Monitoring and Management Strategies for Harmful Algal Blooms in Coastal Waters

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3.4 Early Warning, Detection and Prediction of Blooms

Early warning and prediction of algal blooms requires observations to characterize algal distributions in relation to environmental factors (e.g., advection, mixing, light, nutrients), and models that relate algal population dynamics to the observed properties of the environment. Observations range from visual detection of discolored water and analysis of water samples to autonomous measurements from moorings to remote sensing. Models can range from empirical predictions (e.g., blooms will occur after major runoff events) to detailed numerical forecasts based on simulations of algal growth and behavior in hydrodynamic models. Predictive models can be developed and validated only if appropriate observations are available. Thus, physical-chemical-biological observation systems are essential to early warning and prediction of algal blooms.

Because algal blooms are episodic and patchy, observations of algal distributions in relation to physical and chemical properties should be both continuous and synoptic. Although this ideal is unachievable, a new generation of oceanographic instruments can provide continuous measurements of many physical, chemical and biological properties from autonomous moorings, in vertical profile and along ship-tracks. Also, remote sensing from aircraft and satellites can provide synoptic views of coastal processes when conditions allow. If analyzed carefully, data from well-designed observation systems could contribute effectively to early warning and prediction of algal blooms. However, costs for instruments are high, some of the measurements are difficult to interpret or to correct for interference, and autonomous systems (e.g., moorings) are subject to fouling, disturbance, vandalism or theft. Therefore, an evaluation of different strategies for early warning and prediction of algal blooms involves careful consideration of costs versus effectiveness and risk. Several observation technologies are described in the following section, including the simplest instruments and complex systems that are still under development. Generally, as the systems become more complex, our evaluations become much less quantitative.

3.4.1 Observing algal distributions in relation to environmental variability

Hands-on collection of water is an essential component of all programs to detect and monitor algal blooms in coastal waters. Samples are generally taken for enumeration of phytoplankton and determination of several environmental parameters, such as temperature, salinity, turbidity, dissolved oxygen, and nutrient concentrations. This sampling is conducted from boats, or from wharves or piers. In many countries, regular monitoring is conducted at fixed stations, with samples taken at a few depths in the water column. These sampling programs can miss episodic events such as initiation and termination of blooms, and subsurface features in the distributions of phytoplankton. Supplementary technologies for detection and monitoring of algal distributions in relation to environmental factors can help to improve the temporal and spatial coverage of sampling programs. They are discussed below.

3.4.1.1 Secchi disk

The Secchi disk, introduced to oceanography in the 19th century, is an extremely effective tool for observing variations in water clarity. It is a 30-cm white (or white and black) disk, which is lowered into the water until it is no longer visible (the Secchi depth). The Secchi depth is correlated with the penetration of solar irradiance into the water column, and it is influenced by phytoplankton, dissolved organic matter and suspended sediment. Measurements of Secchi depth in isolation are not very helpful for describing algal dynamics in relation to environmental forcing, but long-term records from a network of stations can reveal important trends, such as the long-term decline of water clarity in the Seto Inland Sea, associated with eutrophication, that was stopped by the imposition of environmental controls in 1973 (Yanagi and Okaichi 1997). A dramatic increase in algal blooms occurred during the final stages of the decline in water clarity (Figure 3.1).

A lesson from the Secchi disk is that a simple but quantitative measurement, made often enough, can be extremely useful in describing environmental variability associated with algal blooms. The technology is inexpensive, and appropriate for frequent, routine measurements by a network of observers, such as fish farmers. It is also easy to incorporate into any monitoring program for algal blooms. The measurements are of little use, however, unless patterns are analyzed in the context of environmental forcing and the dynamics of algal blooms.

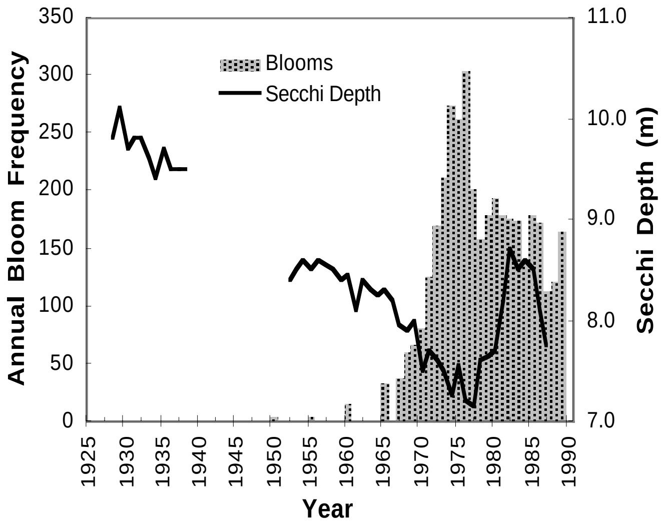

FIGURE 3.1. **Records of water transparency (i.e., Secchi depth, 5-year running mean) and the reported frequency of blooms in the Seto Inland Sea, Japan, before and after the imposition of pollution controls in 1973.** This figure is combined and redrawn from Manabe and Ishio (1991) and Honjo (1993). Secchi depth is a simple optical measurement that is quantitative and adequate to show long-term changes associated with eutrophication of a coastal system.

3.4.1.2 Chlorophyll *a*

Because all of the photosynthetic phytoplankton contain chlorophyll *a* (the prochlorophytes contain the closely related divinyl chlorophyll *a*), the measurement of chlorophyll is routine in research and monitoring. Samples are filtered, extracted in solvent, and the extract is analyzed for pigment. Spectrophotometric and fluorometric methods for the determination of chlorophyll are both relatively simple and affordable, but fluorometric methods are significantly more sensitive than spectrophotometric methods (i.e., much more sample must be filtered for a spectrophotometric determination). Even when a correction is made for degradation products (e.g., phaeopigments) or accessory pigments, both methods are subject to interference from pigments other than chlorophyll *a* (Lorenzen and Jeffrey 1980). A recent improvement in the fluorometric method minimizes this interference with a modest loss in sensitivity (Welschmeyer 1994). However, if long term records for a region have been acquired using established methods, it may not be prudent to switch to a different technique, even if it is somewhat better, because continuity in the record would be broken. It should be recognized that chlorophyll *a* is an imprecise indicator of phytoplankton biomass (Cullen 1982), so that even accurate determinations of chlorophyll *a* bear uncertain relationships to the abundance and species composition of phytoplankton.

Chlorophyll *a*, along with most other pigments of phytoplankton and their degradation products, can be determined accurately using high performance liquid chromatography (HPLC). Because certain pigments are characteristic of particular phytoplankton taxa, including some groups that are predominantly harmful (Johnsen et al. 1994), HPLC analysis can be an effective tool in characterizing variability in dominant species groups - it is therefore a good complement and a partial replacement for microscopic analysis, especially when a large number of samples is taken and resources for enumerating samples are strained. Costs for HPLC analysis are significantly higher than for fluorometric or spectrophotometric methods.

3.4.1.3 Fluorescence of chlorophyll *in vivo*

The chlorophyll *a* in live phytoplankton fluoresces red when photosynthetic pigments absorb light, so fluorometers can be used to assess distributions of phytoplankton *in situ* (Lorenzen 1966). Natural samples can be pumped continuously through an on-deck fluorometer (e.g., Turner Designs 10-AU Fluorometer) to assess distributions in vertical profile or during transects. Several types of compact, submersible, *in situ* fluorometers are commercially available from manufacturers including Chelsea Instruments, Dr Haardt, SeaPoint, Turner Designs, and WET Labs. These are generally less expensive than bench-top fluorometers (several have prices ranging from about $3,000 to $5,000 US), and they are more convenient and effective than flow-through fluorometers for use in the field. They are designed for deployment on small instrument packages for monitoring or profiling salinity, temperature and other properties. Submersible fluorometers are readily adapted for flow-through systems, such as on ferries (e.g., McKenzie et al. 1998) or for moorings with samples pumped sequentially from one or several depths (Lee and Lee 1995). The WET Labs *ECO* sensors have an integrated anti-fouling shutter as an option; the Turner Designs SCUFA can be fitted with a copper screen that retards fouling. When used for vertical profiling, submersible fluorometers can provide critical information on the distributions of phytoplankton relative to density structure and light in the water column. They are sensitive enough to detect the lowest concentrations of phytoplankton in coastal waters. Response times (which are not necessarily the same as sampling rate) should be sufficiently fast to resolve thin features (about 10-30 cm) in vertical profiles during routine deployments.

Calibration of *in vivo* fluorescence. Fluorescence is an indicator of chlorophyll, and an imprecise one at that (Cullen 1982). The ratio of *in vivo* fluorescence to chlorophyll *a* varies widely (see Kiefer 1973) as a function of irradiance and irradiance history, nutritional state, accessory pigmentation and taxonomic grouping. Also, the patterns of variability with these factors differ, depending on the manner of measurement (excitation irradiance and duration), which is different for each instrument (Neale et al. 1989). Consequently, *in situ* fluorometry is much better suited for characterizing patterns in distributions of chlorophyll, such as subsurface layers (Derenbach et al. 1979) or patchiness along transects, than for quantifying accurately either chlorophyll *a* or the biomass of phytoplankton. Nonetheless, fluorometry can provide high-resolution records of chlorophyll if the measurements are carefully calibrated with discrete samples from the same waters, paying special attention to the influence of irradiance on fluorescence yield (Cullen and Lewis 1995). This may not be possible when fluorometers are used in autonomous systems. For example, there will be a depression in near-surface fluorescence when it is sunny (a physiological response to bright light) that could be interpreted as avoidance of the surface by phytoplankton. Besides making efforts to understand such natural variations in fluorescence responses of phytoplankton, it is essential to characterize shifts in instrument sensitivity and instrument blank on a regular basis. Distilled water and a fluorescent standard such as rhodamine can be used for this purpose in most coastal waters (McKenzie et al. 1998), but more rigorous procedures are preferable, especially for oceanic waters, where filtered sea water is the appropriate blank.

3.4.1.4 Spectral fluorescence excitation and emission *in situ*

Spectral characteristics of algal fluorescence reveal taxonomically important differences in algal pigmentation (Yentsch and Phinney 1985). That is, by measuring the red fluorescence emitted by algal chlorophyll *a* when excited by a spectrum of blue to green wavelengths (i.e., an excitation spectrum), one can discern influences of different accessory pigments, some of which are characteristic of particular taxa. In turn, the emission spectrum of algal fluorescence, when stimulated by blue light for example, can reveal taxonomically significant differences in the pigmentation and organization of photosynthetic systems (e.g., some cyanobacteria and cryptophytes fluoresce orange). Until recently, spectral fluorescence of phytoplankton has been measured for research purposes using laboratory instruments (Nelson et al. 1993; Sosik and Mitchell 1995) or highly specialized systems (Cowles et al. 1993). Now, a robust, commercially available instrument (WET Labs SAFIRE; about $30,000 US) can be used to measure spectral fluorescence. The SAFIRE is designed for *in situ* characterization of water fluorescence from the UV throughout the visible spectrum. The instrument employs a flashlamp source and a rotating filter wheel that provides excitation light at six wavelengths. Sixteen emission detectors built into the flow tube provide a 6 excitation, 16 emission data matrix. The resulting 96 channels are sampled at 5 Hz, providing information on colored dissolved organic matter as well as on algal pigmentation and aspects of physiology (Nelson et al. 1993; Sosik and Mitchell 1995). However, interpretations of spectral fluorescence as measured by SAFIRE are still very much under development, so it is not yet a tool for operational monitoring.

The fast repetition rate fluorometer (FRRF; Chelsea FASTracka, about $70,000 US) directly assesses photosynthetic physiology of the phytoplankton assemblage (Falkowski and Kolber 1995). It is an extremely useful tool for research that could, in principle, be used for monitoring. Interpretations of the measurements require some refinement and validation, and instrument performance has yet to be fully evaluated under a broad range of conditions. Also, the cost of the instrument and requirements for careful maintenance are issues. The use of chemical anti-fouling agents during moored applications might affect phytoplankton physiology, compromising system performance.

3.4.1.5 Spectral attenuation and absorption

Absorption spectra. Phytoplankton in suspension absorb and scatter light. Attenuation is the sum of absorption and scatter: it can be quantified by measuring the transmission of a beam of light through a path of water to a target. It is well recognized that differences in pigmentation between algal groups can be detected in measurements of their absorption spectra (Johnsen et al. 1994). Absorption spectra of phytoplankton can be measured spectrophotometrically if modifications are made so that photons scattered out of the light path (scattering by phytoplankton is principally in the forward direction) are detected with the same efficiency as those that are neither scattered nor absorbed (Shibata 1958). This can be accomplished by collecting particulate matter on a glass-fiber filter, which serves the dual purpose of concentrating the sample and acting as a diffuser for ensuring the detection of forward-scattered light (Yentsch 1962). The measurement requires hands-on manipulation of samples and results must be corrected for the tortuous path of light through the sample (Mitchell and Kiefer 1988; Cleveland and Weidemann 1993) and the contribution of detritus to particulate absorption (Kishino et al. 1985). Thus, filter-pad measurements of phytoplankton absorption are used primarily for research, not monitoring. It is conceivable, however, that estimates of absorption could be made autonomously by the measurement of reflectance on filters (Balch and Kirkpatrick 1992) prepared in an autonomous unit. (See Kirkpatrick et al. 2000 for discussion of an alternate approach.)

Spectral absorption and scatter *in situ*. Systems have recently been developed for continuous *in situ* measurement of the absorption coefficient of natural waters (see Cullen et al. 1997; Schofield et al. 1999). The commercially available WET Labs ac-9 dual-path absorption meter (about $20,000 US) uses a quartz cylinder to reflect scattered photons toward the detector (Zaneveld et al. 1990). Attenuation (scattering plus absorption) is measured in a second chamber, so spectral scattering can be calculated by difference. The scattering coefficient is used in the calculation of a correction factor for photons scattered away from the detector of the absorption meter (Zaneveld et al. 1994). Using selectable filters, the ac-9 concurrently determines the spectral transmittance and spectral absorption of water over nine wavelengths. The ac-9 is available with 25 and 10 cm pathlength configurations, appropriate for coastal waters. More highly resolved spectra (3.3 nm spectral resolution throughout the visible range) can be obtained with the WET Labs HISTAR high-spectral-resolution absorption and attenuation meter (about $32,000 US).

Great care must be taken to acquire accurate data with the WETLabs absorption and attenuation meters, especially in oceanic waters, where the determination of blanks has a large influence on results. Also, fouling, bubbles and temperature shifts can cause problems. Nonetheless, instruments like the ac-9 have been shown to be effective for detecting vertical (Roesler and Zaneveld 1994) and temporal (Cullen et al. 1997) variability of phytoplankton in coastal or shelf waters. Fouling of the reflecting tube during long deployments can be retarded by using copper tubing on the intake port and pumping water through the instrument only periodically (T.D. Dickey, pers. comm.). Absorption meters with sensors for backscatter and fluorescence are also sold by HOBI Labs (**www.hobilabs.com**).

To date, the measurements of spectral absorption have been used more to resolve the red peak of chlorophyll absorption (a reasonably robust measure of chlorophyll *a*; see Figure 3.2) than to distinguish groups of phytoplankton according to their absorption characteristics (Johnsen et al. 1994; Millie et al. 1996; Schofield et al. 1999).

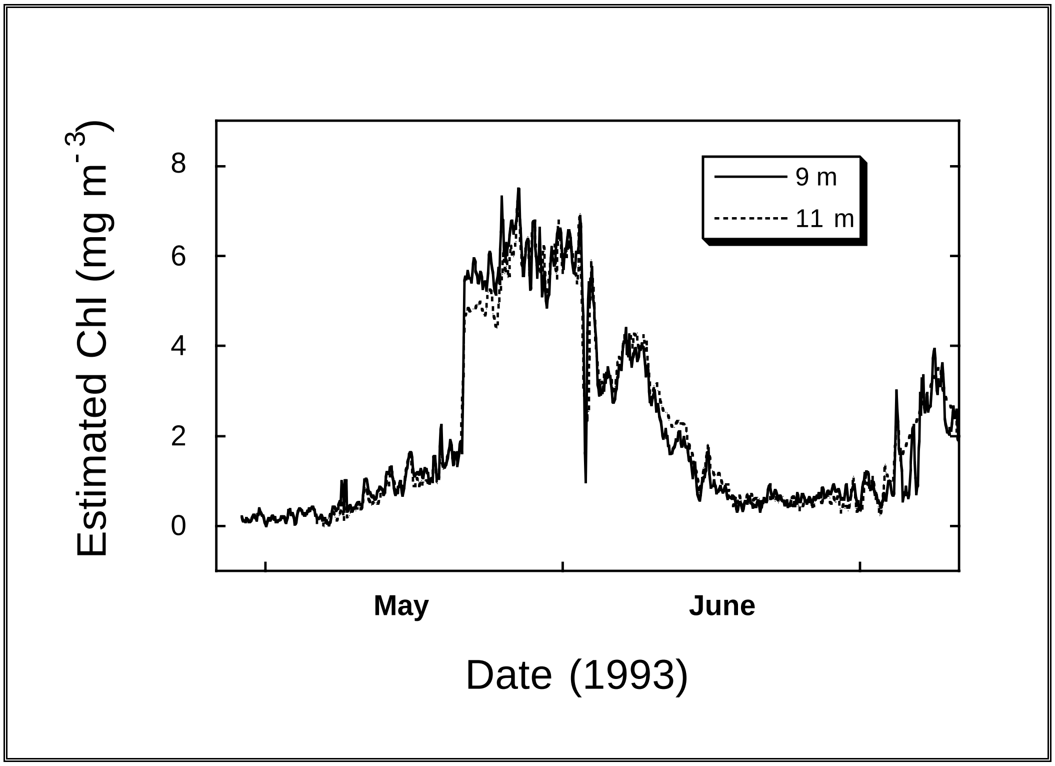

FIGURE 3.2. **Estimates of chlorophyll concentration based on measurements obtained with moored spectral absorption meters in the southeast Bering Sea, 1993.** A three-waveband absorbance meter (a-3: 650 nm, 676 nm and 710 nm; WET Labs, Inc.) was deployed at 9 m and a six-waveband meter (WET Labs ac-6: relevant wavelengths, 650 nm, 676 nm and 694 nm) was deployed at 11 m. Absorption associated with the red peak for chlorophyll *a* was estimated by subtracting from measured absorption at 676 nm a baseline described by a simple exponential curve connecting measurements at the lower and higher wavelengths. The concentration of chlorophyll was calculated from absorption using a coefficient from the literature (Bricaud et al. 1995). Later during the same deployment, the instruments became fouled and performance degraded. Records like this would now be obtained with an ac-9 instrument. (Source: Cullen et al. 1997.)

Limitations. It should be recognized that the technology for measuring absorption *in situ* is still emerging. Despite the sound theoretical foundations of the measurement systems, accuracy and precision is not assured; for example, although several methods show the same general patterns in absorption, measured ratios between wavelengths, as well as absorption coefficients, differ between instruments (Pegau et al. 1995). Thus, it may be some time before detailed analysis of *in situ* absorption spectra (Johnsen et al. 1994; Millie et al. 1996) will be practical. However, new techniques with better resolution of phytoplankton absorption provide some promise for detecting some species of phytoplankton from their spectral signatures (Kirkpatrick et al. 2000).

Spectral attenuation *in situ*. Measurements of spectral light-beam attenuation (LBA) have been made in a variety of environments (Voss 1992; Volent and Johnsen 1993), and Optisens (OCEANOR), a three-waveband LBA meter (blue/480 nm, green/550 nm, red/650 nm), has been incorporated into the SEAWATCH system (Johnsen et al. 1997; Tangen 1997). Chelsea Instruments can provide similar measurements. It is suggested that the ratio of attenuation in these different wavebands may indicate which component of the water - phytoplankton, colored dissolved organic matter, or inorganic particulate material - is dominating (see Tangen 1997). Descriptions of Optisens generally include references to research showing how the absorption characteristics of phytoplankton can be used to distinguish taxa, including some harmful species (Johnsen et al. 1994), supporting the implication that measurements of spectral attenuation are potentially useful for distinguishing phytoplankton *in situ*.

It is important to recognize, however, that spectral attenuation includes both scattering and absorption, and that in surface waters, the scattering coefficient of phytoplankton is generally much greater than the absorption coefficient (Morel 1990). Consequently, measures of LBA are dominated by scattering, which for phytoplankton has weaker spectral features in the visible range than does absorption (Morel 1990; Stramski and Reynolds 1993; Roesler and Zaneveld 1994). Thus, although it is feasible to measure spectral LBA to detect phytoplankton (Volent and Johnsen 1993), on first principles the approach is less sensitive than absorption-based techniques (Stramski and Reynolds 1993). The same conclusions apply to measurements of spectral backscatter using commercially available instruments (e.g., HOBI Labs): they are very important for optical oceanography (Voss and Smart 1994), but are not especially effective on their own for discerning the contribution of phytoplankton, except, perhaps, in fluorescence mode. New applications may be developed because several research groups are pursuing the discrimination of algal groups from the measurement of a suite of optical properties, and progress is likely.

Attenuation at one wavelength, measured *in situ*. Profiling transmissometers that measure attenuation at 660 nm (e.g., from WET Labs, Chelsea Instruments, and HOBI Labs; from about $4,000 to $7,000 US) are now used routinely in oceanographic research. Data have proved to be extremely useful in several contexts (Pak et al. 1988; Siegel et al. 1989; Stramska and Dickey 1992); an important feature of attenuation at 660 nm is that it is a measure of particle concentration, not strongly affected by algal pigments (Cullen and Lewis 1995). Thus the comparison of beam attenuation vs. chlorophyll fluorescence is potentially useful for distinguishing some microbial assemblages (weakly pigmented vs. strongly pigmented plankton; cf. Mitchell and Holm-Hansen 1991) and for characterizing the relative contributions to subsurface layers of suspended sediment vs phytoplankton. Profiling instruments that measure attenuation in more than one wavelength are becoming more common.

Turbidity. Long used in programs to monitor water quality, turbidity sensors (e.g., instruments that measure sidescatter or backscatter in the infrared) quantify water clarity by measuring an optical signal related to particle load. Instruments for measuring optical backscatter (OBS) *in situ* range in price from about US $1,000 to $4,000 and can be calibrated in turbidity units tied to standards. Measurements can be related empirically to water clarity (diffuse attenuation coefficient) or to particle load, but turbidity is not a direct measurement of either property. Turbidity sensors are not suited for detecting variability of phytoplankton *per se*, but like transmissometers, they can be used in conjunction with fluorometers to detect subsurface layers of particles and to characterize to some extent the relative contribution of microalgae to the particle load. Oceanographers tend to work with beam attenuation, because the attenuation coefficient (c: units, m^{-1}) is an absolute measure (an inherent optical property) that can be compared directly between instruments.

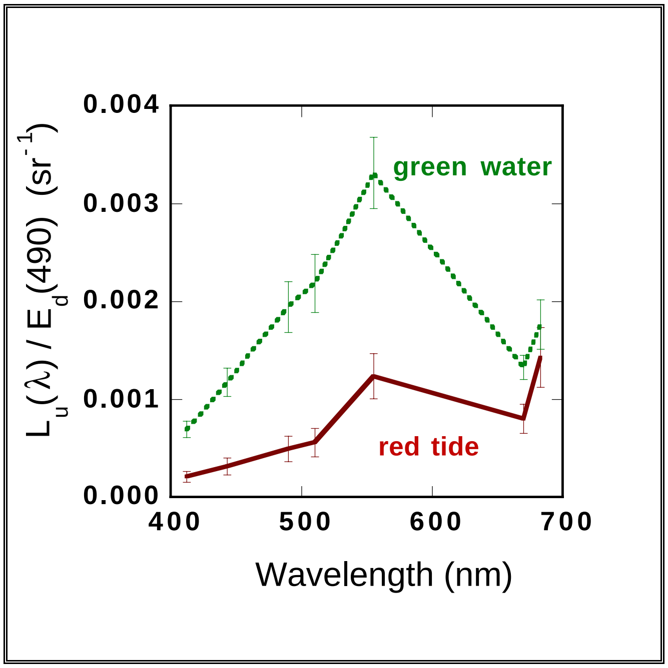

FIGURE 3.3. Detection of a dinoflagellate bloom with a radiometer buoy measuring ocean color, Aug. 18, 1993, during patchy discoloration of surface waters by high concentrations of the non-toxic dinoflagellate *Gonyaulax digitale*. The red water spectrum is the average for 1345 - 1350 h, and the green water spectrum is for 1354 - 1359 h. Error bars are s.d. for measures recorded 1 s^{-1}. The signal near 673 nm is sun-induced fluorescence of chlorophyll, which can be helpful in distinguishing red tide from muddy red water. (Source: Cullen et al. 1997.)

3.4.1.6 Ocean color

The absorption and scattering of light by algae, other micro-organisms, particles, dissolved substances and water modify both the underwater and upwelling (emergent) light fields. The influences of algae, which are generally distinct from those of other components (Morel 1990), can be detected and quantified by measuring reflected and fluoresced light using near-surface and above-water radiometers and satellite sensors. Ocean color is generally measured as upwelling spectral radiance, $L_u(\lambda)$ (W m^{-2} nm^{-1} sr^{-1}) and normalized to downwelling solar irradiance ($E_d(\lambda)$; W m^{-2} nm^{-1}) to calculate radiance reflectance (*Rr*; sr^{-1}).

Where algal blooms occur at sufficient biomass, they may be detected by passive optical instruments (radiometers), including ocean-color sensors on moorings, aircraft, or satellites (Figure 3.3). Passive optical sensors cannot detect toxic algae that occur as minor components of the phytoplankton, but estimates of total pigment and information such as spectral attenuation from these sensors can provide important data for biological-chemical-physical models of algal dynamics (Schofield et al. 1999; Glenn et al. 2000). Well-recognized limitations of satellite remote sensing, including interference by clouds, relatively coarse spatial resolution (for coastal processes), and discrete observation periods can be overcome by deployment of *in situ* ocean-color radiometers on moorings or drifters (Abbott and Letelier 1996) and by using radiometers on aircraft for surveys during events or process studies (Pettersson et al. 1993; Harding et al. 1995; Davis et al. 1997). One great strength of ocean-color measurements is that they are radiometric quantities that retain their validity for long-term and wide-ranging comparisons over time or between sites (e.g., for resolving influences of eutrophication or climate variability). Interpretations of the measurements may change for the better, but the data should never become obsolete.

Ocean color is often related to near-surface chlorophyll concentration through empirically derived algorithms. These have been particularly successful in open ocean (Case I) waters where bio-optical variability results principally from algal biomass. Coastal waters (Case II), where algal blooms occur, present problems since the algorithms have to discriminate the absorption and scattering of algae from the absorption and scattering of the terrigenous inputs of colored dissolved organic matter and sediment. These problems are being addressed vigorously by the ocean-color remote sensing community, and progress has been good (Sathyendranath 2000). Local algorithms can be developed by sampling for chlorophyll and particulate absorption while measuring ocean color with a radiometer buoy or profiler. Although absorption contributes strongly to ocean color (reviewed by Cullen et al. 1997) and groups of phytoplankton can be distinguished on the basis of highly resolved absorption spectra (Johnsen et al. 1994; Millie et al. 1996), research to date indicates that species composition of phytoplankton cannot be determined from measurements of ocean color alone (e.g., Garver et al. 1994; but see Schofield et al. 1999).

Instruments for measuring ocean color from boats or ships. Ocean color and downwelling irradiance are measured *in situ* with profiling radiometers (about $25,000 to $75,000 US, depending on numbers of wavebands and extra sensors; e.g., from Biospherical Inc. or Satlantic, Inc.) or hand-deployed radiometer buoys (about US $15,000 for simple systems from either supplier, to about $35,000 for a hyperspectral version from Satlantic). Radiometers can also be used on the deck of a ship or boat for some applications (Carder and Steward 1985; Lazin 1998): hand-held, high-resolution units are available for about US $20,000 from Analytical Spectral Devices, and deck-mountable, multiple-waveband units (including downwelling irradiance) are available from Biospherical and Satlantic for prices in a similar range. These boat-deployed tools are extremely useful for the development of local algorithms to interpret remote sensing from aircraft or satellites, and they can be used for estimating variability in surface pigments during transects. Ocean color sensors on moorings and aircraft can be very useful in the early warning and prediction of algal blooms. Those applications will be discussed below.

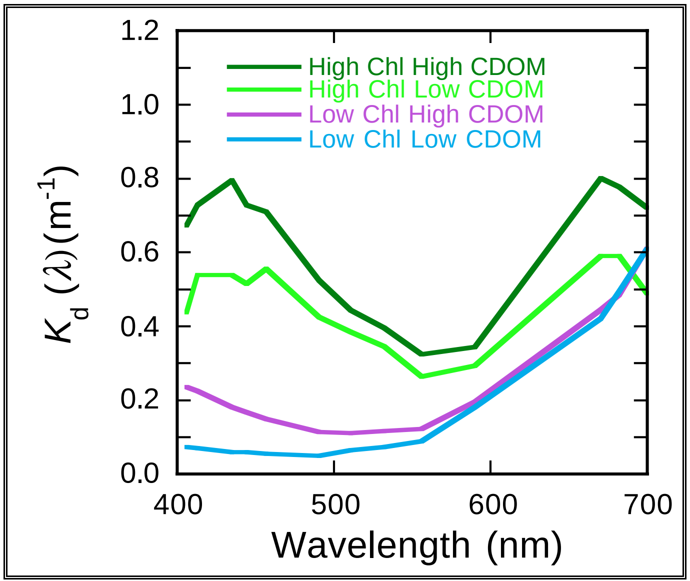

FIGURE 3.4. Measurements of spectral diffuse attenuation coefficients [$K_d(\lambda)$, m^{-1}] in coastal waters off Oregon (US). Vertical profiles of $E_d(\lambda)$ were obtained with a multichannel profiling radiometer (Satlantic, Inc.), and $K_d(\lambda)$ was computed as the slope of $\ln(E_d(\lambda))$ vs depth for the upper 5 - 10 m of the water column. The contributions of chlorophyll (Chl) and CDOM (gelbstoff) to absorption can be seen in these spectra: Chl concentrations for the highest-absorbance to lowest-absorbance spectra were 24.5, 20.8, 0.57, and 0.25 mg m^{-3}, respectively. (Source: Cullen et al. 1997.)

Instruments for measuring attenuation of solar irradiance in the water. While ocean color is largely determined by both absorption and scattering by phytoplankton and other constituents of the water, spectral characteristics of the vertical attenuation of solar irradiance are mostly affected by absorption. Thus, measurements of the diffuse attenuation of solar irradiance [$K_d(\lambda)$; m^{-1}], generally made with a profiling radiometer or a chain of sensors, can reveal the influences of phytoplankton as well as other absorbing constituents, such as colored dissolved organic matter, or gelbstoff (Figure 3.4). Another important characteristic of diffuse attenuation is that the measurement integrates all influences in the depth range monitored. That is, a thin layer of highly concentrated particles will be detected through its attenuation of light, even if it is not directly resolved by the radiometer. Measurements of attenuation at one wavelength should be effective at detecting subsurface layers of absorbing material. Estimates of attenuation at multiple wavelengths will help to resolve contributions of phytoplankton from other constituents of the water.

3.4.1.7 Flow cytometry

Flow cytometers are extremely powerful tools for characterizing algal assemblages with respect to taxonomic composition and cellular properties, such as chlorophyll content (Li et al. 1993). A suspension of particles is directed into a very narrow stream, such that one particle at a time encounters a focused beam of light. Detectors measure properties such as forward light scatter and side-scatter (to characterize cell size) as well as the fluorescence of chlorophyll *a*, phycoerythrin, or a fluorescent stain (e.g., Pan and Cembella 1998). Some systems are capable of sorting cells on the basis of user-defined characteristics. Flow cytometry has proven to be effective in distinguishing and quantifying different groups on the basis of scattering properties (i.e., size) and fluorescence of photosynthetic pigments (Olson et al. 1989; Li et al. 1993). With the use of stains, flow cytometry can be effective in identifying taxa and quantifying important cell constituents (see Vrieling and Anderson 1996). Flow cytometers are expensive, and not suitable for use on small boats. However, many types of analyses can be done on preserved samples (Vaulot et al. 1989), so routine monitoring or surveys could be practical. Also, new instruments are under development, including the novel Cytobuoy system (**www.cytobuoy.com/**), which have strong potential for use on moorings for autonomous detection and monitoring of algal blooms. Preliminary results from the Cytobuoy system are promising, but it appears that the system is still in the experimental stages. A flow-system, which collects images of larger plankton, including some harmful species, is now being marketed (**www.fluidimaging.com**).

3.4.2 Characterizing Environmental Variability Relevant to Algal Blooms

Most programs to monitor coastal waters for algal blooms include measurements of temperature, salinity, dissolved oxygen and nutrients at the surface and usually at one or more depths. Many programs include continuous profiles of conductivity (salinity) and temperature vs depth (CTD). These sampling programs can miss episodic events such as initiation and termination of blooms, and subsurface features in the distributions of phytoplankton. For example, transport of subsurface populations was found to be extremely important in the dynamics of dinoflagellate populations off France (Gentien et al. 1998) and near the Irish coast (McMahon et al. 1998). Detection of subsurface populations and incorporation of the information into measurement-guided circulation models was critical to resolving important factors that influence the occurrence of these blooms. The information could not have been obtained effectively with CTD profiles and fixed-depth sampling alone. In the preceding sections, we described supplementary technologies for detection and monitoring of algal distributions in relation to environmental factors. Here we describe approaches for characterizing environmental variability concurrently with observations of properties related to algal distributions.

3.4.2.1 Profiling systems

Compact, high-quality CTD systems are widely used for coastal monitoring and research. These systems are designed for use with supplementary sensors that can effectively describe the distributions of microalgae relative to important properties of the water column. For example, the Harmful Algae Monitoring Program of Galicia, Spain (Mariño et al. 1998) has developed an effective system for describing distributions of algae relative to environmental factors. Their profiling system measures temperature, salinity, oxygen, pH, fluorescence, and transmittance (attenuation). Similar systems can be obtained from several suppliers (Table 3.10), with prices ranging from about US $25,000 and up for compact systems that provide good temporal (and thus good spatial) response, real-time read-out (important so that subsurface features can be targeted for sampling and enumeration of phytoplankton), and software for presentation and analysis. Manufacturers such as YSI and Hydrolab market profilers that are widely used and substantially cheaper. Some trade-offs in instrument performance (such as depth tolerance and sensor precision) are made. Nonetheless, they may be a good choice for many applications.

A detailed comparison of different products is difficult, because evaluations depend on who will be using the system, under what conditions the profiler will be deployed (e.g., from a well equipped monitoring vessel or from a small boat), what configuration is chosen, and the level of internal technical support that is available to the user.

A fluorometer should be included in profiling packages, so subsurface distributions of phytoplankton can be characterized and discrete sampling can be targeted to subsurface layers, when they are encountered. With appropriate modifications for mounting and moving water past sensors, the instrument systems from Table 3.10 can be deployed on moorings, but different factors influence the evaluation of relative merits. These will be discussed in the section on moorings.

TABLE 3.10. Compact profiling systems. Prices start at about $25,000 US. Not all systems have exactly the same configuration and some include spare parts or set-up and testing.

Model	Manufacturer	Features	Comments
SBE-19 SEA-CAT Profiler	Sea-Bird Electronics	C, T, Depth, DO, Fl, LBA, OBS	Pump required; 2 Hz sampling
Micro-CTD 3”	Falmouth Scientific, Inc.	C, T, Depth, DO, Fl, LBA, OBS	No pump needed; 6 Hz
AQUApack CTD	Chelsea Instruments	C, T, Depth, Fl, LBA, nephelometer	No pump; includes integration and test
OS200 CTD	Ocean Sensors	C, T, Depth, DO, Fl, LBA, OBS	No pump needed; good sensor response
EMP 2000	Applied Microsystems	C, T, Depth, DO, Fl, LBA	No pump needed

Notes: Laptop computer and cable (about 50 m; cost of about $500 - $800 US) would be required for each. Direct comparisons on the basis of price would be misleading, because there are many differences in sensor response, system integration, and simplicity of use.

3.4.2.2 Underway sampling on ferries

Ferries or other ships offer excellent opportunities for regular sampling of environmental parameters relevant to monitoring and detection of algal blooms. Water can be sampled through the hull, fed through a de-bubbler, and directed through a series of sensors. A Japanese system (Harashima et al. 1997) measures conductivity, temperature, pH and fluorescence, and an automated filtration system collects samples for determination of nitrate, nitrite, ammonium, phosphate, dissolved silica, chlorophyll and phaeopigments. A simpler system, designed for use on fishing vessels, measures conductivity, temperature and fluorescence (McKenzie et al. 1998). The costs for such a simple system would be on the same order as a profiling instrument package: more money would be spent on water handling and calibration systems, but fewer sensors would be operated, because dissolved oxygen cannot be measured reliably in such systems, and the measurement of beam attenuation requires special precautions because of bubbles. Ferry-based sampling is being established elsewhere in the world, and some systems employ underway measurement of ocean color with an on-deck radiometer.

Although it seems reasonable to expect that dramatic surface blooms will be detected through underway sampling, day or night, other benefits of underway sampling systems become evident once long time-series are analyzed (Harashima et al. 1997). Regional patterns of blooms can be determined and related to eutrophication, relationships between blooms and hydrographic features such as fronts can be resolved, and long-term shifts in patterns can be related to nutrient loading. The analysis presented by Harashima et al. (1997) relies heavily on measurements of nutrients, which certainly require a large investment of resources. The measurements were not continuous, but they were numerous and regular.

Autonomous measurement of nutrients. The measurement of nutrient concentrations in discrete samples of seawater is not considered an issue in early warning and prediction of algal blooms, as the two principal options, analysis by hand and using an automated nutrient analyzer, are well known. Since the capability for autonomous measurement of dissolved nutrients in seawater is potentially useful for describing and understanding the dynamics of algal blooms, the technology deserves consideration here.

The concentrations of dissolved nutrients are commonly measured during monitoring programs, and when blooms are detected and sampled intensively. It is problematic, however, to correlate nutrient concentrations with algal biomass: the systems are dynamic, so that even if the initiation of blooms is correlated with higher nutrient concentrations, a negative correlation would exist between algal biomass and nutrients during the development phase of the bloom. Monthly or bimonthly sampling could not resolve these dynamics, but continuous measurement of nutrient concentrations, in conjunction with measures of algal biomass, might. As discussed in the previous section, semi-continuous sampling (including filtration) during underway transects (Harashima et al. 1997) can be effective. Alternatively, nitrate and phosphate can be continuously measured with the commercially available systems from, for example, Chelsea Instruments, WS Oceans or WET Labs. This technology can be used on moorings, though the WET Labs system is designed for profiling applications. In the context of early warning and prediction of algal blooms, the expense of continuous nutrient analysis (roughly US $25,000 per nutrient module) would have to be justified carefully, either by comparing expense to that for discrete samples (Japanese model), or by showing that there were good reasons to believe that patchy or episodic changes of nutrients might be involved with the initiation or termination of blooms (justification for measuring nutrients from a mooring). Even if the information were not necessary for early warning of blooms, continuous measurements of nutrients would be better than data from routine monitoring programs for development and validation of simulation models.

3.4.2.3 Bio-optical moorings

Instrument systems on moorings can describe biological dynamics in the context of physical and chemical forcing, making pertinent observations on appropriate scales (Dickey 1991). Development of moored monitoring systems has begun (Johnsen et al. 1997; Tangen 1997; Glenn et al. 2000), and several ocean observation projects have been established, including the MBARI Ocean Observing System (MOOS), the Bermuda Testbed Mooring (both components of the O-SCOPE program; see the web page of Dr. Tommy Dickey, UCSB), the Coastal Ocean Observation Lab / LEO-15 project (Rutgers University), the Chesapeake Bay Observing System, and the Marine Optical Buoy (MOBY) time series off Hawaii (all have web pages). All are still under active development. Operational monitoring has been conducted by OCEANOR (the SEAWATCH program, www.oceanor.com; Hansen 1995; Johnsen et al. 1997; Tangen 1997). Less comprehensive bio-optical moorings have been deployed by Biospherical, Inc (REOS; biospherical.com/products/reos.html) and Satlantic, Inc. (TACCS; www.satlantic.com). Many of the instruments on these moorings have been discussed in preceding sections. They will be evaluated below in the context of early warning and detection of algal blooms using mooring technology.

Passive optical sensors. In principle, passive optical sensors (radiometers) are extremely well suited for early warning and detection, as well as long-term monitoring, of algal blooms. The presence of algae at the surface is detected continuously (during daylight) in ocean color and sun-induced fluorescence, and subsurface accumulations can be discerned in measurements of diffuse attenuation, measured with a string of sensors. Passive sensors have low power consumption (an important consideration for moorings) and, unlike fluorometers, which have to deal with physiological interactions between the light field and photosynthetic systems, they can be rigorously calibrated. In practice, problems are encountered with biofouling, some consequences of shading, and confounding optical influences of colored dissolved organic matter and suspended sediment. Still, there are very good reasons for believing that passive optical measurements from moorings will become a cornerstone of detection and monitoring of biological variability in aquatic systems, including algal blooms (Dickey 1991; White et al. 1991; Abbott and Letelier 1996; Cullen et al. 1997).

One operational sensor system is the Remote Electro-Optical Sensor (REOS) from Biospherical, Inc. (White et al. 1991; Morrow et al. 1999). Systems have been installed in several water reservoirs operated by the Los Angeles Department of Water and Power. The systems were designed to provide reservoir managers with the daily data needed to recognize and react to incipient algal blooms before water quality is degraded. The first prototype was deployed in 1989, with some success. The third generation systems measure spectral reflectance and spectral diffuse attenuation (upwelling and downwelling sensors, seven wavebands each, at 2 and 5m), ancillary measurements (YSI 600 for oxidation-reduction potential, pH and temperature), and surface irradiance. Algorithms were developed to estimate chlorophyll concentration accurately from passive optical measurements. Real-time data from the system are sent through armored cable (hydrowire), but other communications could be employed. The system supports early intervention of nuisance algal blooms and complements monitoring. Continuous daytime data from the system also provide useful information on episodic processes such as algal blooms, thermal destratification, and rain runoff events. A REOS system costs about $100,000 US, exclusive of the cost of the mooring. They have been effective in reservoirs - deployment in busy, rough coastal waters has not been tested. It is nonetheless noteworthy that this bio-optical system has worked well to describe biological variability, and that optical sensors from Biospherical have been deployed on many coastal and oceanic moorings. A thermistor string would provide more information on physical structure of the water column.

Passive optical systems have been developed by Satlantic, Inc. and deployed in coastal waters using simple weight-and-float moorings. The Tethered Attenuation Coefficient Chain Sensor (TACCS) has proven effective in characterizing biological and optical variability in coastal waters of Nova Scotia over deployments of several months. It measures ocean color (upwelling radiance in seven wavebands) at the surface, and downwelling irradiance above the surface (one or three wavebands) and at four depths (one waveband), with communication by cell phone or other options. Variation in ocean color revealed day-to-day variability of algal biomass, and patterns in the diffuse attenuation coefficient showed not only seasonal patterns in the vertical distributions of phytoplankton, but also the vertical migration of layers of phytoplankton and the sinking of a surface bloom (Figure 3.5). Cost for a system would be about US$25,000-35,000, depending on options. Incorporation in a rugged, proven mooring system might raise the cost to about US$125,000 US. The next generation of TACCS moorings can accommodate hyperspectral radiance and irradiance at the surface and four wavebands of downwelling irradiance at four depths. Satlantic reports that they have developed a mechanism to clean fouling from the windows of their radiance sensors. This could be an important development, because fouling would require fairly frequent checking of the sensors during coastal deployments.

Commercially available radiometric sensors can be incorporated into moorings in a variety of configurations. However, care must be taken to avoid problems with shading and changes in orientation. For many applications, these problems can be countered. Depending on requirements, optical systems can be configured to minimize cost (perhaps US $10,000 for rudiments of ocean color) or to maximize information ($100,000 for REOS-type suite of sensors).

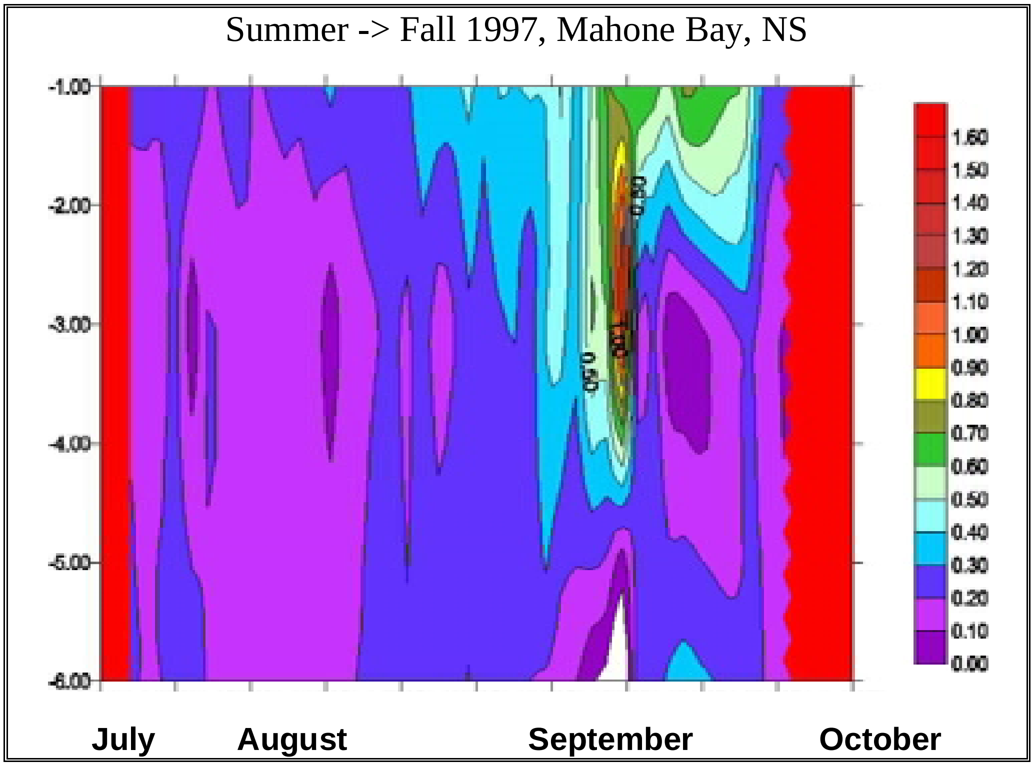

FIGURE 3.5. Diffuse attenuation coefficient at 490 nm (K_d(490); m^{-1}) in the upper 6 m, summer to fall 1997, Mahone Bay, Nova Scotia, Canada measured with a Tethered Attenuation Coefficient Chain Sensor. The sensor chain detected the consequences of summer stratification and the occurrence of a fall bloom. (Source: Satlantic, Inc.)

Active optical sensors. Fluorometers and instruments to measure absorption and attenuation were discussed in Section 3.4.1.5. If these instruments are to be deployed on moorings, biofouling and power consumption must be considered. If moorings are to be tended frequently (perhaps once per week), then fouling may not be much of a problem, provided instruments can be easily cleaned. Toxic coatings have been used to retard fouling, but these have only limited success. More recently, copper screening close to *in situ* sensors and copper tubing on flow-through sensors has effectively retarded fouling. It thus appears that moored active optical instruments should be used in the flow-through mode. This could be arranged for most of the instruments, with the added advantage of permitting more than one depth to be sampled sequentially through the same sensor package. Power consumption is still a problem: the SAFIRE spectral fluorescence meter may provide some of the most informative data on phytoplankton *in situ*, but it is also more power-hungry than many of the other instruments. The fluorescence of phytoplankton is depressed in bright light near the surface (Marra 1992; Cullen and Lewis 1995; Falkowski and Kolber 1995), so records of fluorescence at the surface during the day must be interpreted with caution.

CTD profiles. In coastal environments where salinity contributes significantly to density, a mooring should record temperature and conductivity. Much more could be described and understood if salinity and temperature could be measured in vertical profile. One approach is a string of CTD sensors (e.g., OCEANOR SeaProfiler, offered as one possible component of the Seawatch system). Strings could also be built from commercially available CTD units, but integration and communication would have to be developed. These problems have already been addressed in the Seaprofiler, and through the use of inductive modem technology, for example from SeaBird Electronics.

Currents. Currents at one point can be measured using several approaches (e.g., Marsh-McBirney electromagnetic current meter as used by Lee and Lee 1995). In many environments, depth-profiles of currents are a better complement to measurements of salinity and temperature, providing crucial data for the development and validation of models. An acoustic doppler current profiler is appropriate for this task. Downward looking and upward-looking acoustic doppler profilers are available. For example, SonTek (San Diego, CA; www.sontek.com/) can recommend a bottom-mounted, upward-looking unit for autonomous deployment for roughly $25,000 US. A 500 kHz unit can profile currents with maximum resolution of 1-m in depth and 0.1 cm/s in velocity. Choices for current-measuring devices would be strongly influenced by the needs of the user, for example the nature of the environment where the mooring is deployed (is advection important to algal dynamics at the site?), resolution of the model(s) to which the data might be applied, and the vertical resolution of the biological measurements that are made from the mooring.

3.4.2.4 Moored profiler

Brooke Ocean Technology, Ltd. offers a novel solution to the problem of characterizing vertical profiles of properties from moorings. Their SeaHorse Wave-Powered Moored Profiler (**www.brooke-ocean.com/s_horse1.html**) resides at depth and, on programmed cues, rises to the surface while recording data from a suite of sensors. At the surface, it can communicate its data. Then, a ratchet system engages, and the package climbs down the wire by harnessing wave action. A SeaHorse mooring was operated off Nova Scotia for five weeks in late 1997, profiling conductivity, temperature and turbidity over about 15 m of water (report by Jim Hamilton, Fisheries and Oceans Canada). The system performed well, as it has during several other deployments, for example with CTD and fluorescence (**www.brooke-ocean.com/graphs-sh-01.html**). Radiometric sensors (7 wavebands downwelling irradiance) could be incorporated into a SeaHorse package with CTD for about US $75,000 total. A fluorometer could also be included. A comprehensive system would include a surface buoy with downwelling irradiance at the surface and optional ocean color, CTD and ancillary measurements. In principle, such a system would be very effective and probably less susceptible to some of the hazards encountered by moorings. However, an integrated optics-SeaHorse package has not been tested to date.

SeaHorse technology may be particularly well suited for areas where tampering with buoys by third parties is a real concern. The SeaHorse instrument package resides near the bottom most of the time; only a float appears at the surface. If the mooring is attached to a very heavy weight (e.g., several railroad wheels), it could not easily be taken by small, fast boats. If a frustrated vandal cut the float, the instrument package would remain on the bottom, where it could be retrieved. Some modifications would have to be made to prevent the module from deploying when the line goes slack, and an alarm system with GPS should be installed to notify the user if the instrument is moved. These modifications would have to be developed.

Apprise Technologies, Inc. (www.apprisetech.com), has developed profiling systems based on buoyancy modulation. Their Remote Underwater Sampling Station (RUSS) can be outfitted with third-party sensors: it is generally connected to a buoy or platform with solar panels. The price range seems to be similar to SeaHorse.

3.4.3 SEAWATCH™ system

OCEANOR has developed SEAWATCH™, the only complete operational marine monitoring and information system available on the open market (Sørås et al. 1998). SEAWATCH is an integrated monitoring system, including: buoys equipped with instruments to assess a range of processes; other data sources such as satellites, coastal stations and research vessels; networks of observers, communication links; information processing (including analysis and forecasting), and information distribution (Johnsen et al. 1997; Tangen 1997). Applications include acquisition of surface meteorological observations and coastal zone management, oil spill contingency and oil spill forecasting, environmental monitoring and documentation (including radioactivity), as well as monitoring and forecasting algal blooms.

As of 1998, SEAWATCH systems had been installed in Europe, Thailand, Vietnam, and Indonesia, with deployments planned for Spain, Latvia and India (Sørås et al. 1998). Each system is tailor-made, representing a wide range of choices, depending on objectives. For example: SEAWATCH Europe is an on-line monitoring surveillance system for the North Sea, and a regional component of the Global Ocean Observing System (Stel and Mannix 1996); SEAWATCH Indonesia is an environmental monitoring, forecasting and information system; while SEAWATCH Vietnam is tailored to improve typhoon forecasting and monitoring capabilities (Sørås et al. 1998).

It is clear that SEAWATCH systems have a wide range of potential benefits that should be considered when contemplating the cost of such systems (Stel and Mannix 1996). Estimating costs of a new system is complicated, because each system is tailor-made, and different countries have different needs in terms of the complexity of their coastal environments and the amount of existing infrastructure available to support a system. It is difficult, and in fact unfair, to compare the costs of SEAWATCH to the other technologies for early warning and prediction of algal blooms, because only SEAWATCH is a fully integrated system, and in all likelihood SEAWATCH systems would serve a much broader range of users than an observation system specially designed to monitor and predict algal blooms. Still, it is necessary to have a rough idea of costs in order to evaluate SEAWATCH technology in the context of early warning and prediction of algal blooms.

3.4.3.1 Estimated costs and requirements for support

Buoys. Because each system is custom-built, it would be essential to consult with OCEANOR to obtain cost estimates. In a benefit-cost analysis of SEAWATCH, Stel and Mannix (1996) consider a ‘planning unit’ consisting of 10 buoys, with an annual cost of between US$2 and $3 million. The costs mentioned only relate to the buoys. The distribution of data is another expense that largely depends on the availability of software and hardware at the customer’s offices. The estimated costs for buoys would not include third party damage or other accidents. In busy waters, it is important to consider the potential consequences of such losses, and who bears the financial risk. Education of the local fishing community about the benefits of the system can reduce incidents of third party damage to buoys.

According to Mr. P. Sørås of OCEANOR, there is no minimum commitment related to number of years or number of buoys. Also, OCEANOR can include third party sensors, etc. on their buoys/systems. This flexibility is important, as the technologies for ocean observation from buoys is improving rapidly, and some third party sensors might be more effective than OCEANOR’s for particular applications. Mr. Sørås indicates that OCEANOR is quite happy to work with their potential customers and to conduct their own investigations to design and price the systems that best serves the needs of the user.

3.4.3.2 Monitoring algal blooms with SEAWATCH™

Capabilities of the system. The capabilities of SEAWATCH for monitoring algal blooms is well described by Johnsen et al.(1997) and Tangen (1997). Blooms have been observed, and their progression along the coastline has been well described. The Optisens LBA sensor has detected variations in attenuation that reflect algal dynamics, but identification of the species has been accomplished through conventional enumeration of samples collected manually (Stel and Mannix 1996). A network of observers in the coastal region is thus necessary for operational monitoring and forecasting of potentially harmful algae (Tangen 1997). Successes of SEAWATCH can be attributed to the efforts spent designing the structure, management and integration of the phytoplankton monitoring, which includes both high-tech (buoys) and low-tech (network of fish-farmers who act as samplers and observers) components. It is not clear from available information the degree to which the buoy system enhanced the monitoring capability of the network of observers. A published benefit-cost analysis (Stel and Mannix 1996) did not break down the relative benefits and costs of hi-tech vs. low-tech components of the SEAWATCH system.

3.4.3.3 Forecasting algal blooms with SEAWATCH™

OCEANOR employs the integration of data from several sources for producing forecasts of phytoplankton dynamics. During regular forecasting meetings, an analysis or assessment of present conditions is use as a basis for formulating predictions. The process is comparable to meteorological forecasting (Tangen 1997). However, as Tangen states, "phytoplankton forecasting is more primitive or non-mature than meteorological forecasting in the sense that operational, prognostic models are not yet available, and it is not realistic to expect that models in the near future will give indications on the species specific level for safe forecasting of toxic phytoplankton." This cautious assessment is consistent with a generally held view in the oceanographic/harmful algal bloom community that, although new technologies and approaches show great promise for the development of predictive simulation models for algal blooms using real-time data, the capability has not yet been developed. That is, "models are not presently capable of predicting the occurrence, distribution, toxicity, and environmental response of HABs" (GEOHAB 1998). Despite this somewhat gloomy assessment, planning groups for both GEOHAB (Global Ecology and Oceanography of Harmful Algal Blooms) and the Coastal Global Ocean Observing System (C-GOOS) have strongly endorsed further research and technological development toward coastal observation systems linked with forecasting models.

3.4.3.4 A general assessment of SEAWATCH for monitoring and predicting algal blooms

OCEANOR's approach to marine monitoring and prediction is consistent with strong trends in oceanography, and in many ways, SEAWATCH has led the way. As the only complete operational marine monitoring and information system available on the open market, SEAWATCH deserves very careful consideration by any user group committed to substantial improvements in marine monitoring. The capabilities of SEAWATCH are consistent with some key requirements of GOOS, the Global Ocean Observing System (Hansen 1995). If similar technologies are applied broadly throughout the world, capabilities for environmental assessment will improve, to the benefit of all. It seems appropriate, however, for the systems to include the most appropriate sensors, regardless of supplier.

The great strengths of OCEANOR and SEAWATCH, then, are their capabilities to integrate observation systems, and their real-world operational experience. Also, the data from SEAWATCH systems are valuable to a broad range of users, independent of the benefits for monitoring and prediction of algal blooms. This must be kept in mind when costs are considered. Consider an initial investment of several million dollars US, plus about US $500,000 per year for upkeep, roughly enough for an integrated system of 10 buoys. This investment could probably support a networked system of 30 vertically profiling moorings with CTD, fluorescence, and measurements of spectral diffuse attenuation and ocean color. Or, it would be enough for perhaps 20 fixed moorings with spectral absorption meters and CTD, and 20 underway systems on ferries, including nutrient analyses (these are very rough guesses). Taking another direction, it would be possible to support inexpensive monitoring systems for measuring temperature, salinity, fluorescence, oxygen, at several depths, plus irradiance and winds on fish farms (after Lee and

Lee 1995) in 25 mariculture regions, plus several telemetered buoys in more open water, leaving money for personnel committed to working with the data in the context of early warning and prediction of algal blooms. Each of these alternatives lacks the critical elements that OCEANOR can offer: integration of the system and proven success at implementation.

To summarize, SEAWATCH is a special product, reflecting OCEANOR's well developed capabilities for designing and operating ocean observation systems. Given the rapid developments in ocean observation technology over the past several years, it seems that, with respect to the harmful algal bloom problem, the best value could be obtained by designing new systems that exploit improved capabilities of third-party sensors.

3.4.4 Observations from Aircraft

Many blooms are visible at the sea surface, and sometimes the boundaries of blooms are clearly evident to an observer. It is thus reasonable to use aerial surveys to monitor and detect algal blooms, a practice that has been conducted for decades, for example off California in the 1960's. Blooms can be observed visually, through aerial photography or video, or by using a radiometer, either fixed-point or imaging. Phytoplankton can also be detected with laser-induced fluorescence (Hoge and Swift 1983), but this approach does not offer significant benefit-cost advantages for algal bloom detection.

3.4.4.1 Visual detection of blooms

Visual surveys of algal blooms can be very effective, if conducted by trained observers, such as is being done in the Puget Sound region (WA State, US) by fish farmers routinely and more intensively on emergency basis. Aerial surveys in conjunction with regular monitoring could be very useful in the early warning and prediction of blooms. For surveys near coastlines, the observer could sketch the distributions of blooms on a chart, which could be digitized and used for purposes of short-term forecasts (according to oil-spill models or more sophisticated hydraulic models). They could also be archived for the development of empirical models of the occurrence and movements of blooms. Visual observations can also be backed up by video or digital photography. Costs for this type of aerial monitoring would be low, especially if the observer could join surveys that were underway for other purposes. New systems integrate photographic images with GIS. A contingency plan would have to be in place for special surveys when harmful blooms are detected.

There are several limitations to visual detection of blooms. First, the identification and delineation of blooms is subjective. Also, the human eye can detect only fairly large differences in concentrations of phytoplankton in the water. Sometimes it can be difficult to distinguish reddish-brown blooms from muddy water, and subsurface blooms cannot be detected.

3.4.4.2 Quantitative observations of ocean color from aircraft

As discussed in Section 3.4.1.6, ocean color is a useful, though imperfect indicator of the distributions of phytoplankton in coastal waters. Generally, blooms of phytoplankton are detectable even in the presence of colored dissolved organic matter and suspended sediment (Carder and Steward 1985); sun-induced fluorescence is helpful in this regard (Gower and Borstad 1981), even though the relationships between fluorescence and chlorophyll are poorly resolved for phytoplankton near the surface (Cullen and Lewis 1995). Quantitative measures of ocean color are much more sensitive than the human eye to small changes in chlorophyll, and quantitative measurements can be entered directly into databases, so aerial surveys with quantitative radiometry are in principle far superior to visual surveys for characterizing the variability of surface phytoplankton in coastal waters.

Technical considerations. It is not a simple matter to obtain estimates of ocean color from an airborne radiometer, because upwelled light from the ocean is attenuated through the atmosphere, and light from other sources reaches the sensor and contaminates the signal (Figure 3.6). Consequently, steps must be taken to minimize and correct for contributions from: atmospheric scattering (sunlight that is scattered into the path of the sensor), sun-glint (sunlight that is reflected off the surface), and sky-glint (diffuse light from the sky that is reflected off the sea surface). It is also necessary to characterize solar irradiance (the reflectance of which constitutes ocean color), and the attenuation of irradiance through the atmosphere.

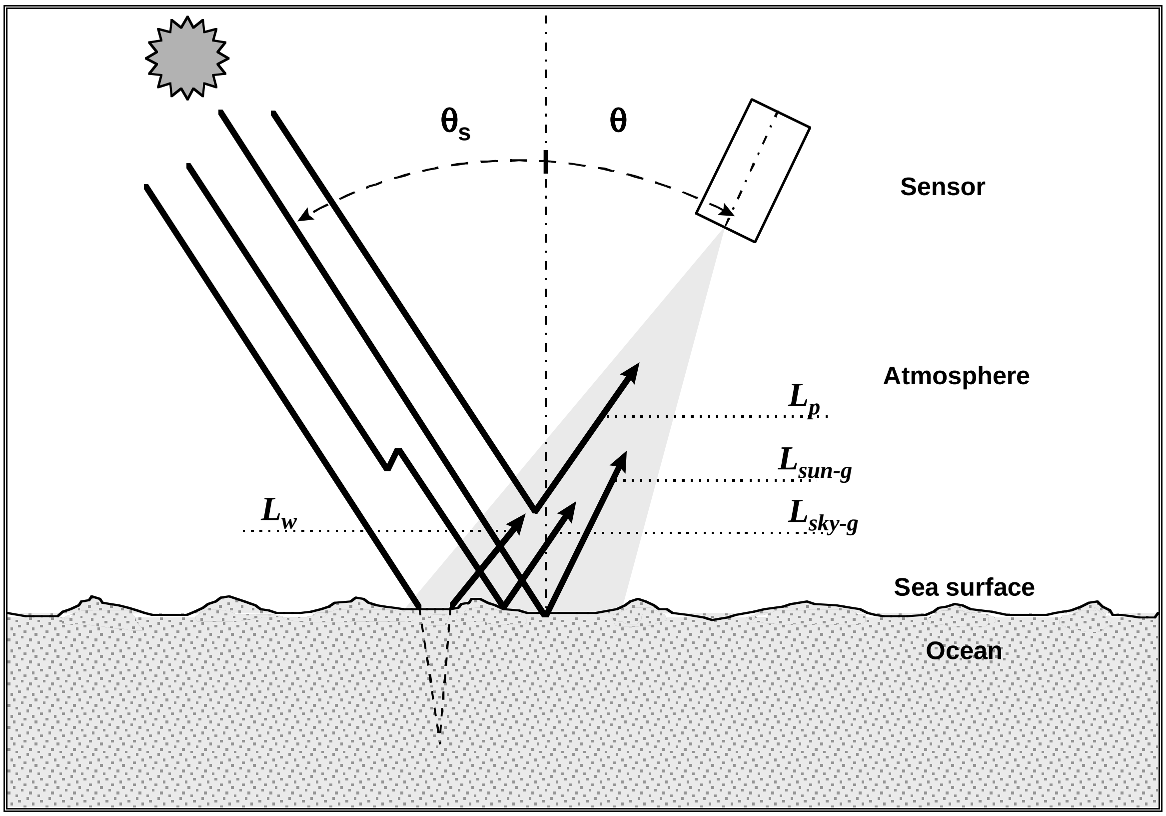

FIGURE 3.6. The different origins of light received by a remote sensor pointed to the ocean surface. L_p is path radiance (due to atmospheric scattering), L_{sun-g} is sun-glint radiance, L_{sky-g} is sky-glint radiance, and L_w is water-leaving radiance. To quantify ocean color (L_w in this figure), it is necessary to minimize or correct for the other contributions. (Source: Lazin 1998.)

Procedures have been developed to characterize atmospheric attenuation and to correct for atmospheric scatter. Corrections are relatively small for low-flying aircraft, and they can be checked for particular situations. Problems from sun-glint can be minimized by pointing the sensor away from the direction of the sun; bright outliers in the data are discarded for being contaminated by glint. This procedure works well when color is measured with a simple radiometer (i.e., a spectral sensor directed at one point, for example the SAS-II SeaWiFS Airborne Simulator from Satlantic — roughly US$26,000, including GPS). An imaging radiometer (discussed below) looks in more directions, so problems with glint can be greater.

There are several methods for dealing with sky-glint (see Lazin 1998 and references therein). Perhaps the best approach to getting quantitative data would be to fly an imaging radiometer with a SAS-II radiometer pointed in the appropriate direction to log more easily corrected and calibrated data for one line along the track. Corrections can be made under clear skies or uniform clouds, but partial clouds seriously compromise any correction scheme.

The problem of partial clouds can be visualized by looking at greenish waters under a sky with patchy clouds. A pattern of light green patches contrasts with darker, bluer water. An ocean-color sensor would interpret these green patches as having more chlorophyll (Gordon et al. 1988), and the pattern might be regarded as a patchy bloom. However, the real cause is that the indirect sunlight in the cloud-shaded water surrounding these patches is bluer, diffuse skylight, so the patches exposed to direct sun appear greener by comparison (Cullen et al. 1994). Consequently, it is recommended that quantitative remote sensing of ocean color be conducted only under clear skies or uniform cloud (Mueller and Austin 1995). Algal blooms do not respect such rules.

An additional problem with remote sensing of ocean color in coastal waters is the influence of submerged vegetation and the bottom, which can be significant in shallow waters. It can be concluded that any program of quantitative ocean-color remote sensing in coastal waters from aircraft would have to incorporate stringent quality control, and it would have to expect difficult-to-interpret data under unfavorable conditions. Still, it is very likely that imaging radiometry would be very useful for detecting algal blooms (see Figure 3.6).

3.4.4.3 Imaging spectroradiometer

There are a number of imaging spectroradiometers, appropriate for detecting algal blooms, that are in use or under development (e.g., Gower and Borstad 1990; Millie et al. 1992; Pettersson et al. 1993; Harding et al. 1995). We discuss here a commercially available turnkey system that has been widely used.

The Compact Airborne Spectrographic Imager (casi), from ITRES Research Ltd. (www.itres.com/) can be used from most aircraft platforms. It is one of the few commercially available imaging spectrographs in use worldwide. According to ITRES, multiple systems have been sold throughout Canada, Europe, Japan, and the United States. In addition, systems have been leased and utilized in the South Pacific, Southeast Asia, Africa, the West Indies, Central and South America. The casi technology has developed through time, and, judging by performance demonstrated in publications, the imager can be considered an effective tool for characterizing optical variability in coastal waters.

The instrument can be mounted on small fixed-wing aircraft, with some minor modifications, like a hole in which to mount the sensor head. Flying at 600m, casi can image a swath about 300 m wide, with a resolution of 60 cm. At 1200 m, it would be about 500 m wide with 1-m resolution. Data can be integrated into a GIS system. There are several other features to make the system appropriate for operational use. As mentioned above, imaging under patchy clouds is problematic. Under cloudy skies, the signal (upwelling radiance) is sometimes too small to measure precisely.

The cost for a casi system is in the range of about US$500,000. About 4 people would be required for support: a trained survey pilot, an operator/technician, a data analyst, and a scientist who understood the system and who could analyze the data critically and effectively. This represents a major commitment of money and resources, and would likely require recruitment of personnel with appropriate skills. It is likely that, in the near future, other systems will come on the market for lower prices, but a monitoring program would still require a large commitment of resources.

3.4.4.4 Satellite remote sensing

Remote sensing has long been considered a tool with great potential for monitoring the distribution of red tide organisms over larger spatial and shorter time scales than is possible with ship-based sampling. It has not yet fully lived up to this promise, however. Although multi-spectral scanners (e.g. Coastal Zone Color Scanner; CZCS, and Sea-viewing Wide Field-of-view Sensor, SeaWiFS) can be used to detect chlorophyll and other pigments from algae, these efforts have been constrained by the inability of the sensors to discriminate phytoplankton populations at the species level (Garver et al. 1994). In established, nearly mono-specific red tides, ocean color can nevertheless be useful, as was shown for several blooms of *Gymnodinium breve* (Steidinger and Haddad 1981; Tester and Steidinger 1997).

Another approach that is not dependent on identifiable pigments requires that specific water masses be linked to red tide blooms, and those water masses are then tracked with an appropriate remote sensing technique. Remotely-sensed sea surface temperatures (SST) have been used to follow the movement of fronts, water masses, or other physical features where toxic species accumulate. A coastal current that dominates the dynamics of *Alexandrium tamarense* in the southwestern Gulf of Maine is easily identified by its temperature signature (Keafer and Anderson 1993). Likewise, the long-distance advection of *Gymnodinium breve* from Florida into the nearshore waters of North Carolina via the Gulf Stream was documented with this SST approach (Tester et al. 1991). These successes in tracking blooms within water masses (see also Gentien et al. 1998) suggest that, if blooms are detected and water masses defined, movements of the blooms can be forecast.

Even though ocean color is unlikely to provide adequate information to determine species composition (but see Schofield et al. 1999), remote sensing can be very useful in studies of HABs. For example, remote sensing can provide the oceanographic context for areas where HABs occur. Satellite sensors can provide data to describe patterns of wind, rainfall (between 40°N to 40°S), sea surface temperature, sea surface height (thus geostrophic currents), salinity and ocean color, although of coarser resolution than desirable to describe key aspects of algal bloom dynamics (cf. Uno and Yokota 1989). These data would provide insights into models of algal development, in some cases providing good information on the transport of blooms. New satellite sensors will have better spatial and spectral resolution for ocean color, and thus may be even more useful.

3.4.4.5 Remote sensing and forecasts of bloom dynamics

This integration of real-time and near-real-time environmental observations into atmospherically-forced numerical simulations of ocean processes is an example of data assimilation modeling (the procedure used in operational meteorology). The essential feature of data assimilation models is that information is used not only to initialize a forecast model, but newer observations are used to correct the model, so simulations of present conditions and predictions of future changes are as accurate as possible (see Schofield et al. 1999). Data-assimilation modeling of coastal processes is being actively pursued by research groups in many countries. The incorporation of biological processes into these models is only in its infancy, so operational forecasting of algal blooms does not yet utilize operational, prognostic models of species-specific bloom dynamics (see Section 3.4.3.2).

3.4.4.6 Remote sensing and research on algal blooms

The present situation is still one of potential rather than actual application of remote sensing as a forecasting or prediction tool for HABs. Cloud cover and the need for high-resolution imagery may obviate the use of remote sensing for operational forecasting. However, there are strong reasons for using remote sensing as a research tool to develop empirical and conceptual models of bloom development and transport. Studies are needed that obtain satellite images of ocean color and SST concurrent with field measurements on bloom distribution or toxicity under a variety of meteorological conditions. With sufficient background information of this type, development of conceptual models will be possible, allowing observations from a variety of sources, including remote sensing images (if available) to be used for actual forecasts of impending outbreaks along specific sections of the coast. Progress in this area should be rapid in the immediate future, due to the launch of several satellites designed to collect ocean color data, including satellites (**www.ioccg.org/sensors/500m.html#2**).

The US Department of the Navy is developing a satellite-based hyperspectral ocean color imager with a planned launch date in the year 2001. The satellite, Navy EarthMap Observer (NEMO), will have a 2.5 day site reaccess time, and a 3-5 year mission lifetime. The hyperspectral sensor, Coastal Ocean Imaging Spectrometer (COIS), will have 10 nm spectral resolution in the visible to near-infrared and also short-wave to infrared, with excellent signal-to-noise ratio. A typical scene will be 30 km wide by 200 km in length, with 30 m by 30 m pixel resolution, yielding nine image strips per orbit (number of strips limited by on-board data storage capacity). A co-aligned 0.45-0.68 micron Panchromatic Imaging Camera (PIC) with 5 m resolution will also be on board. The aircraft sensor that most resembles COIS in signal-to-noise ratio, footprint, and spectral resolution is the Airborne Visible / Infrared Imaging Spectrometer (AVIRIS). COIS and PIC are designed to provide hyperspectral data on spatial scales comparable to optical features typical of coastal regions. This tool will be used in targeted research by the US Office of Naval Research. Commercial applications (mostly land-based) will also be developed. The technology, if shown to be robust, should be very effective in the remote sensing of algal blooms in coastal waters.

A great deal of research on remote sensing in coastal waters is being conducted in many countries. Advances are likely to be rapid. Research is especially cost-effective, because operational use of satellite data can be very expensive.

3.4.5 Modeling

As discussed above, operational forecasting of algal bloom dynamics seems not to be possible at this time, even though retrospective analyses have been quite successful at describing important factors that influence the distributions and persistence of algal blooms. The lesson to date is that as better and better observations of algal distributions in relation to environmental factors are accumulated, better and better models follow. Eventually, predictive capabilities will develop and improve. Availability of observations to test and refine these predictions (i.e., data from a network of sensors and information from monitoring programs) is essential for progress toward the goal of prediction with measurable accuracy.

Important decisions relevant to mitigation of harmful blooms rely on empirical or conceptual models relating algal population dynamics to environmental forcing, such as climate variability (e.g., El Niño) or human influences such as nutrient loading. In some regions a great deal of work has been done addressing the influences of nutrient loading on the occurrence and nature of algal blooms. Evaluation of the conclusions and implicit predictions of these studies can only be improved if observation systems are upgraded so that more data can be acquired with improved temporal and spatial resolution.

Simulation models can be effective in revealing which factors dominate in the control of algal bloom dynamics. Water quality models incorporate information on many processes that influence the distributions of nutrients, oxygen, phytoplankton and light. Rarely can the models be parameterized using data from the environment to be modeled, or the target species to be considered. Consequently, although species groups can be treated simultaneously, the conditions that lead to the dominance of a particular species are difficult to resolve with such detailed, but still generalized, models. Nevertheless, multiparameter simulation models can be an important tool to explore the controls (e.g., nutrient loading, light, tidal flushing) on the biomass and growth rates of phytoplankton in particular environments.

Large amounts of information on the physiology and behavior (or sinking characteristics) of individual species is key to understanding its dominance in particular environments - the better the information, the better the description. Knowledge of the interactions of algal behavior and physiology with hydrographic forcing (e.g., Yamamoto and Okai 2000) has allowed the description of important features of the dynamics of *Prorocentrum mariae labouriae* in the Chesapeake Bay (Tyler and Seliger 1981), *Gymnodinium catenatum* off the coast of Spain (Figueiras et al. 1998), and *Heterosigma akashiwo* (Taylor 1993; Rensel 1995) and *Chatonella antigua* in the Seto Inland Sea of Japan. A recent study by Amano et al. (1998) epitomizes what can be done with the results of years of study on an organism. They simulate nutrient uptake (nitrate, ammonium, phosphate) of *C. antiqua*, as affected by light, temperature and vertical migration in a model that includes zooplankton grazing, advection and dispersion. The results of their modeling are quantitatively consistent with hypotheses that had been developed about the environmental conditions that promote the growth of *C. antiqua* in the Seto Inland Sea. This work exemplifies the best that can be done at this time. The model relies on species-specific information that required many years of targeted research. Application of this approach to different species would likely require similar background work. Another complication is that information on a species isolated from one region might not apply to the same species from elsewhere. For example, the vertical migration patterns and nocturnal nutrient uptake of *Alexandrium tamarense* from the Gulf of St. Lawrence, Canada (MacIntyre et al. 1997) are not shared by a strain of *A. tamarense* from Casco Bay, Maine (Poulton 2000).

One can conclude that continued research is extremely important to understanding and modeling algal dynamics, and that environmentally relevant work on individual species (local strains) should be emphasized, if it is feasible. However, it seems that the best predictions, for some time to come, will be made by people who have worked on the problem for a very long time, and have accumulated a great deal of information on which to base assessments and forecasts.