6.10: Light in the Ocean and Absorption of Light

Sunlight in the ocean is important for many reasons: It heats sea water, warming the surface layers; it provides energy required by phytoplankton; it is used for navigation by animals near the surface; and reflected subsurface light is used for mapping chlorophyll concentration from space.

Light in the ocean travels at a velocity equal to the velocity of light in a vacuum divided by the index of refraction (n), which is typically $n = 1.33$. Hence the velocity in water is about 2.25×10^8 m/s. Because light travels slower in water than in air, some light is reflected at the sea surface. For light shining straight down on the sea, the reflectivity is $(n-1)^2/(n+1)^2$. For seawater, the reflectivity is $0.02 = 2\%$. Hence most sunlight reaching the sea surface is transmitted into the sea, little is reflected. This means that sunlight incident on the ocean in the tropics is mostly absorbed below the sea surface.

The rate at which sunlight is attenuated determines the depth which is lighted and heated by the sun. Attenuation is due to absorption by pigments and scattering by molecules and particles. Attenuation depends on wavelength. Blue light is absorbed least, red light is absorbed most strongly. Attenuation per unit distance is proportional to the radiance or the irradiance of light:

$$\frac{dI}{dx} = -cI$$

where x is the distance along beam, c is an attenuation coefficient (figure $6.10.1$), and I is irradiance or radiance.

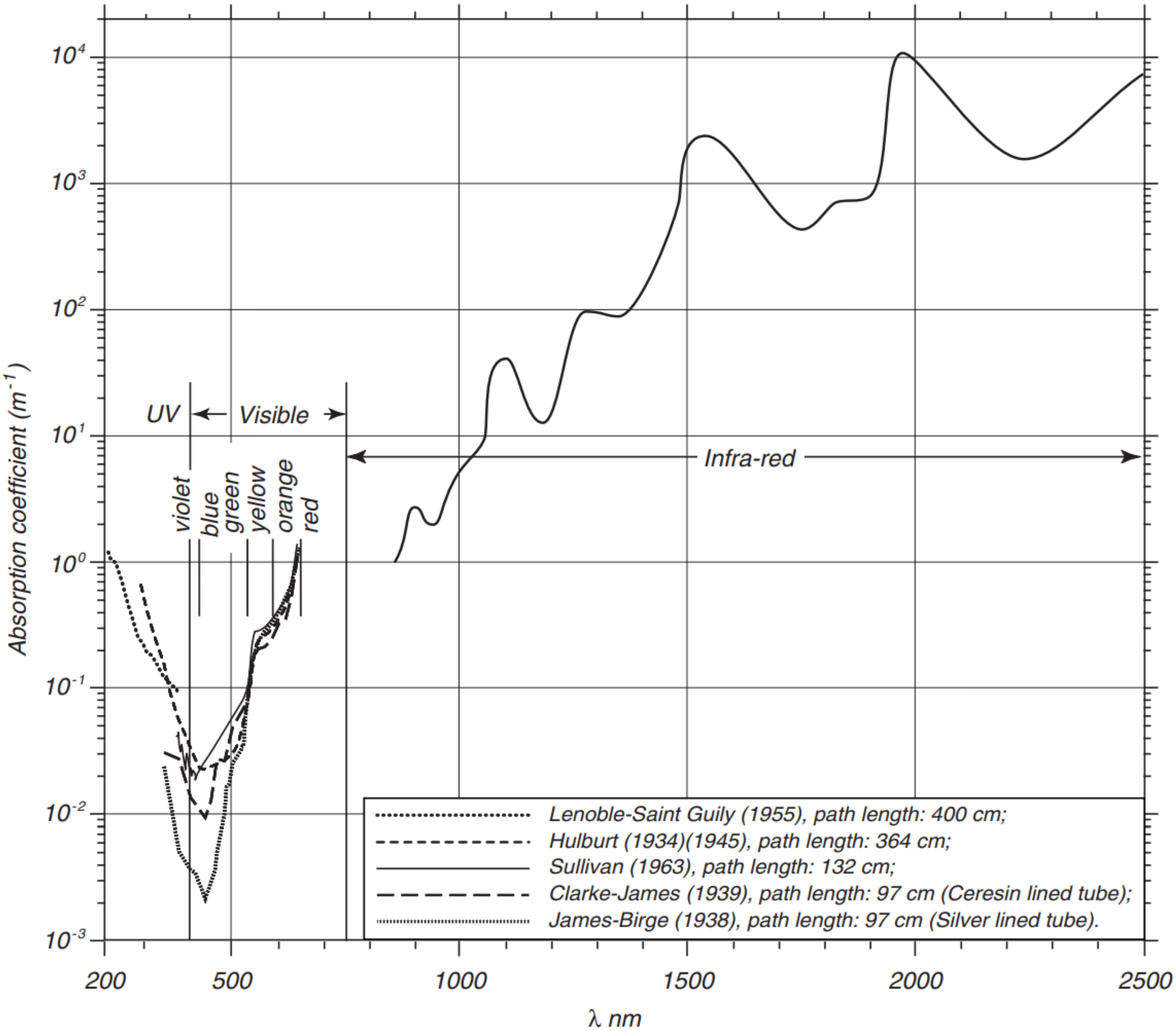

Figure 6.10.1: Absorption coefficient for pure water as a function of wavelength λ of the radiation. Redrawn from Morel (1974: 18, 19). See Morel (1974) for references.

Radiance is the power per unit area per solid angle. It is useful for describing the energy in a beam of light coming from a particular direction. Sometimes we want to know how much light reaches some depth in the ocean regardless of which direction it is going. In this case we use **irradiance**, which is the power per unit area of surface.

If the absorption coefficient is constant, the light intensity decreases exponentially with distance.

$$I_2 = I_1 \exp(-cx)$$

where I_1 is the original radiance or irradiance of light, and I_2 is the radiance or irradiance of light after absorption.

Clarity of Ocean Water

Sea water in the middle of the ocean is very clear— clearer than distilled water. These waters are a very deep, cobalt, blue—almost black. Thus the strong current which flows northward offshore of Japan carrying very clear water from the central Pacific into higher latitudes is known as the Black Current, or Kuroshio in Japanese. The clearest ocean water is called Type I waters by Jerlov (figure $6.10.2$). The water is so clear that 10% of the light transmitted below the sea surface reaches a depth of 90 m.

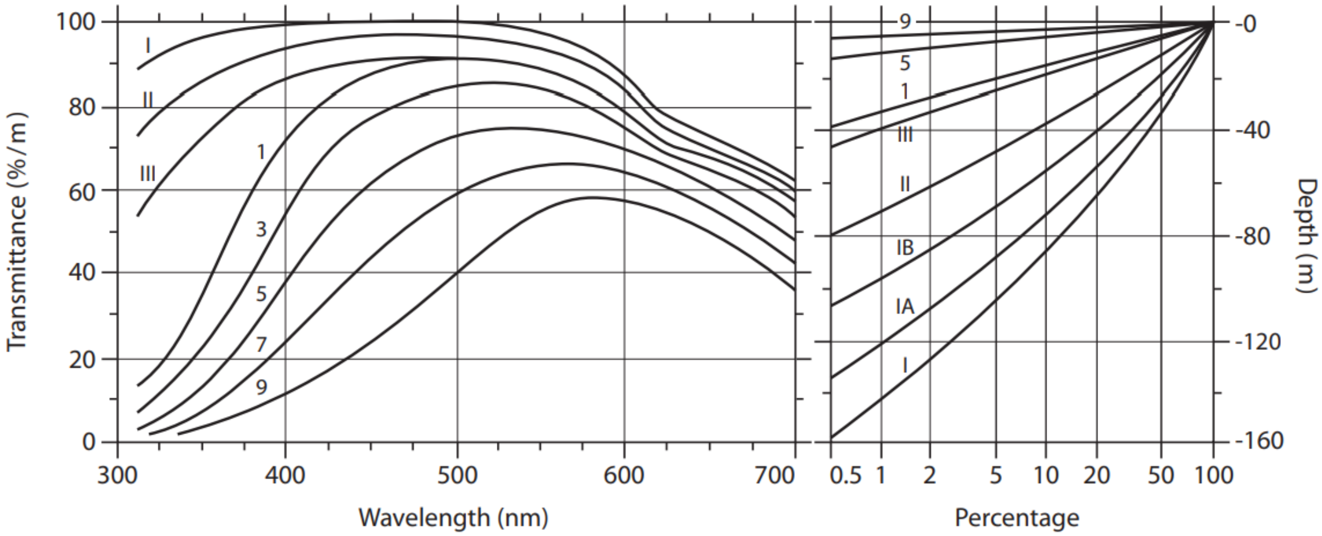

Figure 6.10.1: **Left:** Transmittance of daylight in the ocean in % per meter as a function of wavelength. I: extremely pure ocean water; II: turbid tropical-subtropical water; III: mid-latitude water; 1-9: coastal waters of increasing turbidity. Incidence angle is 90 ° for the first three cases, 45° for the other cases. **Right:** Percentage of 465 nm light reaching indicated depths for the same types of water. After Jerlov (1976).

In the subtropics and mid-latitudes closer to the coast, sea water contains more phytoplankton than the very clear central-ocean waters. Chlorophyll pigments in phytoplankton absorb light, and the plants themselves scatter light. Together, the processes change the color of the ocean as seen by observer looking downward into the sea. Very productive waters, those with high concentrations of phytoplankton, appear blue-green or green (figure 6.10.3). On clear days the color can be observed from space. This allows ocean-color scanners, such as those on SeaWiFS, to map the distribution of phytoplankton over large areas.

As the concentration of phytoplankton increases, the depth where sunlight is absorbed in the ocean decreases. The more turbid tropical and mid-latitude waters are classified as type II and III waters by Jerlov (figure 6.10.2). Thus the depth where sunlight warms the water depends on the productivity of the waters. This complicates the calculation of solar heating of the mixed layer.

Coastal waters are much less clear than waters offshore. These are the type 1–9 waters shown in figure 6.10.2. They contain pigments from land, sometimes called gelbstoffe (which just means yellow stuff), muddy water from rivers, and mud stirred up by waves in shallow water. Very little light penetrates more than a few meters into these waters.

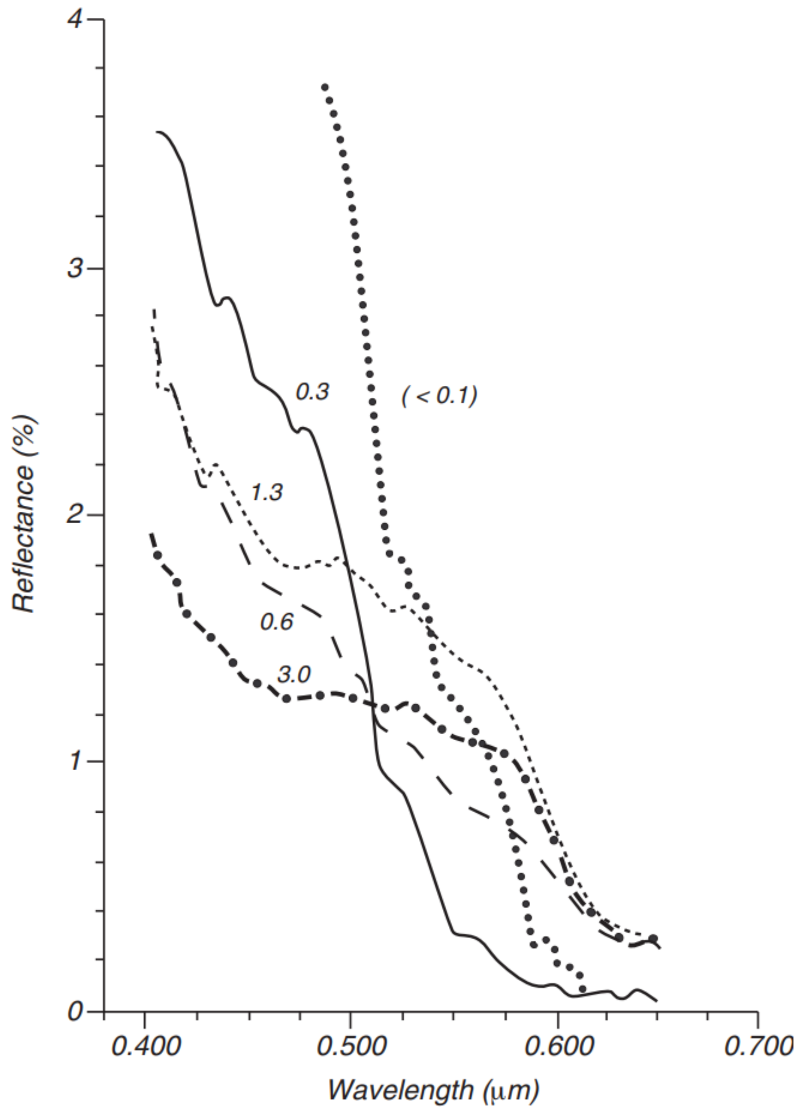

Figure 6.10.3: Spectral reflectance of sea water observed from an aircraft flying at 305 m over waters of different colors in the Northwest Atlantic. The numerical values are the average chlorophyll concentration in the euphotic (sunlit) zone in units of mg/m^3. The reflectance is for vertically polarized light observed at Brewster's angle of 53°. This angle minimizes reflected skylight and emphasizes the light from below the sea surface. After Clarke, Ewing, and Lorenzen (1970).

Measurement of Chlorophyll from Space

The color of the ocean, and hence the chlorophyll concentration in the upper layers of the ocean, have been measured by the Coastal Zone Color Scanner carried on the Nimbus-7 satellite launched in 1978; by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) carried on SeaStar, launched in 1997; and on the Moderate Resolution Imaging Spectrometer (MODIS) carried on the Terra and Aqua satellites launched in 1999 and 2002 respectively. modis measures upwelling radiance in 36 wavelength bands between 405 nm and 14,385 nm.

Most of the upwelling radiance seen by the satellite comes from the atmosphere. Only about 10% comes from the sea surface. Both air molecules and aerosols scatter light, and very accurate techniques have been developed to remove the influence of the atmosphere.

The total radiance L_t received by an instrument in space is:

$$L_t(\lambda_i) = t(\lambda_i) L_W(\lambda_i) + L_r(\lambda_i) + L_a(\lambda_i)$$

where λ_i is the wavelength of the radiation in the band measured by the instrument, L_W is the radiance leaving the sea surface, L_r is radiance scattered by molecules, called the Rayleigh radiance, L_a is radiance scattered from aerosols, and t is the transmittance of the atmosphere. L_r can be calculated from theory, and L_a can be calculated from the amount of red light received at the instrument because very little red light is reflected from the water. Therefore L_W can be calculated from the radiance measured at the spacecraft.

Chlorophyll concentration in the water column is calculated from the ratio of L_W at two frequencies. Using data from the Coastal Zone Color Scanner, Gordon et al. (1983) proposed

$$C_{13} = 1.1298 \left[\frac{L_W(443)}{L_W(550)}\right]^{-1.71}$$

$$C_{23} = 3.3266 \left[\frac{L_W(520)}{L_W(550)}\right]^{-2.40}$$

where C is the chlorophyll concentration in the surface layers in mg pigment/m^3, and $L_W(443)$, $L_W(520)$, and $L_W(550)$ is the radiance at wavelengths of 443, 520, and 550 nm. C_{13} is used when $C_{13} \leq 1.5 \text{ mg/m}^3$, otherwise C_{23} is used.

The technique is used to calculate chlorophyll concentration within a factor of 50% over a wide range of concentrations from 0.01 to 10 mg/m^3.