THE INFLUENCE OF HURRICANE ISABEL ON CHESAPEAKE BAY PHYTOPLANKTON DYNAMICS

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ABSTRACT

Phytoplankton biomass in mid- to lower Chesapeake Bay increased significantly following Hurricane Isabel in September 2003. Observations of ocean color from aircraft before (11 September) and after (24 September) Isabel revealed a two-fold increase of chlorophyll *a* (chl-a) in a large area of the Bay encompassing ~3000 km^2. Continuing flights and shipboard sampling indicated that the increase dissipated by early October as chl-a returned to typical fall values. Average fall conditions show decreasing phytoplankton biomass from the head (~11 mg chl-a·m^{-3}) to the mouth (~5 mg chl-a·m^{-3}) of the estuary. Resolving the effect of Isabel on chl-a was complicated by record freshwater flow into the Bay in 2003 that strongly affected phytoplankton dynamics. Measurements of water column structure from before and after Isabel suggest that the Bay was rapidly destratified by the passage of the storm. The increased chl-a was caused by wind mixing and storm surge that introduced nutrients from bottom waters into the photic layer at a time of year when nitrogen is usually the limiting macronutrient for phytoplankton.

INTRODUCTION

Only three storms made landfall as hurricanes in Virginia and Maryland between 1851 and 1996, although numerous tropical storms have influenced the region [1]. Hurricane Isabel reached the coast on 18 September 2003 near Cape Lookout, North Carolina and moved quickly to the northwest, arriving in Canada by mid-day on 19 September. The storm passed to the west of Chesapeake Bay, producing strong and sustained winds from the south. The speed and track of the storm, along with the winds, created a set of physical conditions in the Bay that enhanced the storm surge [2], causing tidal flooding along western shore tributaries. The last major storm to follow that path was an unnamed hurricane in August 1933 that had a similar effect on water level. Winds and storm surge were exceptional during Isabel, although precipitation was not. Only the eastern half of Virginia received more than 5 cm of rain during the storm. The most significant environmental forcing, therefore, came from wind and surge rather than freshwater flow.

The response of estuarine phytoplankton to hurricane or tropical storm passage has been documented for several systems [3, 4, 5]. In all examples, phytoplankton biomass increased in response to storm passage. However, there appear to be two distinct mechanisms underlying storm effects on phytoplankton dynamics. Zubkoff and Warinner [3] and Paerl et al. [5] in Chesapeake Bay and Pamlico Sound, respectively, reported biomass increases in response to record-setting freshwater flow and nutrient delivery associated with tropical storm/hurricane passage, whereas Valiela et al. [4] described a short-lived phytoplankton bloom in response to water column mixing and nutrient release from the sediment in Waquoit Bay.

Aircraft remote sensing of ocean color and sea surface temperature in Chesapeake Bay before and after the passage of Hurricane Isabel was used to quantify the effect of the storm on phytoplankton biomass in the Bay. Supporting data were obtained from an analysis of 15 years (1989–2004) of archived data on fall chl-a from remote sensing to place the phytoplankton response in the context of contemporary conditions. Finally, shipboard data on water column structure and constituents before and after the storm were examined to infer a mechanism for the response observed.

METHODS AND MATERIALS

Phytoplankton biomass as chl-a was obtained as part of the Chesapeake Bay Remote Sensing Program (CBRSP; *www.cbrsp.org*). Ocean color data were collected using a multi-spectral radiometer (SeaWiFS Aircraft Simulator, SAS III, Satlantic, Inc. Halifax, NS, Canada) from light aircraft operating at low altitude (~150 m) and low speed (~50 m·s^{-1}), following a defined set of flight lines covering approximately 750 km. The nadir-viewing radiometers sample at 10 Hz with a 3.5^{o} field of view. At flight parameters given above, this sampling creates a footprint of 5 m x 50 m when averaged to 1 sec, providing approximately 12,000 data points per flight. We used a spectral curvature algorithm [6, 7] to convert water-leaving radiances in the blue-green region of the spectrum [$L_w(443)$, $L_w(490)$, and $L_w(555)$] to chl-a. Empirical relationships have been developed to calibrate the general curvature algorithm to *in situ* observations made in Chesapeake Bay [8, 9, 10, 11, 12]. Flight data were then interpolated to a 1-km^2 grid of the Bay using a two-dimensional, inverse-distance-squared, octant search. Interpolation was performed on $\log_{10}$ chl-a to achieve normality. Flights have been conducted 20 to 30 times per year, concentrating on the productive period (March to October), with tracks that extend into all regions of the mainstem Bay to produce a chl-a climatology for the full period of the study (1989–2004). The long-term average chl-a for September is comprised of data from 35 flights, totaling 245,000 data points. All analyses were performed on interpolated data using SAS version 8.0 (Cary, NC) and mapped in Surfer version 8.0 (Golden, CO).

In situ data were obtained from water quality monitoring cruises of the Chesapeake Bay Program (CBP) that collect information on water column structure and constituent concentrations from approximately 50 stations in the mainstem Bay roughly 14 times per year. Data were drawn from nine stations in the deep central channel of the mid-Bay (CB3.3C, CB4.1C, CB4.2C, CB4.3C, CB4.4, CB5.1, CB5.2, CB5.3, LE2.3) collected during the month of September. This region has an average depth of 25 m and is an area where bottom-water nutrient concentrations tend to be high and dissolved oxygen low, with sub-pycnocline waters becoming hypoxic or anoxic in summer. Information on the collection protocols for parameters used in this study can be obtained from the CBP website (*www.chesapeakebay.net*).

RESULTS AND DISCUSSION

Long-term average chl-a for September is characterized by decreasing concentrations from north to south following the main axis of the Bay (Figure 1a), and gradients of other major constituents, including salinity, nutrients, and light attenuation. Based on long-term data from aircraft remote sensing, September appears to be a rather quiescent period in the annual phytoplankton cycle, with large blooms (magnitude, duration, or areal extent) infrequent for the period of record. Standard deviations of the mean for each grid cell are typically less than 2 mg·m^{-3}, suggesting that conditions do not vary appreciably from the long-term average.

Chl-a, prior to Isabel (11 September 2003; Figure 1b), was not very different from the long-term average, with only slightly elevated concentrations in the northern part of the Bay. Six days after the passage of the hurricane (13 days after the last remote sensing image), chl-a greatly increased over a significant part of the mid- to lower Bay. The area of increased chl-a covered approximately 3000 km^2 and represented a rise of 2–3 times the long-term average. Our 15-year remote sensing record shows that biomass levels of this magnitude and areal extent are rare in September in the mid- to lower Chesapeake. Shipboard chl-a in the Bay's Maryland portion on 24 September 2003 was consistent with remotely sensed retrievals. Figure 1d shows the difference

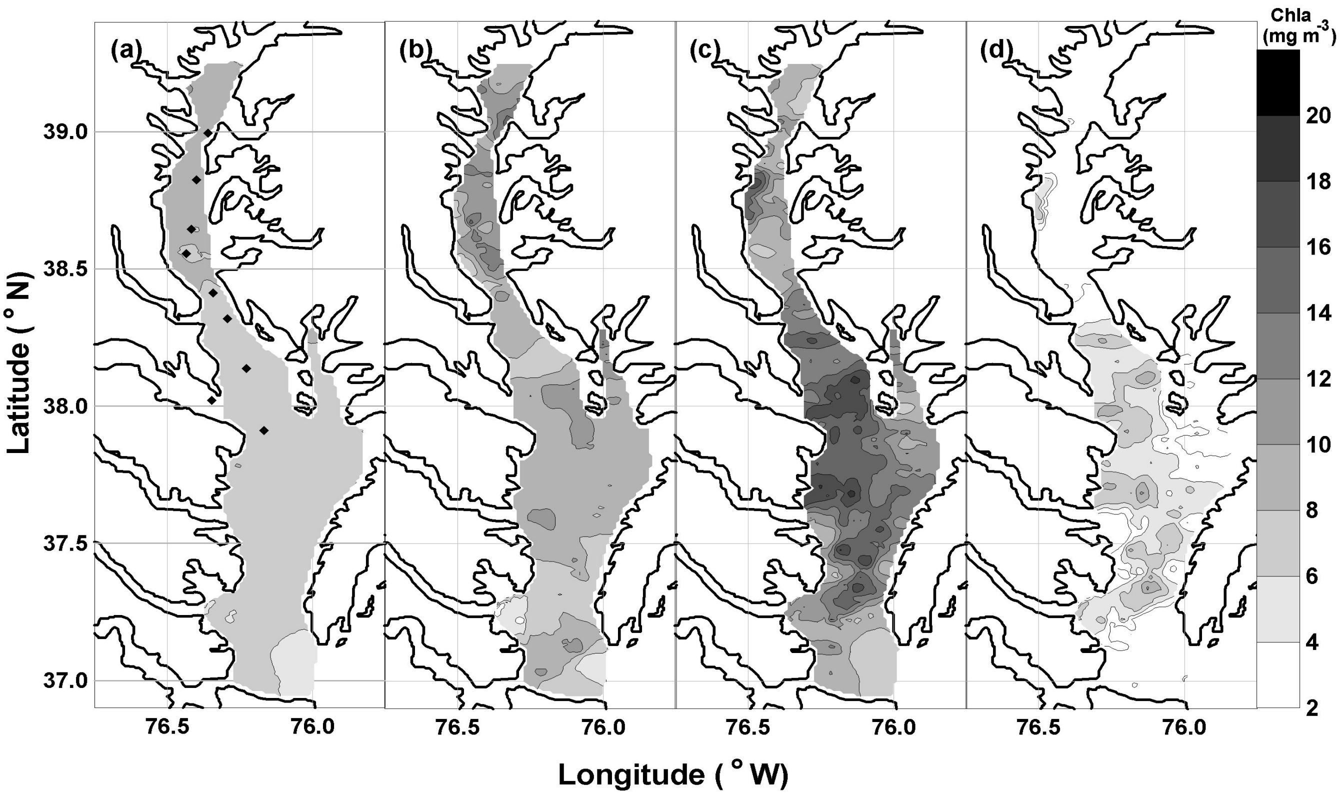

Figure 1. Remotely sensed phytoplankton biomass: a) Long-term September average; b) Pre-Isabel biomass, 11 September 2003; c) Post-Isabel biomass, 24 September 2003; and d) Difference plot, post-Isabel minus pre-Isabel biomass. Diamonds in panel a indicate location of CBP monitoring stations used in these analyses.

in chl-a between pre- and post-Isabel flights, with chl-a increases between 4 and 10 mg·m^{-3} common in the region between the Patuxent and York rivers. The rapid biomass increase was followed by an equally rapid decrease as a remote sensing flight on October 2 (image not shown) and shipboard data collected as part of an NSF biocomplexity project on 2 to 4 October showed that chl-a levels had returned to typical fall values (range = 5.0–12.9 mg chl-a·m^{-3}; mean = 6.65 mg chl-a·m^{-3}).

During fall, the mid- to lower Chesapeake Bay is nitrogen limited [13]. Therefore, increases of phytoplankton biomass in response to the passage of a hurricane likely resulted from an input of nutrients to the photic zone. Nutrient supply from freshwater runoff associated with heavy precipitation from Isabel was not likely a major contributor given the short time lag between storm passage and phytoplankton response. Typically, phytoplankton responses to pulses of freshwater flow occur weeks to months after the passage of a storm [14, 15], rather than days later, so the rapid biomass response observed on 24 September 2003 was probably not related to precipitation in the western portion of the Chesapeake Bay watershed. In addition, surface salinities in the mid-Bay were significantly higher in the post-Isabel sampling (11.96 vs. 10.29; t-test $p = 0.0098$), suggesting mixing of high-salinity bottom water rather than any appreciable input of fresh water.

Whereas freshwater flow is not directly linked to the bloom observed on 24 September, flow during the months prior to Isabel clearly affected Bay phytoplankton dynamics in 2003. Record flow delivered substantial quantities of nutrients to the Bay that were assimilated into phytoplankton biomass that sedimented from the photic layer and were retained in bottom waters of the mid-Bay by two-layer circulation [16]. Nutrients may also have been entrained directly into the sub-pycnocline waters at the onset of summer stratification. Average dissolved inorganic nitrogen (DIN = NO_2

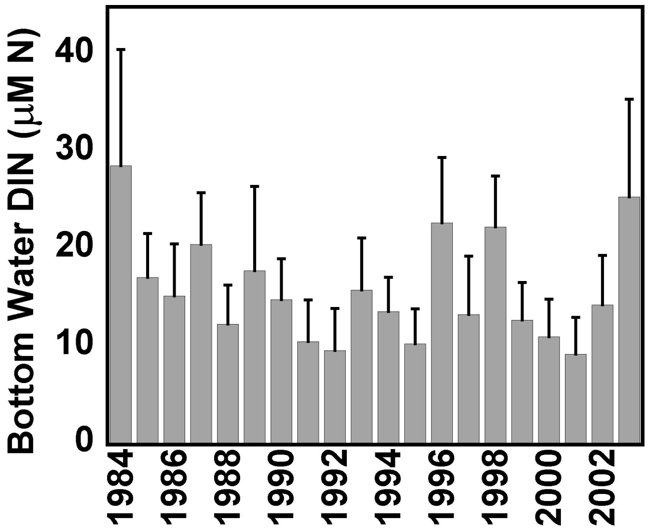

Figure 2. Average September bottom-water DIN concentrations from mid-Bay channel stations from 1984 to 2003. Data from CBP monitoring cruises. Error bars = 1 SD.

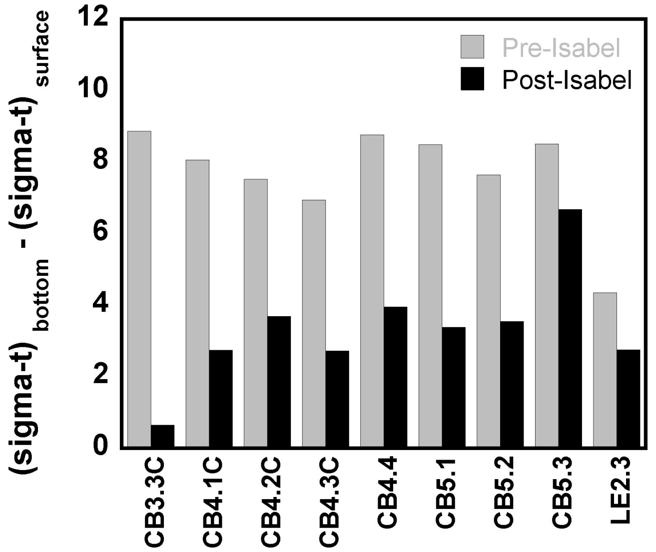

Figure 4. Pre- (9/15) and post-Isabel (9/25) density difference between surface and bottom samples for mid-Bay channel stations (CB3.3C northernmost station). Data from CBP monitoring cruises.

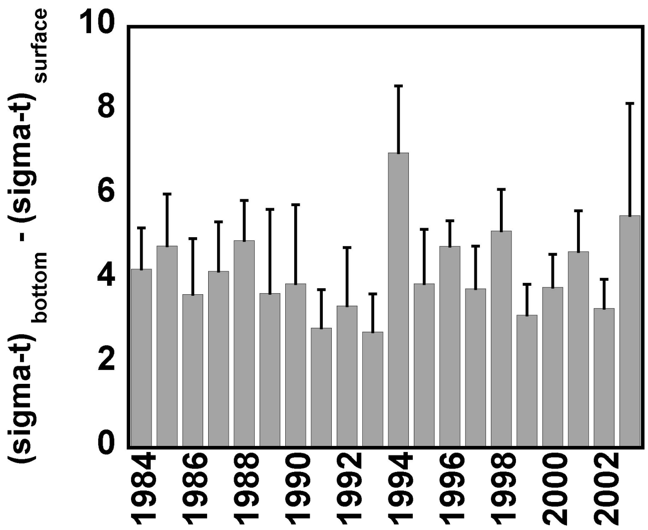

Figure 3. Average September density differences between surface and bottom samples for mid-Bay channel stations from 1984–2003. Data from CBP monitoring cruises. Error bars = 1 SD.

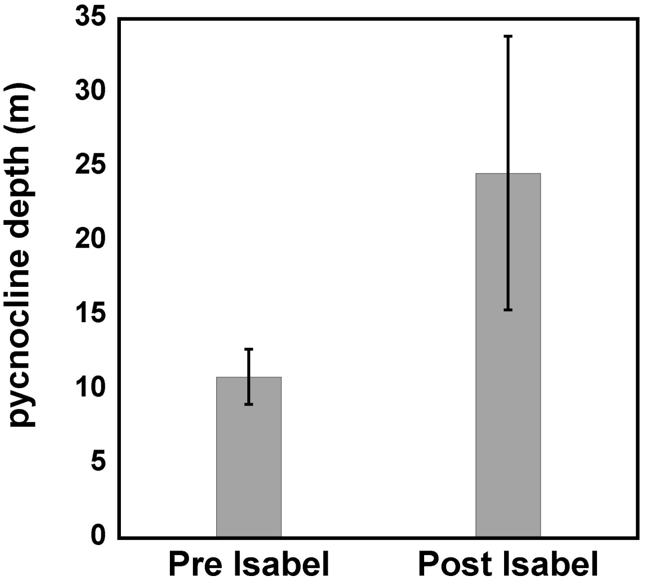

Figure 5. Average pycnocline depth for mid-Bay channel stations, pre- (9/15/03) and post-Isabel (9/25/03). Data from CBP monitoring cruises. Error bars = 1 SD. Note six of nine stations in post-Isabel sampling had no pycnocline and were mixed surface to bottom.

+ NO_3 + NH_4) concentrations in bottom waters for the month of September at mid-Bay stations show that high nutrient concentrations were prevalent (Figure 2). The DIN in 2003 was the highest of any year since 1984, suggesting sufficient nitrogen existed in bottom waters to support a bloom once mixing occurred. Surface DIN concentrations in 2003 were significantly greater than the long-term average condition for September in the mid-Bay (0.177 vs. 0.052; t-test $p < 0.0001$), however, the post-Isabel surface DIN was not statistically different from the pre-Isabel conditions (0.177 vs. 0.143; t-test $p < 0.651$), most likely because excess DIN had already been incorporated into phytoplankton biomass.

Density differences between surface and bottom layers provide a metric for the intensity of stratification. Stratification in the mid-Bay was particularly strong in September 2003 (Figure 3) associated with high freshwater flow in the spring and summer preceding the storm. Strong stratification separates regenerated nutrients in bottom waters from the photic layer except during extreme events.

Sustained strong winds out of the south, together with an ~2-m storm surge, likely broke down the stratification that existed in the mid-Bay prior to the storm [2]. The density gradient, expressed as differences of surface and bottom water densities before and after the storm's passage, showed a large decrease suggesting that mixing had occurred (Figure 4). Other evidence for mixing was the 13-m increase of the average depth of the pycnocline in the mid-Bay following the storm, including six of nine stations where the water column was mixed top to bottom (24.61 vs. 10.88; t-test $p = 0.0005$; Figure 5).

Mixing associated with the passage of Isabel was essential to inject nutrients from below the pycnocline into the photic zone, while the partial re-stratification of the lower Chesapeake was also necessary to retain the nutrients and phytoplankton in well-illuminated surface waters. The turbulent mixing may have also supplied sub-pycnocline and benthic phytoplankton to the surface layer, providing additional biomass and a potential seed population for bloom formation. The rapid formation and cessation of the post-Isabel bloom in the mid- to lower Chesapeake Bay, together with nutrient and water column properties, suggest a phytoplankton response that was fueled by (and quickly exhausted) the nutrients mixed into the photic zone by Isabel.

CONCLUSIONS

The predominant short-term impact of Hurricane Isabel on phytoplankton dynamics in Chesapeake Bay was a ~two to threefold increase in biomass in the mid- to lower Bay, from the Patuxent to York rivers and covering approximately 3,000 km^2. The likely physical mechanism underlying this response was storm surge and wind mixing of bottom-water nutrients into the photic zone during a time of year when surface waters are usually nitrogen-limited. Phytoplankton responses to the passage of Hurricane Isabel were also influenced by the preceding "wet" year and associated high freshwater flow that produced higher-than-normal concentrations of DIN below the pycnocline.

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REFERENCES

1. J.B. Elsner and A.B. Kara. 1999. *Hurricanes of the North Atlantic, Climate and Society.* Oxford University Press, New York. 488 pp.
2. M.R. Roman, J.E. Adolf, J. Bichy, W.C. Boicourt, L.W. Harding, Jr., E.D. Houde, S. Jung, D.G. Kimmel, W.D. Miller, and X. Zhang. In press. Enhancement of plankton and fish abundance in Chesapeake Bay by Hurricane Isabel. *EOS*.
3. P.L. Zubkoff and J.E. Warinner III. 1977. The effect of Tropical Storm Agnes as reflected in chlorophyll *a* and heterotrophic potential of the lower Chesapeake Bay. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). Chesapeake Research Consortium Publication No. 54. The Johns Hopkins University Press, Baltimore, MD. pp. 368–387.
4. I. Valiela, P. Peckol, C. D'Avanzo, J. Kremer, D. Hersh, K. Foreman, K. Lajtha, B. Seely, W.R. Geyer, T. Isaji, and R. Crawford. 1998. Ecological effects of major storms on coastal watersheds and coastal waters: Hurricane Bob on Cape Cod. *J. Coast. Res.* 14: 218–238.

5. H.W. Paerl, J.D. Bales, L.W. Ausley, C.P. Buzzelli, L.B. Crowder, L.A. Eby, J.M. Fear, M. Go, B.L. Peierls, T.L. Richardson, and J.S. Ramus. 2001. Ecosystem impacts of three sequential hurricanes (Dennis, Floyd, and Irene) on the United States' largest lagoonal estuary, Pamlico Sound, NC. *Proc. Natl. Acad. Sci.* 98: 5655–5660.
6. G.W. Grew. 1981. Real-time test of MOCS algorithm during Superflux. NASA Publication CP-2188, pp. 301–322.
7. J.W. Campbell and W.E. Esaias. 1983. Basis for spectral curvature algorithms in remote sensing of chlorophyll. *Appl. Opt.* 22: 1084–1093.
8. L.W. Harding, Jr. and E.C. Itsweire. 1991. Synoptic measurements of the distribution of chlorophyll in the Chesapeake Bay using aircraft remote sensing. In: New Perspectives in the Chesapeake System: A Research and Management Partnership. J.A. Mihursky and A. Chaney (eds.). Chesapeake Research Consortium Publication No. 137. Baltimore, MD. pp. 147–160.
9. E.C. Itsweire, L.W. Harding, Jr., and L.H. Bahner. 1991. Comparison of phytoplankton biomass estimates for Chesapeake Bay using aircraft remote sensing and *in situ* chlorophyll data. In: New Perspectives in the Chesapeake System: A Research and Management Partnership. J.A. Mihursky and A. Chaney (eds.), Chesapeake Research Consortium. Publication No. 137. Baltimore, MD. pp. 161–168.
10. L.W. Harding, Jr., E.C. Itsweire, and W.E. Esaias. 1992. Determination of phytoplankton chlorophyll concentrations in the Chesapeake Bay with aircraft remote sensing. *Remote Sens. Environ.* 40: 79–100.
11. L.W. Harding, Jr., E.C. Itsweire, and W.E. Esaias. 1994. Estimates of phytoplankton biomass in the Chesapeake Bay from aircraft remote sensing of chlorophyll concentrations. *Remote Sens. Environ.* 49: 41–56.
12. L.W. Harding, Jr., E.C. Itsweire, and W.E. Esaias. 1995. Algorithm development for recovering chlorophyll concentrations in the Chesapeake Bay using aircraft remote sensing. *Photogramm. Eng. Remote Sens.* 61: 177–185.
13. T.R. Fisher, E.R. Peele, J.W. Ammermann, and L.W. Harding, Jr. 1992. Nutrient limitation of phytoplankton in Chesapeake Bay. *Mar. Ecol. Prog. Ser.* 82: 51–63.
14. T.C. Malone, L.H. Crocker, S.E. Pike, and B.W. Wendler. 1988. Influence of river flow on the dynamics of phytoplankton production in a partially stratified estuary. *Mar. Ecol. Prog. Ser.* 48: 235–249.
15. L.W. Harding, Jr. and E.S. Perry. 1997. Long-term increase of phytoplankton biomass in Chesapeake Bay, 1950–1994. *Mar. Ecol. Prog. Ser.* 157: 39–52.
16. W.C. Boicourt. 1992. Influence of circulation processes on dissolved oxygen in the Chesapeake Bay. In: D.E. Smith, M. Leffler, and G.E. Mackiernan. (eds.), *Oxygen Dynamics in the Chesapeake Bay. A Synthesis of Recent Research*. Maryland Sea Grant College, University of Maryland, College Park, MD, pp. 7–59.