Algorithm Development for Recovering Chlorophyll Concentrations in the Chesapeake Bay Using Aircraft Remote Sensing, 1989-91*

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Abstract

A study using aircraft remote sensing of chlorophyll concentrations was conducted in the Chesapeake Bay from 1989 to 1991. The goal was to improve spatial and temporal resolution of the distribution of phytoplankton in this highly dynamic and variable estuary. The focus of the study was on improving our ability to estimate chlorophyll a [Chl a] *from aircraft by developing local algorithms for individual years, and by exploring the use of seasonally and spatially specific algorithms. Our findings suggest that an overall, multi-year algorithm can be used predictively to estimate the distribution of* Chl a *i.e., the location, duration, and spatial extent of phytoplankton blooms — in near real time—. Refinements that improve the recovery of* Chl a *include the separation of spring data from the data for other seasons, and the use of separate local algorithms for regions of low and high turbidity. These developments improve the accuracy with which we recover* Chl a *in the Chesapeake Bay using aircraft remote sensing, and have implications for the detection of changes in algal biomass that are expected to accompany nutrient reductions between now and the turn of the century. Our results suggest that the shipboard sampling of the Monitoring Program may underestimate the biomass of phytoplankton blooms and, hence, the amount of particulate carbon produced in the Bay. This finding has ramifications for detecting changes in phytoplankton abundance that are expected to accompany nutrient reductions, and for processes such as hypoxia (i.e., low oxygen concentrations) that are driven by organic material derived from the spring phytoplankton bloom in the mesohaline region of the Chesapeake Bay.*

Introduction

Estuaries are very heterogenous bodies of water that exhibit strong gradients in both conservative and non-conservative properties. One highly variable, non-conservative property is the concentration of chlorophyll, reflecting spatial and temporal variations in the distribution and abundance of phytoplankton. The concentration of chlorophyll is an important measure of water quality in estuaries because these systems have a propensity for eutrophication from anthropogenic inputs of nutrients.

The Chesapeake Bay has experienced cultural eutrophication over the past three centuries. Deforestation of the watershed, increased agriculture, and population growth since colonization have had significant impacts on this productive estuary (U.S. EPA, 1983). Intense efforts to reverse the negative trends in water quality associated with man's activities have been undertaken in the 1980s and are focused on the reduction of nutrient inputs (Boynton *et al.*, 1982; D'Elia *et al.*, 1986; Correll, 1987; Fisher *et al.*, 1988). Of paramount importance is the legislative mandate to reduce nitrogen and phosphorus inputs 40 percent by the turn of the century. This step is expected to lessen the growth of phytoplanktonic algae, reduce the substrate available for seasonal, microbial degradation culminating in hypoxic conditions, and eventually lead to replenished stocks of stressed commercial fisheries (Harding *et al.*, 1992b).

As the desired improvements in water quality begin to occur, it is important that we quantify the distribution of chlorophyll accurately to detect lowered concentrations that should result from the reduction of nutrient inputs. To address the need for data on phytoplankton abundance, the Bay-wide Mainstem Monitoring Program of Maryland and Virginia measures "water quality" at time scales from weeks to years. Among the parameters that are monitored are chlorophyll *a* [*Chl a*] and phaeopigments, phytoplankton species composition and productivity, temperature, salinity, water transparency, nutrient concentrations, toxics, and dissolved oxygen. However, the dynamics of phytoplankton populations in estuaries make even intensive shipboard studies inadequate for determining the concentrations, spatial extent, longevity, and biomass of phytoplankton. It is critical that data with improved spatial and temporal resolution be obtained to enable a separation of *changes* in the distribution and abundance of phytoplankton from the *variability* that is known to be very high in the Chesapeake Bay.

To overcome the limitations of shipboard sampling, we

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have been using aircraft remote sensing of ocean color from 1989 to 1991 to measure chlorophyll concentrations in the Bay. Our initial interest was to scale the size and longevity of the winter-spring bloom in the estuary. This annual event occurs from March to May in most years, and is principally composed of large, centric diatoms that attain high population densities in the mesohaline to polyhaline regions of the Bay. The ecological significance with respect to estuarine and coastal nutrient loading is the particulate organic material that is produced in these diatom blooms. This material is the major substrate that fuels high rates of microbial metabolism, culminating in low dissolved oxygen conditions in bottom waters during spring and summer.

Earlier papers described the development of algorithms for recovering chlorophyll concentrations from remote measurements of upwelling radiance in the blue- to blue-green region of the visible spectrum (Harding and Itsweire, 1991; Itsweire *et al.*, 1991; Harding *et al.*, 1992a). This paper describes seasonal and spatial differences in the relations of upwelling radiance to chlorophyll based on the three years of data obtained in our program. We present the local chlorophyll algorithms developed using matching ODAS data and *in situ* data for 1989 through 1991.

Methods

The ODAS instrument package has three radiometers with 15 nm bands in the blue to blue-green part of the visible spectrum (R_1 = 460 nm, R_2 = 490 nm, R_3 = 520 nm), an infrared temperature sensor (PRT-5), downwelling irradiance sensors (modified Li-Cor) at the ODAS wavebands, Loran-C navigation, and a PC for data acquisition. The upwelled radiance with a 2° field of view is sampled every 0.1 s. The Loran-C updates at approximately 8-s intervals. The instrument is generally flown at an altitude of 500 feet and 100 knots (~50 m s^{-1}), giving a spatial resolution of 5.2 m (5 by 50 m when averaged over 1 s). ODAS operates as a line-of-flight (not scanning) instrument.

We conducted 16 flights from 13 March to 18 July, 1989, 28 flights from 14 March through 28 September, 1990, and 31 flights from 17 February to 16 September, 1991 (Figures 1a, 1b, and 1c). The DeHavilland "Beaver" operated by the Virginia Institute of Marine Science was used for all of our flights. Flight tracks were designed to provide both lateral and along-axis coverage of the Bay, and to coincide with shipboard sampling by the Chesapeake Bay Program (CBP)-sponsored Monitoring Program. An example of typical daily coverage for 15 May 1990 is shown as Figure 2.

The radiances from three channels, R_1, R_2, and R_3, are treated with a spectral curvature algorithm (Grew, 1981) of the form shown in Equation 1 to obtain estimates of the concentrations of chlorophyll or pigment: i.e.,

$$\text{Log}_{10}[Chl \text{ or } Pigment] = a + b\,(-Log_{10}\,G) \quad [1]$$

where $G = [(R_2)^2/(R_1R_3)]$, and a and b are constants that are determined empirically using *in situ* chlorophyll concentrations. The output of the curvature algorithm is less responsive to variations in incoming solar radiation than is the simple ratio algorithm (Campbell and Esaias, 1983), and we have found it to be useful for recovering chlorophyll concentrations from remotely sensed radiances in the Chesapeake Bay (Harding and Itsweire, 1991; Harding *et al.*, 1992a).

The main sources of *in situ* data are semi-monthly to monthly cruises conducted by the Monitoring Program and transect data provided by the University of Maryland's Land-Margin Ecosystem Research (LMER) program sponsored by the National Science Foundation. The relations between shipboard measurements of chlorophyll and radiances measured from aircraft are determined using data that match within ± 1 day, and ± 0.01° latitude and ± 0.005° longitude. Some comparisons of shipboard and aircraft data have been restricted to same-day matches, as the data would permit, to minimize temporal differences in the data comparisons.

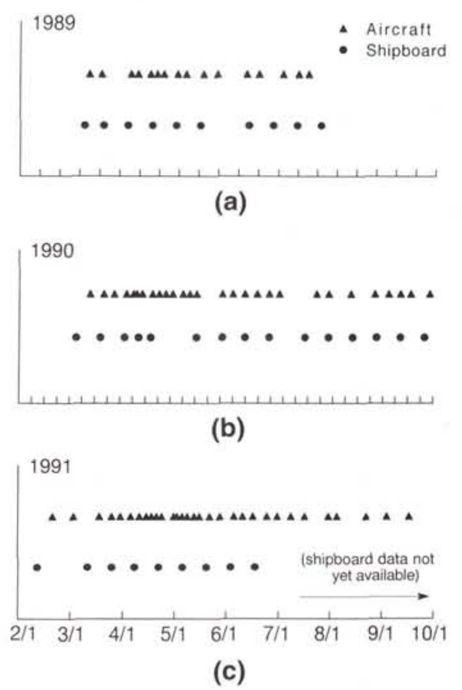

Figure 1. Dates of ODAS flights and Monitoring Program cruises, 1989 through 1991.

Flight data were processed on a UNIX workstation using software we developed to check for errors in the navigation data, eliminate radiance data affected by sun glint, average radiances from the data collection frequency of 0.1 s to 1-, 2-, or 5-s averages, merge the navigation and radiance data files, and grid and interpolate the data using an octant search approach. Details of the methods have been presented elsewhere (Harding and Itsweire, 1991; Harding *et al.*, 1992a).

Results

The approach we have used to assess the accuracy of chlorophyll estimates obtained from radiances measured with ODAS has been described previously (see Harding *et al.*, 1992b). Briefly, we have compared (1) the matching aircraft and shipboard data using linear regressions of *in situ* chlorophyll data on outputs of the spectral curvature algorithm to produce local algorithm(s); (2) maps of the chlorophyll distributions from ODAS flights to maps of the *in situ* data from the Monitoring Program; (3) the frequency distributions of data from aircraft and shipboard studies; and (4) data from direct fly-overs wherein aircraft and shipboard measurements were made within 1 h. In this paper, we focus on separations of the matching aircraft and *in situ* data by year, season, and

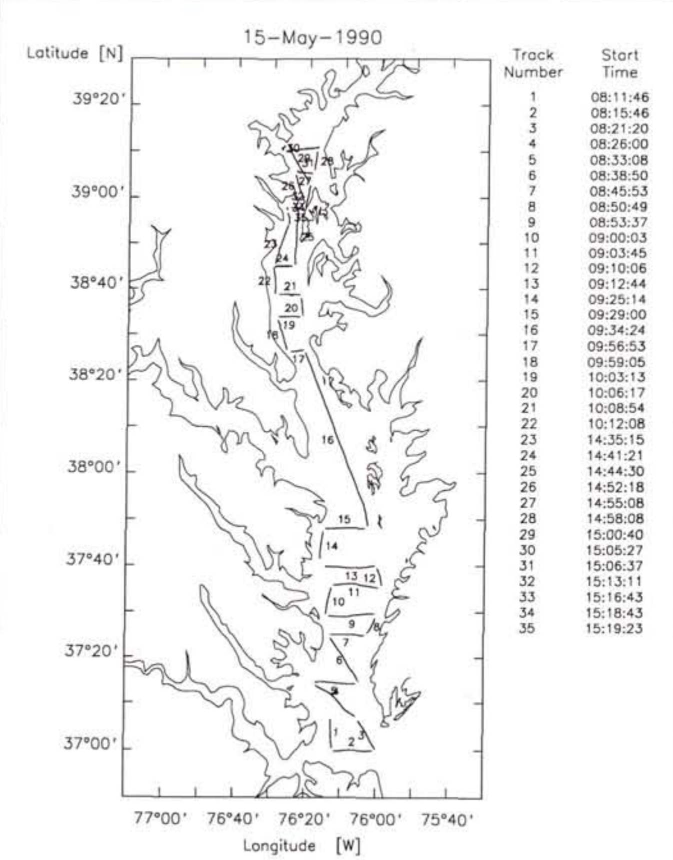

Figure 2. Flight tracks for ODAS in the Chesapeake Bay, 15 May 1990.

geographic location using a correction for turbidity, in order to develop improved algorithms for recovering *Chl a*.

Interannual Comparisons of Local Algorithms

Significant relationships ($p < 0.0001$) were derived for each of the three years of the study for matching *in situ* chlorophyll concentrations and the outputs of the spectral curvature algorithm, $-\text{Log}_{10}\, G$ (Figures 3a, 3b, and 3c). Equations 2 through 4 describe these regressions.

$$\text{Log}_{10}\, Chl\ a = 0.784 - 20.74\ \text{Log}_{10}\, G \quad (1989) \qquad [2]$$

$$\text{Log}_{10}\, Chl\ a = 0.869 - 17.26\ \text{Log}_{10}\, G \quad (1990) \qquad [3]$$

$$\text{Log}_{10}\, Chl\ a = 0.808 - 11.54\ \text{Log}_{10}\, G \quad (1991) \qquad [4]$$

The cumulative data from 1989 to 1991 are shown in Figure 3d, and the regression is given as Equation 5.

$$\text{Log}_{10}\, Chl\ a = 0.833 - 16.36\ \text{Log}_{10}\, G\ (1989\text{-}91) \qquad [5]$$

The regression statistics for these relations are presented in Table 1. RMS (root mean square) residuals for the regressions ranged from 0.226 to 0.320 (Log units), over a *Chl a* range of about 10^2 mg m^{-3}, with an RMS residual for the cumulative 1989 to 1991 data set of 0.286. This indicates a recovery of *Chl a* at an accuracy comparable to that of the Nimbus-7 Coastal Zone Color Scanner (CZCS) for general cases (Gordon and Morel, 1983; Smith *et al.*, 1987). Earlier work with two other aircraft instruments, the Multichannel Ocean Color Sensor (MOCS) and the Airborne Oceanographic Lidar (AOL), on Nantucket shoals recovered *Chl a* with a higher accuracy for synoptic comparisons (Campbell *et al.*, 1985). Those analyses were for waters of Case 1 optical properties ("blue water", oligotrophic open ocean conditions) and for comparisons of aircraft and *in situ* data that were very close in time and space, as discussed by Smith *et al.* (1987).

Our acquisition of matching data relied on ships of opportunity from the Monitoring and LMER programs and we could not always assure coincident sampling. Nonetheless, the abundance of data from these sources allowed us to select data that matched within reasonably narrow time and space windows, and served the purpose of developing annual algorithms. It is preferable to conduct concurrent sampling from aircraft and ship, as we reported earlier for an experiment using ODAS and AOL (see Harding *et al.*, 1992a), as the fits of aircraft and *in situ* data can be improved by lessening the time and space differences in sampling. But, for the purpose of developing a general, local algorithm, the approach we used was successful and encompassed a variety of conditions that occur seasonally and spatially in the Chesapeake Bay.

For the three years of data, there were sufficient interannual differences in the local chlorophyll algorithm to warrant correction of individual (annual) data sets derived from aircraft remote sensing once *in situ* data became available 6 to 12 months after each year's sampling (see Figures 3b, and

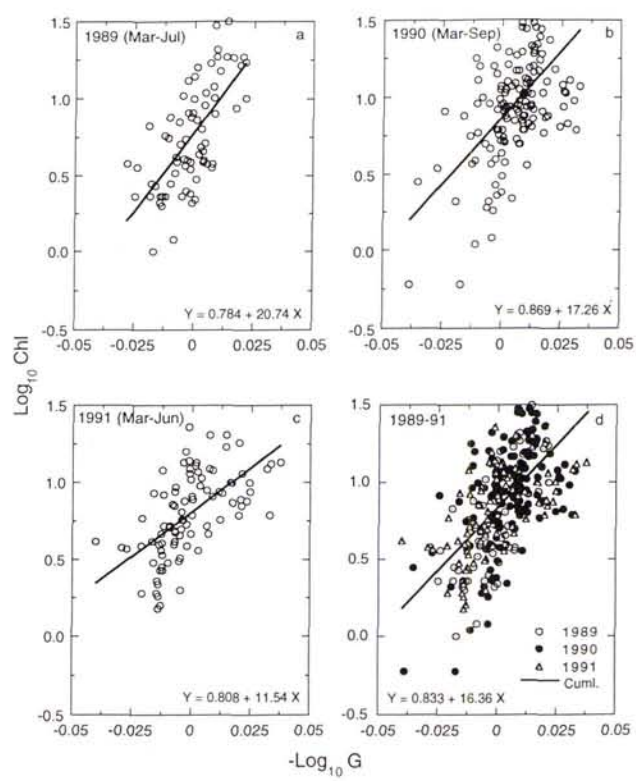

Figure 3. Regressions of matching $-\text{Log}_{10}\, G$ from ODAS and $\text{Log}_{10}\, Chl$ from *in situ* measurements for 1989 through 1991.

Table 1. Regression Statistics for Relations of Log_{10} *Chl a* to $-Log_{10}$ *G*, 1989 through 1991.

Regression	*n*	r_2	Slope	95% UL	95% LL	Intercept	RMS Residual	*p*-value
1989[a]	73	0.446	20.74	26.21	15.27	0.784	0.257	0.0001
1990[a]	152	0.302	17.26	21.45	13.08	0.869	0.320	0.0001
1991 (Feb-Jun)[a]	94	0.368	11.54	14.68	8.41	0.808	0.226	0.0001
1989-91 (cuml.)[a]	319	0.365	16.36	18.75	13.97	0.833	0.286	0.0001
1989[b]	11	0.818	17.40	23.60	11.20	0.830	0.144	0.0001
1990[b]	13	0.766	14.66	20.04	9.29	0.787	0.181	0.0001
1991 (Feb-Jun)[b]	14	0.796	8.67	11.42	5.91	0.829	0.107	0.0001
1989-91 (cuml.)[b]	17	0.628	13.83	19.69	7.98	0.765	0.278	0.0001
Spring 1990[b]	9	0.720	31.63	49.25	14.02	0.773	0.309	0.0038
Spr 90, $k_t<1.0m^{-1}$[b]	9	0.723	31.68	49.20	14.15	0.773	0.308	0.0037
Spr 90, $K_t\geq1.0m^{-1}$[b]	7	0.472	17.71	39.25	−3.82	0.926	0.222	0.0881[NS]

[a]regression of unbinned data
[b]regression of data binned at 0.005 intervals of $-Log_{10}$ *G*
[NS]not significant, $p>0.05$

3c). These differences may be associated with interannual variability in properties other than the bulk pigment concentration that contribute to the upwelling radiance signature, i.e., concentrations of dissolved and particulate materials, species composition of phytoplankton, and complement of algal pigments, including other light-harvesting components. They may also reflect sampling differences between years, as the interval sampled in each of the three years of our study differed, i.e., March to mid-July, 1989; February through September, 1990; and March through September, 1991 (the complete set of *in situ* data for 1991 was available only through June as of this writing). Thus, the differences in local algorithms derived from the matching aircraft and shipboard data for 1989, 1990, and 1991 may be, in part, the result of sampling differences.

Local Algorithms Produced by Binning of Data

We binned, i.e., grouped the data for specified intervals, the matching aircraft and *in-situ* data and recomputed the regressions from the mean *Chl a* in each bin and the centerpoint of the bin. This approach was used to eliminate bias in the local algorithm(s) (see Figures 3a through 3d) that is associated with the large differences in spatial and temporal coverages afforded by the two methodologies, i.e., to minimize the bias toward the mean value at the expense of the extremes that are better sampled in the aircraft surveys. Figures 4a through 4d depict the local algorithms that resulted from binning of the data in increments of 0.005 $-Log_{10}$ *G* for each year and for the cumulative data set of 1989 through 1991. Binning of the data eliminated much of the scatter associated with unequal sampling from aircraft and ships. The statistics for these regressions are also presented in Table 1.

The distributions of both ODAS and shipboard *Chl a* are lognormal and unequal in sample size. For scale, the collection of data from all flights/cruises from 1989 through 1991 produced aircraft estimates of *Chl a* with a sample size of ~153,000 based on 5-s averages (250-m along-track resolution), compared to a sample size <1,800 for the corresponding shipboard sampling at fixed stations (see Harding *et al.*, 1992b). These characteristics of the shipboard data and their collection reduce the chance of sampling either very high or very low concentrations, as compared to the chance of sampling the average concentration.

In the much smaller set of matching aircraft/shipboard data, the problem is exacerbated by the restriction of comparisons to flights/cruises that fall within a day of one another. This makes the chances of concurrently sampling from aircraft and ship extremely high concentrations of chlorophyll in ephemeral, localized blooms diminishingly small. The chances of sampling very low concentrations are reasonable if they persist for a significant period of time over a substantial area of the Bay, as occurs in late spring through summer in the polyhaline region of the estuary (<37.5° N. Lat.).

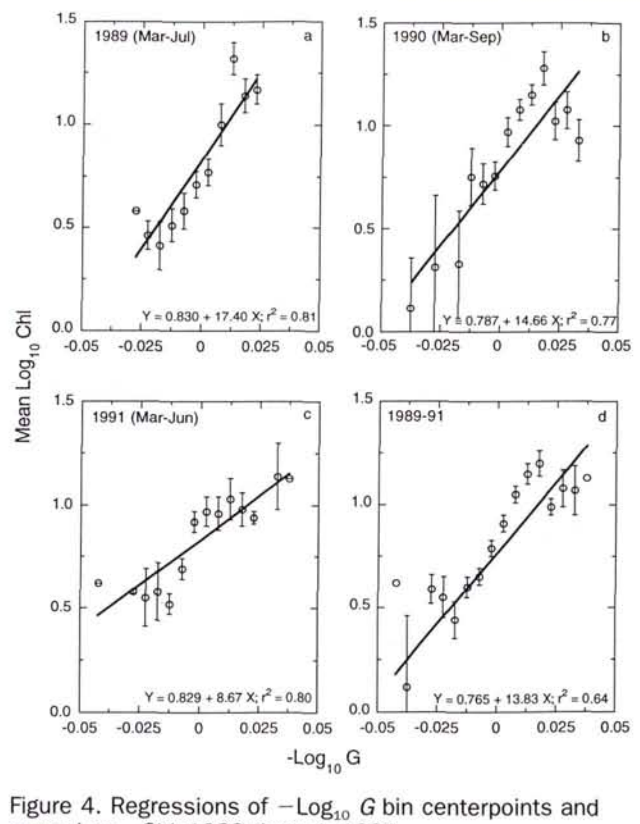

Figure 4. Regressions of $-Log_{10}$ *G* bin centerpoints and mean Log_{10} *Chl*, 1989 through 1991.

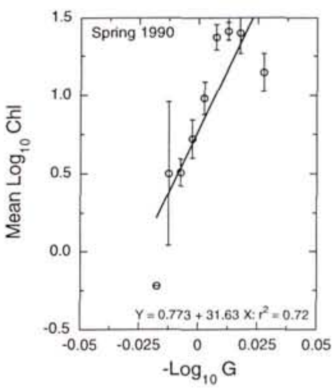

Figure 5. Regressions of $-\text{Log}_{10}$ *G* bin centerpoints and mean Log $_{10}$*Chl* for spring 1990.

Based on these findings, we suggest that an overall relation derived from the binned data and covering several years of sampling, such as is shown in Figure 4d, may be used to provide general information on the distribution of chlorophyll in near real time. With an algorithm of this form, we can determine when and where blooms occur, and define their spatial scale and longevity in a predictive manner. Such an overall algorithm is very useful as it takes into account interannual variability that is known to be high in the Chesapeake Bay, and produces an acceptable estimate of the chlorophyll distribution. It follows that improved accuracy in retrieving *Chl a* should be attained by using more specific algorithms. For example, once shipboard data become available for individual year(s), they may be used to refine *Chl a* estimates and improve the accuracy of *Chl a* recovery. These refinements are discussed in the following sections.

Seasonal Comparisons of Local Algorithms

The principal factor we expected would contribute to differences in the local chlorophyll algorithms was the *seasonality* of properties influencing the upwelling spectral signature. As discussed previously, there is a pronounced transition in phytoplankton species composition in the Chesapeake Bay during spring; both the size structure and the taxonomic composition of the flora change in mid-May to early June from large diatoms to small flagellates. This transition coincides with increased vertical density stratification, decreased turbidity as flow from the Susquehanna River subsides, vernal warming of the surface mixed layer, and a shift from silicon and phosphorus limitation in winter-spring to nitrogen limitation in summer.

For 1990, the year with the best spatial and temporal coverage, we analyzed the spring ODAS data and *in situ* data separately from the summer and fall data. (Note: there are also sufficient data for this separation for 1991, but the *in situ* data for summer-fall are incomplete at this time.) Separating the matching data by season produced the relation between Log_{10} *Chl a* and $-\text{Log}_{10}$ *G* shown in Figure 5, as distinguished from the relation for the entire year (1990), shown in Figure 4(b). The significance of implementing a seasonal algorithm is addressed in the Discussion section using an example from 15 May 1990.

Spatial Separation of Data Based on Turbidity

The spatial gradient in turbidity in the Chesapeake Bay is pronounced, decreasing from north to south as flow from the Susquehanna River at the northern extreme dominates the input of suspended particulates to the Bay. This produces a corresponding spatial gradient in the diffuse attenuation coefficient, K_t, that has the potential to affect the relationship between *Chl a* and the upwelling radiances measured with ODAS. To develop a correction for this effect, we examined the influence of turbidity on the local *Chl a* algorithm by separating the station data from the Monitoring Program into two categories, $K_t \geq 1.0\ \text{m}^{-1}$ (high turbidity) and $K_t < 1.0\ \text{m}^{-1}$ (low turbidity). This K_t value was used because areas of the Bay with $K_t \geq 1.0\ \text{m}^{-1}$ are considered to be strongly light-limited, whereas areas with $K_t < 1.0\ \text{m}^{-1}$ are more likely to be nutrient-limited (Harding *et al.*, 1986; Fisher *et al.*, 1988; Fisher, 1992). It should be noted that the strong covariance of K_t with latitude makes a geographic separation of the data useful, as well, in correcting the local chlorophyll algorithm for the influence of non-living particulates that dominate the attenuation of light in the upper estuary.

The original separation of data by K_t was done for 1989 data, and is reported in Harding and Itsweire (1991) and Harding *et al.* (1992a); the relations we reported for different turbidity regimes are given as Equations 6 and 7. The effect of high turbidity was a decrease in the intercept (0.911 to 0.642) and slope (22.13 to 11.68).

$$\text{Log}_{10}\ Chl\ a = 0.911 - 22.13\ \text{Log}_{10}\ G, \quad K_t < 1.0\ \text{m}^{-1} \quad (1989) \qquad [6]$$

$$\text{Log}_{10}\ Chl\ a = 0.642 - 11.68\ \text{Log}_{10}\ G, \quad K_t \geq 1.0\ \text{m}^{-1} \quad (1989) \qquad [7]$$

These results were consistent with an analysis given by Campbell and Esaias (1983), suggesting that the recovery of *Chl a* from ODAS data may be improved by using specific equations based on *in situ* K_t. A more extensive data set was acquired in 1990 from the greater number of flights and shipboard measurements. We pursued a correction of the local *Chl a* algorithm for turbidity using binned data and the same criterion, $K_t < 1.0\ \text{m}^{-1}$, as for the 1989 data. The relationships derived are given as Equations 8 and 9, and are depicted in Figures 6a and 6b.

$$\text{Log}_{10}\ Chl\ a = 0.773 - 31.68\ \text{Log}_{10}\ G, \quad K_t < 1.0\ \text{m}^{-1}\ (1989\text{-}91) \qquad [8]$$

$$\text{Log}_{10}\ Chl\ a = 0.926 - 18.54\ \text{Log}_{10}\ G, \quad K_t \geq 1.0\ \text{m}^{-1}\ (1989\text{-}91) \qquad [9]$$

These results confirm published results for the 1989 data (Harding and Itsweire, 1991; Harding et al., 1992a), generating distinct algorithms for recovering *Chl a* in the northern part of the estuary where K_t tends to be higher and the southern part of the estuary where K_t is generally lower. This outcome suggests that an independent measure of K_t made concurrently with measurements of upwelled radiances could be used to improve the initial estimates of *Chl a*. One possible approach to obtain this information in near-real time is the use of visible channel AVHRR imagery to generate estimates of the K_t distribution in the Bay. This method was developed by Stumpf (1988), and we are presently testing the accuracy of K_t recoveries for the period of our aircraft sampling by using concurrently collected satellite imagery and *in situ* measurements of diffuse light attenuation from the Monitoring Program.

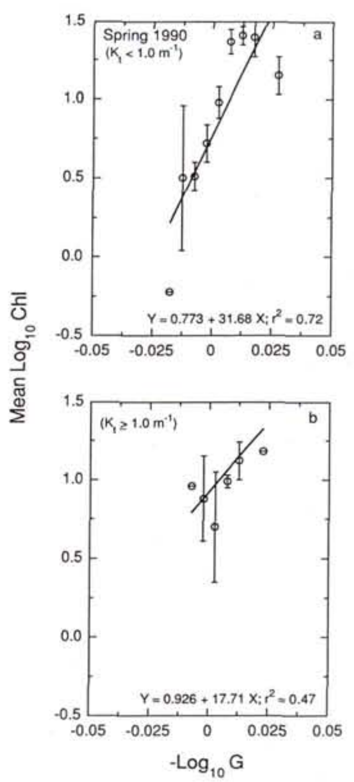

Figure 6. Regressions of $-\text{Log}_{10}$ G bin centerpoints and mean Log_{10} *Chl* for spring data 1990, from waters of high ($K_t \geq 1.0$ m^{-1}) and low ($K_t < 1.0$ m^{-1}) turbidity.

Discussion

We have used an aircraft-borne radiometer system, ODAS, to determine the distribution of surface *Chl a* in the Chesapeake Bay from 1989 through 1991. In earlier papers, significant relations between the spectral curvature of upwelling radiance, $-\text{Log}_{10}$ *G*, applied to the radiances measured at 460, 490, and 520 nm by ODAS were reported for data collected in 1989 (see Harding and Itsweire, 1991; Itsweire *et al.*, 1991; Harding *et al.*, 1992a). The work described here extends those measurements to include two subsequent years of data and over 50 additional flights. Our purpose was to analyze interannual variability in the algorithm(s) used to recover *Chl a* and to improve those recoveries by using algorithms specific for season and location along the estuary's axis to account for both the shift in species composition and the strong spatial gradient in turbidity that occur from spring through fall.

The initial purpose of developing a local chlorophyll algorithm was to use the once to twice weekly flights of ODAS to track seasonal changes in the phytoplankton distribution. To accomplish this goal, we developed a relation of the radiances measured with ODAS to *Chl a* encompassing seasonal and spatial variability in the Bay. This approach combined all matching data and generated predictive algorithms that could be applied to the complete ODAS data set. We accepted that any single day would have significant error associated with the range of conditions occurring in time and space (i.e., *Chl a*, species composition, and *in situ* optical properties). Thus, we have used the class of algorithms depicted in Figures 4a through 4d predictively, and follow-on studies have addressed improvements in the estimates of *Chl a* that can be obtained by including data on time- and space-varying factors.

The relations of $-\text{Log}_{10}$ *G* to Log_{10} *Chl a* presented in Figures 3 through 6 and regression statistics given in Table 1 confirm that annual, seasonal, and spatial separations of the data can yield improved estimates. The impact of these refinements on the ODAS-estimated distribution of chlorophyll is illustrated in Plate 1. These images were developed using gridding, contouring, and interpolation methods described in Harding *et al.* (1992a). They show the distribution of *Chl a* for the flight data collected on 15 May 1990 determined using (1) the overall algorithm for 1989-91, (2) an annual algorithm for 1990, (3) station data from shipboard measurements of the Monitoring Program, 14-16 May 1990, and (4) a seasonal algorithm for spring 1990. Several notable findings emerge from these comparisons.

First, in the example of 15 May 1990, application of an overall, multi-year algorithm derived from the binned data recovers much of the same information as an algorithm based only on data from a particular year (compare Plates 1a and 1b). Both interpolated images show the essential features of the shipboard data illustrated in Plate 1c. These features include chlorophyll concentrations <10 mg m^{-3} in the polyhaline region of the Bay between 37.0° and 37.8° N. Lat, concentrations of 12 to 16 mg m^{-3} in the mesohaline region from 37.8° to 38.7° N. Lat., and lower concentrations of 10 to 12 mg m^{-3} below the Chesapeake Bay Bridge (Annapolis, Maryland) from 38.7° to 39.0°. But *Chl a* recovered for the Potomac River region of the mainstem Bay at ~38.0° N. Lat. were lower than the concentrations of 30 to 40 mg m^{-3} indicated by shipboard data from the Monitoring Program. This discrepancy may be associated with (1) time differences in the aircraft and ship coverage, (2) the relatively few flight lines that are possible at this latitude because of restricted airspace of the Patuxent Naval Air Station between the mouths of the Potomac and Patuxent Rivers, and (3) the limitations of an overall algorithm that encompasses spring-fall conditions (see below).

Second, applying the seasonally specific algorithm for the spring of 1990 improves the recovery of *Chl a* in the mesohaline region of the Bay, i.e., the distribution more closely resembles that indicated by the monitoring data than does that derived using the annual relationship, showing the very high concentrations in the main stem of the Bay from the Rappahannock River to the Patuxent River that typically is the location of the winter-spring diatom bloom (compare Plates 1c and 1d). The difference in the distribution in the area from 38.5° to 38.8° N. Lat. between ship and remote observations is probably attributable to temporal differences in sampling and to the far more extensive sampling that we undertake in that region from the air (see Figure 2).

Third, correction of the data for turbidity (not shown) did not appreciably improve the recovery of *Chl a* for 15 May 1990 as the area of high turbidity was restricted to a small part of the uppermost Bay, north of 39.0° N. Lat. The effect of this correction, for conditions when high turbidity is more pervasive in the oligohaline Bay, is to lessen the overestimation of *Chl a* that occurs with the overall algorithm because of the high reflectance of sediment-laden waters. If data on the spatial and temporal distribution of K_t were rou-

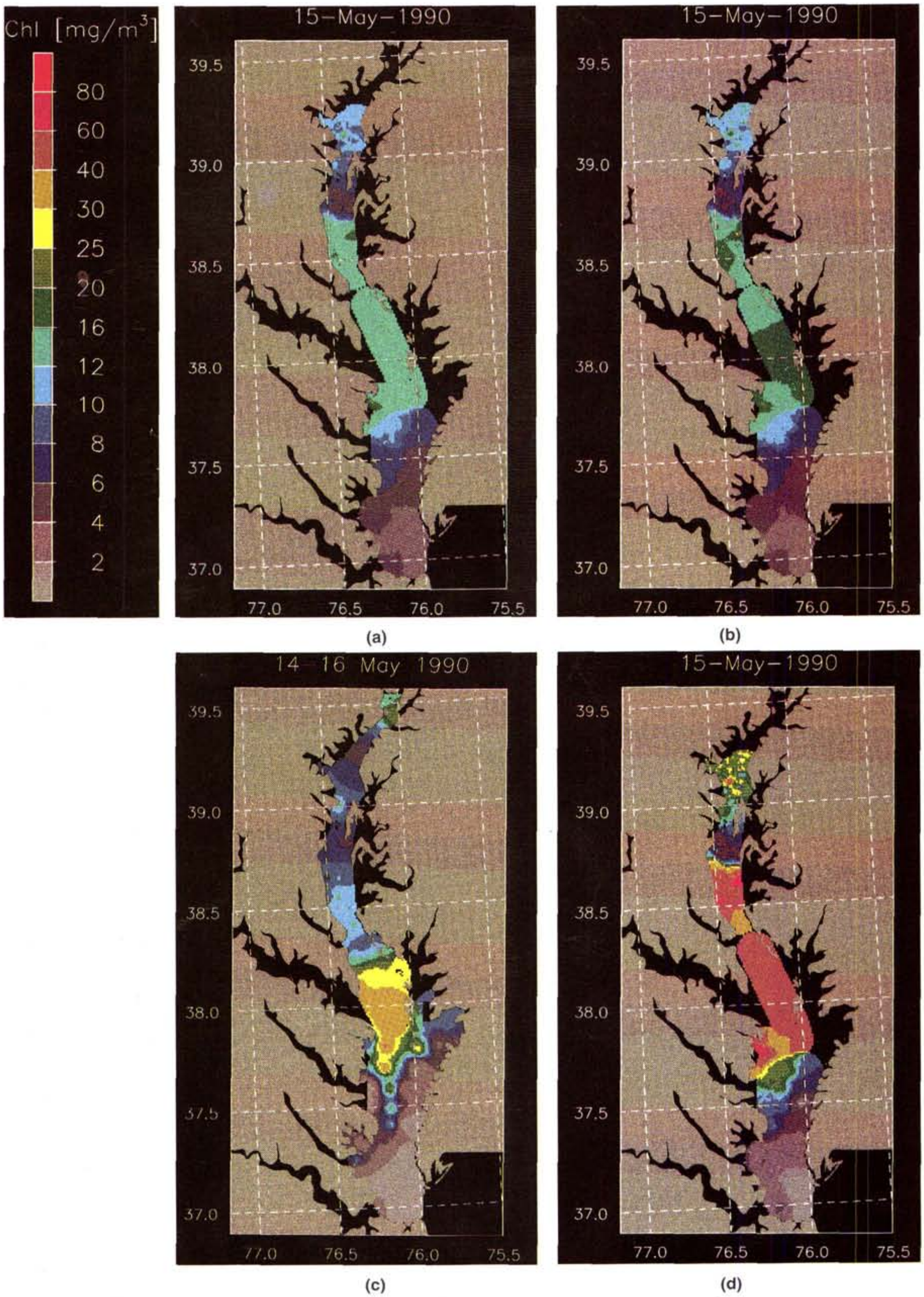

Plate 1. The distribution of *Chl a* for 15 May 1990 determined using (a) the overall algorithm for 1989-91 (b), the annual algorithm for 1990 (c), station data from the Monitoring Program, 14-16 May 1990, and (d) a seasonal algorithm for spring 1990 (d).

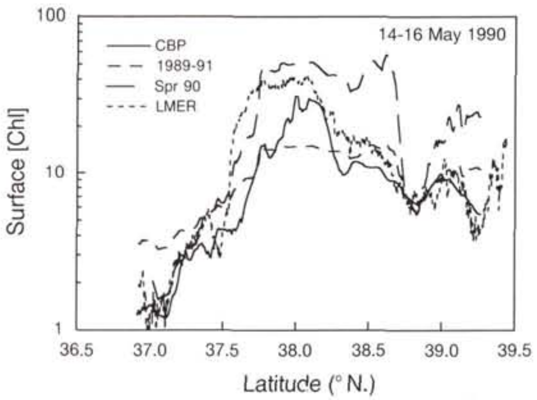

Figure 7. Surface *Chl a* derived from: interpolated images of Monitoring Program data, 14-16 May 1990 (CBP); aircraft-measured radiances subjected to multiyear (1989-91) and seasonal algorithms, 15 May 1990 (ODAS); transect data, 14-15 May 1990 (LMER).

tinely available, they could be used to implement this correction for each flight.

A quantitative estimation of how well the various algorithms recover *Chl a* in the Chesapeake Bay can be obtained by compressing data from the interpolated images of *Chl a* shown in Plate 1 across the Bay, i.e., computing latitudinal averages of *Chl a* (Figure 7). In addition to the latitudinal profiles of *Chl a* from the ODAS flight of 15 May 1990, and the CBP Monitoring Program cruise of 14 to 16 May 1990, *Chl a* collected fluorometrically on a transect along the main axis of the Bay on 14 to 15 May 1990 in the LMER program are shown.

As mentioned earlier, the *Chl a* estimates recovered from the multi-year, annual, and spring algorithms show the same distribution as the *in situ* data, i.e., lowest values near the mouth of the Bay (37.0° to 37.5° N. Lat.), low values south of the Chesapeake Bay Bridge (38.7° to 39.0° N. Lat.), and higher values in the mesohaline region (37.8° to 38.4° N. Lat.). The distributions of mean *Chl a* derived from the multi-year (or annual) algorithms applied to the ODAS data were two to three times those of the Monitoring data, while they were about half in the mesohaline region. In contrast, the use of a seasonal algorithm for the ODAS data shows very good agreement in the lower Bay where *Chl a* is low, and values two to four times higher than the *in situ* data in the mesohaline region. That part of the Bay is highly dynamic in the spring because it is the site of dense but episodic diatom blooms, and the distribution and abundance of phytoplankton commonly change significantly in periods of hours to days.

Given the excellent agreement for the regions of low *Chl a* in the lower and upper Bay, we believe that the elapsed time between the ship sampling (14 May in the mesohaline) and the ODAS overflight (15 May) is primarily responsible for the range of observed *Chl a*. This hypothesis, that the seasonal algorithm recovers *Chl a* accurately, is confirmed by comparing the data from ODAS and the Monitoring Program to the LMER transect data for *Chl a* that were collected during the night of 14 May and the morning of 15 May (see Figure 7). These data agree with the *Chl a* distribution that was estimated for the region from 37.5° to 38.2° N. Lat., but were lower by a factor of two to three from 38.2° to 38.7°. The distribution of *Chl a* from the LMER transect, while not incorporating the lateral data of the Monitoring or ODAS data sets, does represent a more synoptic view from shipboard measurements than does the monitoring data set.

We suggest that the differences among the data sets reflect the dynamic nature of the *Chl a* distribution in this region of the Bay, and the time differences in sampling between the two shipboard programs and the aircraft overflights. The ODAS flight represents the most synoptic sampling of the three approaches and compression of the data from the interpolated maps to give averages incorporates lateral information. Of the two shipboard data sets, agreement with ODAS data subjected to a seasonal algorithm was best using the LMER data that were collected in a continuous transect requiring <24 h, as compared to the three days the Monitoring Program takes to cover the Bay. We believe the ODAS overflight generates a snapshot of conditions in the Bay that may be smeared in a coarse shipboard sampling requiring up to several days to obtain coverage of the entire estuary.

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References

Boynton, W. R., W. M. Kemp, and C. W. Keefe, 1982. A comparative analysis of nutrients and other factors influencing estuarine phytoplankton production, *Estuarine Comparisons* (V. S. Kennedy, editor), Academic Press, New York, pp. 69-90.

Campbell, J. W., and W. E. Esaias, 1983. Basis for spectral curvature algorithms in remote sensing of chlorophyll, *Appl. Optics*, 22: 1084-1093.

———, 1985. Spatial patterns in temperature and chlorophyll on Nantucket Shoals from airborne remote sensing data, May 7-9, 1981, *J. Mar. Res.*, 43:139-161.

Correll, D. W., 1987. Nutrients in Chesapeake Bay, *Contaminant Problems and Management of Living Chesapeake Bay Resources* (S. K. Majumdar, L. W. Hall, and H. M. Austin, editors), Pennsylvania Acad. Sci., pp. 298-320.

D'Elia, C. F., J. G. Sanders, and W. R. Boynton, 1986. Nutrient enrichment studies in a coastal plain estuary: phytoplankton growth in large-scale, continuous cultures, *Can. J. Fish. Aquat. Sci.*, 43:397-406.

Fisher, T. R., L. W. Harding, Jr., D. W. Stanley, and L. G. Ward, 1988. Phytoplankton, nutrients, and turbidity in the Chesapeake, Delaware, and Hudson estuaries, *Est. Coast. Shelf Sci.*, 27:61-93.

Fisher, T. R., E. R. Peele, J. W. Ammerman, and L. W. Harding, Jr.,

1992. Nutrient limitation of phytoplankton in Chesapeake Bay, *Mar. Ecol. Prog. Ser.*, 82:51-63.

Gordon, H. R., and A. Y. Morel, 1983. *Remote Assessment of Ocean Color for Interpretation of Satellite Visible Imagery. A Review, Lecture Notes on Coastal and Estuarine Studies*, Springer-Verlag, New York, 113 p.

Grew, G. W., 1981. *Real-Time Test of MOCS Algorithm During Superflux 1980*, NASA Publ. CP-2188, 301 p.

Harding, L. W., Jr., and E. C. Itsweire, 1991. Synoptic measurements of the distribution of chlorophyll in the Chesapeake Bay using aircraft remote sensing, *Proc. 2nd Chesapeake Bay Research Conference*, Baltimore, Maryland, Dec. 1990.

Harding, L. W., Jr., E. C. Itsweire, and W. E. Esaias, 1992a. Determination of phytoplankton chlorophyll concentrations in the Chesapeake Bay with aircraft remote sensing, *Remote Sens. Environ.*, 40:79-100.

Harding, L. W., Jr., M. Leffler, and G. E. Mackiernan, 1992b. *Dissolved Oxygen in the Chesapeake Bay: A Scientific Consensus*, University of Maryland Sea Grant College Publication No. UM-SG-TS-92-03, 18 p.

Harding, L. W., Jr., B. W. Meeson, and T. R. Fisher, 1986. Phytoplankton production in two East coast estuaries: Photosynthesis-light functions and patterns of carbon assimilation in Chesapeake and Delaware Bays, *Est. Coast. Shelf Sci.*, 23:773-806.

Itsweire, E. C., L. W. Harding, Jr., and L. H. Bahner, 1991. Comparison of phytoplankton biomass estimates for the Chesapeake Bay using aircraft remote sensing and in situ chlorophyll data, *Proc. 2nd Chesapeake Bay Research Conference*, Baltimore, Maryland, Dec. 1990.

Smith, R. C., O. B. Brown, F. E. Hoge, K. S. Baker, R. H. Evans, R. N. Swift, and W. E. Esaias, 1987. Multiplatform sampling (ship, aircraft, and satellite) of a Gulf Stream warm core ring, *Appl. Optics*, 26:2068-2081.

Stumpf, R. P., 1988. Sediment transport in Chesapeake Bay during floods: Analysis using satellite and surface observations, *J. Coastal Res.*, 4:1-15.

U.S. EPA, 1983. *Chesapeake Bay: A Profile of Environmental Change*, United States Environmental Protection Agency, Washington, D.C.

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