Computation of Primary Production
The pelagic ecosystem is an open, dissipative system sustained by regular energy supply from sun, to which it is coupled through the pigment molecules contained in phytoplankton. The light penetrating into the ocean allows biogeochemistry, where otherwise only geochemistry would be possible.

Furthermore, the light that escapes from the ocean (the basis of the ocean-colour signal), carries coded information on ocean biology and biogeochemistry.
A major product of ocean-colour remote sensing is distribution of chlorophyll concentration, the most fundamental property of the ocean ecosystem. It has been designated an Essential Climate Variable (UNFCCC).

The maps are strikingly beautiful. Furthermore, they are based on strict radiative transfer theory, and contain a wealth of information, with many applications.

The technique exploits the absorption of light by the pigment. What happens to the absorbed light? One pathway for the absorbed light is photosynthesis (primary production).
What is Plankton Biomass?

Biomass of plankton is its local abundance. The equivalent term in fisheries is the stock size. For phytoplankton the index is concentration of chlorophyll.
What is Primary Production?

Primary production is the rate of production of phytoplankton. The equivalent term in fisheries is reproduction and growth. If biomass like money in the bank, primary production is like the interest earned by the capital.
The Photosynthesis Equation

\[ \text{H}_2\text{O} + \text{CO}_2 + \text{Available Energy} \rightarrow \text{CH}_2\text{O} + \text{O}_2 + \text{Dissipated Energy} \]

Chlorophyll-a is at the heart of the photosynthetic reaction.
Growth Requirements of Phytoplankton

The growth requirements of phytoplankton are similar to those of any green plant:

- Water
- Carbon dioxide
- Visible light
- Chemical nutrients (nitrogen, phosphorus, … often in short supply)
Primary production varies with region and season, because of changes in those factors essential for phytoplankton growth. These include

- the phytoplankton biomass;
- the intensity and duration of sunshine;
- the intensity of turbulence in the water;
- the concentration of certain chemicals (nutrients) in the water;
- the temperature;
- the kinds of phytoplankton present.
What is the fate of primary production?

Phytoplankton may be lost (erosion of capital) by a number of mechanisms

• They may sink to the bottom;
• They may be swept away by currents;
• They might die from disease;
• They may be eaten.
Oceanic CO2 Pools and Fluxes (Global)

- Surface biota ~ 3 GT C
- Globally, some 50 GT of carbon fixed by marine phytoplankton per annum
- About one third (~16 GT of carbon) is exported from surface layer by sinking

  Biological Pump

- Scales of comparison:
  
  Fossil fuel emissions are ~10 GT of carbon per annum

  Net primary production by terrestrial plants is considered to be roughly the same as marine primary production
CO₂ uptake and release

Time for return to atmosphere: days-months
years-centuries

Photosynthesis
Primary & secondary production; microbial recycling
Respiration

Euphotic zone: 0-200m
Upwelling & diffusion

Thermocline

Terrestrial inputs of DOC and POC

DOC Diss CO₂, HCO₃⁻

POC

DEEP OCEAN

Accumulation in sediments

Respiration & decomposition; transport in deep ocean

Net accumulation?
Determinants of Primary Production

First-order:
- Light
- Pigment Concentration

Second-order:
- Nutrients
- Temperature
- Community structure (cell size, taxa);
- Growth history (light; temperature)
- Stratification/ Vertical mixing
PHOTOSYNTHESIS-IRRADIANCE CURVE

\[ P^B \]

\[ R^B \]

\[ I_c \]

\[ I_k \]

\[ \tan^{-1}(\alpha^B) \]

\[ p^B \]

\[ p^B_m \]

\[ I \]
Inherent spectral optical properties of seawater and its contents

Absorption ($a$)  
Back-scattering ($b_b$)

Seawater (w)

Phytoplankton (B)

Yellow substances (Y)

Non-chlorophyllous particles (X)

Light penetration underwater is influenced by the inherent optical properties and by the angular distribution of light underwater:

$$K = f (a, b_b, \mu_d)$$

where $K$ is the diffuse attenuation coefficient for downwelling light.

Both absorption and back-scattering can be expressed as sum of contributions from individual constituents.

Both absorption and back-scattering vary spectrally in a characteristic manner.
Light Absorbed by Phytoplankton at 1% Light Level

\[ \int I(\lambda) \, d\lambda = 1 \]
\[ a(\lambda) = 1 \]

Chl (mg m\(^{-3}\)) above 1% light level

- **Diatoms**
- **Prymnesiophytes**
- **Cyanobacteria**
- Chlorophytes
- **Prochlorococcus sp**
Vertical Structure in Chlorophyll Concentration

It is also necessary to account for the vertical structure in chlorophyll concentration.

The simplest representation of chlorophyll peaks (for application in primary production studies) is as a Gaussian peak superimposed on a constant background.
**Remote Sensing Algorithm**

\[
\frac{R(\lambda_1)}{R(\lambda_2)} = f(\text{chlorophyll})
\]

**Absorption Spectrum for Phytoplankton**

**Weighting Function**

\[
f(z) = e^{-2 \int_{0}^{z} K(z') \, dz'}
\]

**Effective Biomass Concentration**

\[
B(s) = \frac{\int_{0}^{\lambda_k} B(z) \, f(z) \, dz}{\int_{0}^{\lambda_k} f(z) \, dz}
\]

Effective biomass ("satellite chlorophyll") is a weighted function of actual biomass.
Computation of primary production

Irradiance outside atmosphere

Surface Biomass
- Biomass profile parameters

Surface Irradiance
- Light penetration model
- Photosynthesis-light model

Irradiance at depth

Primary production at depth
- Photosynthetic parameters

Atmospheric transmission model

Sathyendranath and Platt (1989)
Goal: To estimate the daily primary production of the ocean water column

\[ P = P(I) \]

\[ I = I(z) = I_0 e^{-Kz} \]

\[ I_0 = I_0(t) \]

\[ P(I(z, t)) \]

\[ P_{z,T} = \int_0^D \int_0^\infty P(z, t) \, dz \, dt \]
INTEGRATED PRODUCTION

\[ \int_{0}^{z} P \, dz \]

mg C m\(^{-2}\) d\(^{-1}\)

CALCULATED

MEASURED

- CARIBBEAN
- EASTERN ARCTIC
- GRAND BANKS
- N. SARGASSO SEA
- NEW ENGLAND SEAMOUNTS
Basic Methodology for Computation of Primary Production

1. Compute light just below the sea surface
2. Estimate biomass at the surface
3. Define the biomass profile
4. Estimate parameters of the photosynthesis-light model
5. Compute parameters of light transmission underwater
6. Compute water-column primary production
Primary Production at Regional Scale

Computation of primary production at regional scale has two components:

1. Construct local algorithm, assuming all necessary information will be available.

2. Establish protocol for extrapolation of local algorithm to larger scale.
Assignment of Parameters for Computation of Primary Production

The model is robust, but needs a protocol for assignment of parameters relating to

(1) photosynthetic response; and

(2) vertical structure.

The protocol uses remotely-sensed data as input

Platt et al. (2008)
Computed Global Primary Production

May 2004, using OC-CCI data
Utility of Remote Sensing
For Estimation of Oceanic Primary Production

Primary production $P$ can be written as the product of production per unit chlorophyll concentration $P^B$ and the chlorophyll concentration $B$.

$$P = P^B \times B$$

- Effect of environmental conditions (light, temperature, nutrients ...) on primary production is contained explicitly (light) or implicitly (through model parameters) in the chlorophyll-normalised term.

- Chlorophyll concentration has a dynamic range of more than four decades.

- Remote sensing method is an extrapolation tool, which:
  - Uses all available ship data to define model parameters
  - Uses the satellite data to input the state variable (chlorophyll) and the forcing field (light)
  - Sees the ship and satellite as complementary tools
  - It is the method of choice
Measurement of Instantaneous Rates

Dimensions
The dimensions of a rate quantity include time in the denominator

Applicability
The intrinsic time scale for the method, or the time scale on which the results can be expected to apply, is related to the duration of measurement
<table>
<thead>
<tr>
<th>Method</th>
<th>Nominal component of production</th>
<th>Nominal time-scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In vitro</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{14}\text{C}) assimilation</td>
<td>(P_T \ (\equiv P_n))</td>
<td>Hours to 1 d</td>
</tr>
<tr>
<td>(^{15}\text{N} \text{O}_3) assimilation</td>
<td>(P_T)</td>
<td>Hours to 1 d</td>
</tr>
<tr>
<td>(^{15}\text{NH}_4) assimilation</td>
<td>(P_{\text{new}})</td>
<td>Hours to 1 d</td>
</tr>
<tr>
<td>(^{18}\text{O}_2) evolution</td>
<td>(P_T)</td>
<td>Hours to 1 d</td>
</tr>
<tr>
<td></td>
<td>(P_{\text{new}} \ (\equiv P_c))</td>
<td>Hours to 1 d</td>
</tr>
<tr>
<td><strong>Bulk property</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{238}\text{U} / {^{234}}\text{Th})</td>
<td>(P_{\text{new}})</td>
<td>Hours to days</td>
</tr>
<tr>
<td>(^3\text{H} / {^3}\text{He})</td>
<td>(P_{\text{new}})</td>
<td>Seasonal to annual</td>
</tr>
<tr>
<td>(^{2} \text{O}_2) flux to photic zone</td>
<td>(P_{\text{new}})</td>
<td>Seasonal to annual</td>
</tr>
<tr>
<td>(^{2} \text{O}_2) utilization rate OUR below photic zone</td>
<td>(P_{\text{new}})</td>
<td>1d to 300d</td>
</tr>
<tr>
<td>Net (^{2} \text{O}_2) accumulation in photic zone</td>
<td>(P_{\text{new}})</td>
<td>Seasonal and longer</td>
</tr>
<tr>
<td><strong>Optical</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double-flash fluorescence</td>
<td>(P_T)</td>
<td>&lt; 1 s</td>
</tr>
<tr>
<td>Passive fluorescence</td>
<td>(P_T)</td>
<td>&lt; 1 s</td>
</tr>
<tr>
<td>Remote Sensing</td>
<td>(P_T, P_{\text{new}})</td>
<td>Days to annual</td>
</tr>
<tr>
<td><strong>Upper and lower limits</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sedimentation rate below photic zone</td>
<td>(P_{\text{new}} \ (\equiv P_c)): (lower limit)</td>
<td>Days to months</td>
</tr>
<tr>
<td>Optimal conversion of photons absorbed</td>
<td>(P_T) (upper limit)</td>
<td>Any</td>
</tr>
<tr>
<td>Depletion of winter accumulation of (^{2} \text{O}_3)</td>
<td>(P_{\text{new}}) (lower limit)</td>
<td>Seasonal</td>
</tr>
</tbody>
</table>
Problems with Validation

1. No independent method available for comparison. Remote-sensing approach uses all available data, from ship as well as from satellite.

2. Comparison with bulk-property, or indirect, methods compromised by incompatibility of time scales. Further, bulk-property methods and in vitro incubation methods (used to derive photosynthesis parameters) address different components of primary production.

3. Validation by prediction of biomass at some future time requires information on loss terms and on flow field: these are usually unavailable.
Examine precision of each element of the calculation separately:

1. Surface irradiance $\sim 10\%$
2. Satellite-derived biomass $\sim 35\%$
3. Photosynthesis parameters
   a. Measurement error $\sim 5\%$ for $P_m^B$ and $\sim 20\%$ for $\alpha^B$
   b. Error arising from aggregation within domains $\sim 7\%$
4. Vertical profile shape $\leq 10\%$ at the basin scale

The local algorithm for the vertically-uniform, nonspectral model has an estimated precision of $\sim 42\%$ (compounding of errors 1, 2, and 3a).

Combining with the aggregation error (3b) gives a best-case estimate of $\sim 50\%$ for the precision of a primary-production estimate in a spatially-extrapolated calculation.
Monthly time Series of Primary production

Total monthly primary production (Gt C)

(using OC-CCI chlorophyll data and NASA data on surface light)
Do we have “representational” error here when looking at “trends”? Satellite coverage improved in 2002.

What about effect of inter-annual environmental variability on photosynthesis parameters? (Not accounted in this calculation)
Three different methods for assigning Assimilation Number Province-based (no interannual variation)

Nearest Neighbour Method (Platt et al. 2008) based on temperature and chlorophyll

Dynamic assignment based on chlorophyll, temperature and light (Saux-Picart et al. 2013)

This is a challenging area of research where progress has to be made
In Conclusion

1. Remote sensing provides much of the information essential for computing primary production at large scales.

2. Potential exists for assigning parameters of the photosynthesis-irradiance curve using satellite data. This should be a priority for research.

3. Important to maintain a long time series of consistent ocean-colour data to study responses of marine primary production to climate variability and change.
Basic Set of Parameters Needed in Primary Production Models

- Initial slope of photosynthesis-irradiance curve
- Assimilation number of photosynthesis-irradiance curve
- Specific absorption coefficient of phytoplankton
- Carbon-to-chlorophyll ratio of phytoplankton

Of these, the carbon-to-chlorophyll ratio is the property we know the least about.

Carbon-to-chlorophyll ratio is invoked when fields of phytoplankton carbon computed in biogeochemical models are converted to fields of chlorophyll-a, for comparison with satellite data.

Sathyendranath et al. 2009