enrichment experiment. The more recent 1997–1998 El Niño has also been documented using moored bio-optical instrumentation along with SeaWiFS ocean color satellite imagery data sets (Chavez et al., 1998, 1999).

4.2. Biogeochemical Cycling: Biological Pump

The reservoir of dissolved inorganic carbon (DIC) in the oceans is approximately 50-fold higher than the CO_2 in the atmosphere, and on geological time scales the oceans dictate the atmospheric concentration of the gas rather than vice versa. In the oceans there is an inverse gradient in dissolved inorganic carbon such that higher concentrations are found below the upper mixed layer, while to a first order, the upper portion of the water column is in equilibrium with the atmosphere. This inverse gradient is maintained by two carbon "pumps" (Volk and Hoffert, 1985). The solubility pump operates on the thermal contrast between the upper ocean and the ocean interior. The solubilities of cold waters of the deep ocean are on the order of twice as great as near-surface equatorial waters. Thus, the net effect of sinking of surface waters through thermohaline circulation is the enrichment of deeper waters in carbon. Superimposed on the solubility pump is a biological pump. In this process, phytoplankton living in the upper layer (euphotic layer) of the ocean use carbon dioxide to form organic matter. Much of the organic matter is metabolized; however, a significant portion (roughly 20%, but highly variable in terms of location and time) sinks to the deeper reaches of the ocean before being converted back to carbon dioxide (remineralization) by bacteria. Although currents later bring the carbon dioxide back to the surface, the overall effect is to transport carbon to the deep ocean. The solubility and biological pumps have significant impacts on atmospheric carbon dioxide levels (e.g., Sarmiento, 1993). The biological pump includes pathways of carbon to the deeper layers through dissolved organic carbon (DOC) molecules and particulate organic carbon (POC) matter.

There are several interesting connections between bio-optics, biogeochemistry, upper ocean physics, and the biological pump. As described earlier, primary productivity and phytoplankton biomass are dependent on photosynthetic processes, which implicitly involve the availability of light (e.g., PAR) and nutrients. Macronutrients (e.g., nitrate, silicate, and phosphate) and micronutrients (e.g., iron) are important. The spectral quality of light varies with depth and is important for specific phytoplankton species with special pigmentation or photoadaptive characteristics, as described earlier (e.g., see also Bidigare et al., 1990; Bissett et al., 1999). Light exposure for individuals is affected by variation in physical conditions, including mixed layer depth, turbulent mixing, and currents as well as incident solar radiation, which varies in time and space (e.g., astronomical forcing, cloud variability). An important feedback concerns the modulation of the spectral light field at depth as phytoplankton concentrations and communities wax and wane. The determination of primary production in the upper ocean is a vital step in quantifying the carbon flux associated with the biological pump (Laws et al., 2000). Fundamental measurements and models have been developed to estimate primary production [e.g., review by Behrenfeld and Falkowski (1997a) and Table I]. Such models often use measurements of chlorophyll *a* concentration and PAR. The choices of values for spectral absorption and quantum efficiency are often critical, as both of these parameters can vary in time and geographically.