Measuring light and the optical properties of seawater to study plankton communities

Benedetto Barone

Center for Microbial Oceanography: Research and Education
University of Hawaii

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Outline

1. Photons in the sea
2. Diffuse attenuation
3. Light absorption
4. Light scattering
Current section

1. Photons in the sea

2. Diffuse attenuation

3. Light absorption

4. Light scattering
Light at the sea surface

**Light**: electromagnetic radiation between 400 and 700 nm

Average fate of radiant flux on northern hemisphere:
- 34% reflected to space
- 19% absorbed by atmosphere
- 47% reaches Earth's surface

The spectrum of sunlight on a plane perpendicular to the direction to the sun, outside the earth's atmosphere. Adapted from Bjorn (2008).
Measures of light intensity and direction

Photons propagate in different directions. Different quantities can describe light intensity including more or less information about its direction.

- **Radiance**, $L$: radiant flux in a given direction (per unit area per unit solid angle)
- **Downward Irradiance**, $E_d$: radiant flux on a surface due to downwelling light (per unit area)
- **Scalar Irradiance**, $E_0$: radiant flux arriving at a point from all direction (per unit area)

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Photons in the sea

The fate of a photon

Not only particles, but also seawater scatters and absorbs light

Adapted from Boss et al. (2004)
Kinds of scattering

- **Rayleigh scattering**: electrical interaction with single molecules $\propto \lambda^{-4}$
  (in the atmosphere, symmetrical)

- **Einstein-Smoluchowski scattering**: microscopic fluctuations of density $\propto \lambda^{-4.3}$
  (in liquids, symmetrical)

- **Mie scattering**: interaction with particles
  (for particles, asymmetrical)

Adapted from Falkowski & Raven, 2007
Why do we care?

- **Light penetration**: defines the layer where photobiological processes take place
- **Light color**: define niches for different organisms
- **Light absorption**: changes based on the community composition
- **Light scattering**: changes based on particle abundance
- **Scattering angular distribution**: changes based on particle size structure
Inherent & Apparent Optical Properties

**Inherent Optical Properties**: their magnitude does not depend on the direction of light, but only on the substances comprising the aquatic medium

- absorption coefficient, \( a \)
- scattering coefficient, \( b \)
- beam attenuation coefficient, \( c = a + b \)

**Apparent Optical Properties**: they depend on the geometric structure of the light field

- Light diffuse attenuation coefficient, \( K_d \)
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Light decreases exponentially with depth:

\[ E_d(z, \lambda) = E_d(0, \lambda) e^{-K_d(\lambda)z} \]

Different wavelengths are attenuated differently:

- **Blue dominance**: oligotrophic waters
- **Green dominance**: more productive waters

The change in color creates niches for different organisms
Photosynthetically Available Radiation

PAR is the fraction of the spectrum that can promote photochemical charge separation. (Operationally is 400-700 nm)

Optical classification of waters:

- **Case I**: phytoplankton and their products determine light attenuation
- **Case II**: important contribution by other components (sediment, river run-off . . . )

Is station ALOHA Case I?
PAR and DCM dynamics

Adapted from Letelier et al. (2004)
How will we measure light in the seawater?

Profiling radiometer

Main measurements (350-800 nm):
- Downwelling Irradiance, Ed
- Upwelling Radiance, Lu

Accessory measurements:
- Temperature, Salinity and Pressure
- Chlorophyll fluorescence
Diffuse attenuation

Example: light spectra at St. ALOHA, in summer

- Narrow Irradiance maximum around 475 nm, below 100 meters
- Increased light attenuation with depth, particularly blue/violet
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Absorption by different components

Different components contribute to absorption:

- **Water**: red-green
- **Phytoplankton**: blue-green
- **CDOM**: low wavelengths
- **Detritus**: low wavelengths

Reproduced from Nelson & Siegel, 2012 (data from the surface of global ocean)
Chromophoric Dissolved Organic Matter

CDOM is the most important component regulating light absorption

- **Main Source**: microbial degradation of organic matter
- **Main Sink**: photobleaching
- **Molecular structure**: uncertain

Adapted from Swan et al. (2009)
Hemispheric asymmetry of CDOM distribution

Distribution of CDOM in the Pacific Ocean, adapted from Nelson & Siegel (2013)
Water color in the South Pacific

Light absorption

Optical properties of the “clearest” natural waters

André Morel, Bernard Gentili, Hervé Claustre, Marcel Babin, Annick Bricaud, Joséphine Ras, and Fanny Tièche
Laboratoire d’Océanographie de Villefranche, Université Pierre et Marie Curie and CNRS, F-06238 Villefranche-sur-mer, CEDEX, France

Consequences of low CDOM:
- Very low light attenuation
- Water becomes more violet
How will we measure light absorption?

In-situ spectrophotometer

Main measurements (400-730 nm):
- absorption coefficient, $a$
- attenuation coefficient, $c$

Accessory measurements:
- Temperature, Salinity and Pressure
- Chlorophyll fluorescence

By applying filters or not:
- Filtered sea-water absorption
- Total sea-water absorption
Retrieving particle absorption

Method:
- Subtract filtered seawater signal from total signal
- Correct for scattering and residual temperature difference
Chromatic adaptation

- Photoadaptation to dominant wavelengths at high depths
- Higher blue/red absorption ratio at the surface
Estimation of chlorophylls from red absorption

From pigment absorption spectra

Fit on data from Bidigare et al. (1990) [600–750 nm]

To local pigment concentration

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Bio-optics in oceanography

3 June 2013 23 / 33
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Factors determining scattering intensity

Particle characteristics influencing scattering intensity:
- Concentration
- Size distribution
- Shape
- Refractive index
Beam attenuation coefficient at 660 nm

Characteristics of c(660):
- Not influenced by CDOM absorption
- Negligible particle absorption
- Influenced by 0.5 - 20 µm particle abundance

Use of $c_p(660)$ as a proxy of POC:
- Linear relationship between $c_p$ and POC
- $c_p$ influenced by phytoplankton size range

Adapted from Gardner et al., 2006
Example: vertical and temporal variability of POC

- High temporal variability in an oligotrophic environment
- Particle accumulation below the mixed layer
Other uses of $c_p(660)$

To estimate community production
- Diel cycle of $c_p$

To assess photophysiological state
- $c_p^* = c_p/\text{[chl]}$
- $c_p^*$ correlated to $P_{opt}^b$ and $E_k$

Adapted from Claustre et al. (2008)
Adapted from Behrenfeld and Boss (2003)
Scattering and particle size structure

- Particles of different size scatter light at different angles
- From scattering angles to particle size
  - Spherical particles
  - Constant refractive index
Functioning of LISST-100X

Laser In-Situ Scattering and Transmissometry

- Laser emission (670nm)
- Multi-ring detector (0.1-19.5°)

Output:
- Particle size distribution in the 1.25 to 250 μm range

From LISST manual version 4.65
Example: vertical profiles of particle abundance

Vertical distribution of particle fractions:
- 1-2 $\mu m$ size: maximum at the DCM
- 2-20 $\mu m$ size: decreases below 60 m
- > 100 $\mu m$ size: peak below the mixed layer
The small particle maximum follows the depth of the DCM