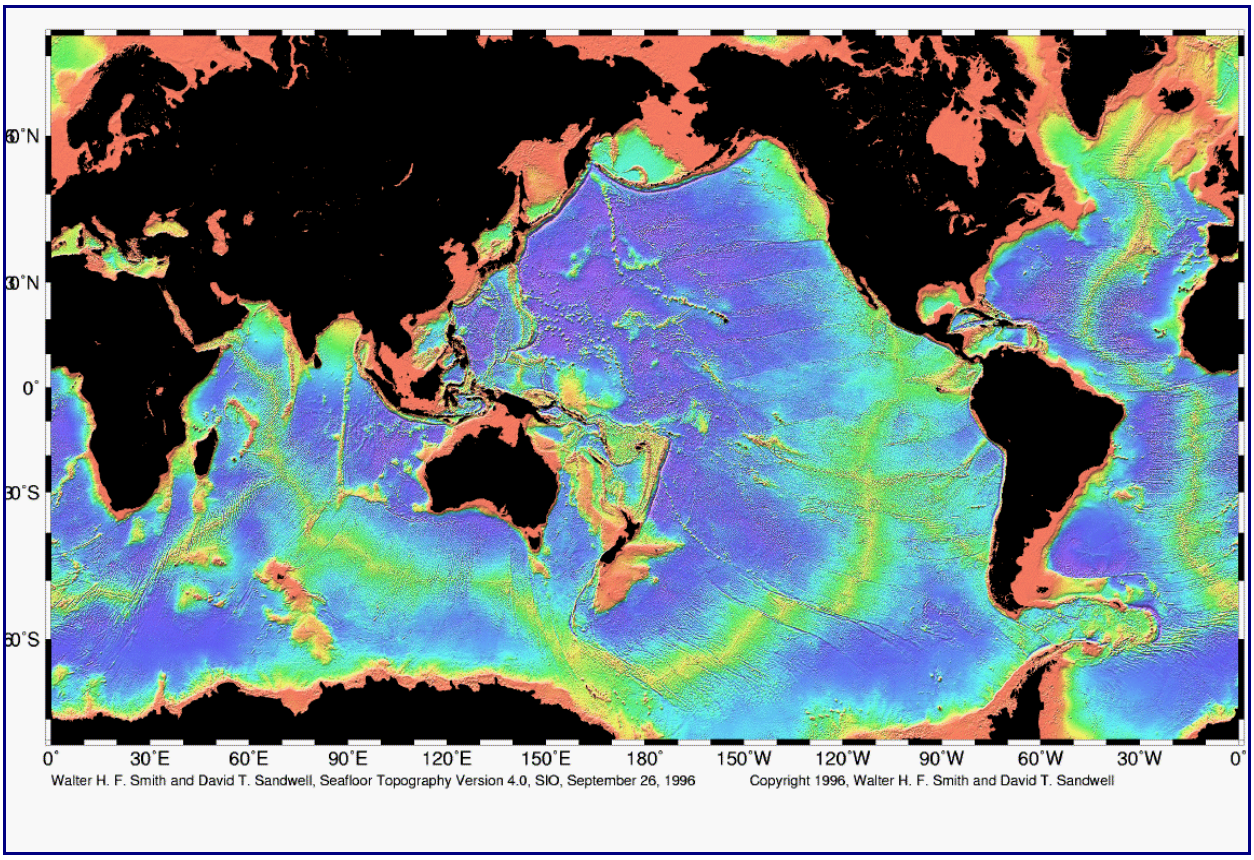

Figure 4. A map of seafloor topography based on sea-surface height (altimetry), and includes known depths to the seafloor. This image is available on the NOAA National geophysics data center web page: **http://www.ngdc.noaa.gov/mgg/announcements/announce_predict.html**