Primary production has been estimated for a variety of geographic regions using remote sensing (Platt and Sathyendranath, 1991; Longhurst et al., 1995; Antoine et al., 1996; Behrenfeld and Falkowski, 1997b) as described earlier and from time series moorings (e.g., Dickey, 1991). For example, primary productivity, $P(z)$, has been estimated using some of the mooring data described earlier along with relatively simple models using Chl(z) and PAR(z) data. In some cases, best estimates or measurements of chlorophyll a, specific absorption coefficient for phytoplankton, a^*, and quantum yield for carbon fixation, $\Phi(z)$, have been utilized (e.g., Falkowski and Raven, 1997; Marra et al., 1999) in the following formulation:

$$P(z) = a^* \Phi(z)\,\mathrm{Chl}(z)\,\mathrm{PAR}(z) \tag{4}$$

Particular examples following this general methodology include the seasonal evolution of primary production in the North Atlantic (e.g., Marra et al., 1992), the ENSO and equatorial longwave effects on primary production in the equatorial Pacific (Foley et al., 1997), and the monsoonal cycle of primary production in the Arabian Sea (Marra et al., 1999). Again, one of the deficiencies of this method is that neither a^* nor Φ is constant because of community structure changes and varying light and nutrient stresses.

For some time there has been an implied connection between upper ocean primary production and export of carbon to the deep ocean; however, quantifying this relationship has been difficult because of the complexity of the processes, disparities in sampling methods and their resolutions, and lack of coincidence of upper ocean and deep-ocean measurements (e.g., Eppley and Peterson, 1979; Lewis, 1992; Platt et al., 1992). Recent collaborative work in the Arabian Sea using moored bio-optical and physical instrumentation (as described above; Dickey et al., 1998b) and deep moored sediment traps has apparently demonstrated that upper ocean primary productivity (Marra et al., 1998) is imprinted in deeper sediment records, which include exported organic and inorganic carbon (Honjo and Weller, 1999). The primary production time series was shown to vary in response to the two major effects described earlier: blooms associated with the northeast and southwest monsoons and the passage of major mesoscale eddies. The variability in the sediment trap carbon data correlated very well with the monsoonal cycle and eddy primary productivity events. These observations and estimates of primary productivity and phytoplankton biomass emphasize the need for high temporal and spatial resolution sampling because of the episodic and highly spatially variable nature of the physical, bio-optical, and biogeochemical processes contributing to the biological pump process.

4.3. Ultraviolet Radiation and Its Effect on Biological Processes

The flux of solar ultraviolet (UV) radiation reaching Earth's surface is critically dependent on the concentration of O_3 and, to a lesser extent, O_2 in the atmospheric column. Absorption bands between 190 and 350 nm are present in a wide variety of biological molecules. Interaction of UV radiation with such molecules can ionize quasistable (i.e., bonding) electrons. As water per se has a very small UV absorption cross section, UV entering the water column has a potential to interact with chromophores in the water column. Three of the most critical chromophores are the aromatic amino acids, quinones, and nucleic acids (Setlow, 1974). The first of these