GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L05601, doi:10.1029/2004GL021852, 2005

Remotely-sensed chl *a* at the Chesapeake Bay mouth is correlated with annual freshwater flow to Chesapeake Bay

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Received 27 October 2004; revised 20 December 2004; accepted 4 February 2005; published 1 March 2005.

[1] High freshwater flow delivers excess nutrients to Chesapeake Bay, leading to increased phytoplankton biomass, turbidity, and eutrophication. Low flow in 2002 was associated with a persistent drought that terminated abruptly in autumn 2002, followed by extremely high flow in 2003. This large difference in flow caused improved water quality in 2002 as nutrient loading subsided, and degraded water quality in 2003 with increased loading associated with high flow. We analyzed remotely sensed chlorophyll (chl *a*) data using an online data analysis tool to quantify the effect of sequential low and high freshwater flow on phytoplankton biomass near the mouth of the Bay. Chl *a* in the study area was significantly higher in 2003 than in 2002, consistent with strong forcing by freshwater flow and nutrient loading in the nutrient-limited region of the Bay. **Citation:** Acker, J. G., L. W. Harding, G. Leptoukh, T. Zhu, and S. Shen (2005), Remotely-sensed chl *a* at the Chesapeake Bay mouth is correlated with annual freshwater flow to Chesapeake Bay, *Geophys. Res. Lett.*, *32*, L05601, doi:10.1029/2004GL021852.

1. Introduction

[2] The ecological integrity of Chesapeake Bay has been detrimentally affected by increased nutrient inputs from sources including agriculture, wastewater treatment plants, and runoff from the extensive watershed [*Breitburg*, 1990]. The most important transport mode for nutrients into the Bay is via streams and rivers. Increased nutrient input has resulted in greater phytoplankton biomass [*Harding and Perry*, 1997], increased turbidity, a substantial reduction of seagrasses, and increased hypoxia and anoxia [*Officer et al.*, 1984; *Seliger et al.*, 1985; *Kemp et al.*, 1992].

[3] Eastern North America experienced a prolonged hydrological drought from 1999–2002 that was particularly acute during summer 2002. In autumn 2002, however, the drought abated with significantly increased precipitation, a trend that continued through 2003. 2002 was one of the lowest precipitation years in history in Baltimore, Maryland, whereas 2003 was the wettest year in over a century (Precipitation summary and temperature observations for the Washington, D. C. and Baltimore, MD area, December 2003 and annual review, report, National Weather Service, 2003, available at http://www.nws.noaa.gov/om/presto/presto2003/2003dectable.pdf).

[4] The contrasting hydrological conditions in 2002 and 2003 had significant effects on Chesapeake Bay, expressed in dissolved oxygen, salinity, and turbidity distributions (Summer 2003 oxygen levels in the Chesapeake Bay report, Chesapeake Bay Program Office, 2003, available at http://www.chesapeakebay.net/pubs/low_do_backgrounder.pdf). Differences observed in 2002 and 2003 are consistent with long-term trends resulting from increasing nutrient inputs in freshwater flow to the Bay [*Boynton et al.*, 1995; *Harding and Perry*, 1997].

[5] High freshwater flow from the Susquehanna River in spring supplies enough nitrogen to alleviate nitrogen limitation of phytoplankton biomass and productivity [*Malone*, 1992]. The magnitude of flow influences the size and duration of the spring phytoplankton bloom, particularly in the nitrogen-limited lower Bay [*Harding et al.*, 2005]. We hypothesized that large differences in freshwater flow and nutrient loading to the Chesapeake Bay in 2002 and 2003 would influence phytoplankton concentrations in the coastal Atlantic Ocean near the mouth of the Bay. We investigated this topic to demonstrate the capability of the recently developed Goddard Earth Science Data and Information Services Center (GES DISC) Interactive Online Visualization and ANalysis System ("Giovanni") to support research-quality data analyses.

2. Hydrological Conditions for the Chesapeake Bay Watershed in 2002 and 2003

[6] The United States Geological Survey (USGS) estimates freshwater flow into Chesapeake Bay using stream gauging stations distributed throughout the watershed. Figure 1 shows freshwater input to the five standard USGS Bay sections, with a Sea-viewing Wide Field-of-view Sensor (SeaWiFS) true-color inset to illustrate the section boundaries. In July, August, and September 2002, flow into Chesapeake Bay averaged 45%, 64%, and 61% below the respective long-term (1937–2001) averages for these months. Annual freshwater flow input was estimated at 24% below average for 2002 (USGS monthly water conditions, U.S. Geological Survey Water Resources Division MD-DE-DC, 2002, available at http://md.water.usgs.gov/publications/press_release/current/#archive).

[7] During the first five months of 2003, freshwater flow was double the volume for this period in 2002, and was 20% above the long-term average for this period. Flow was 83% above average in July, 125% above average in August (a six-fold increase over August 2002), and approximately

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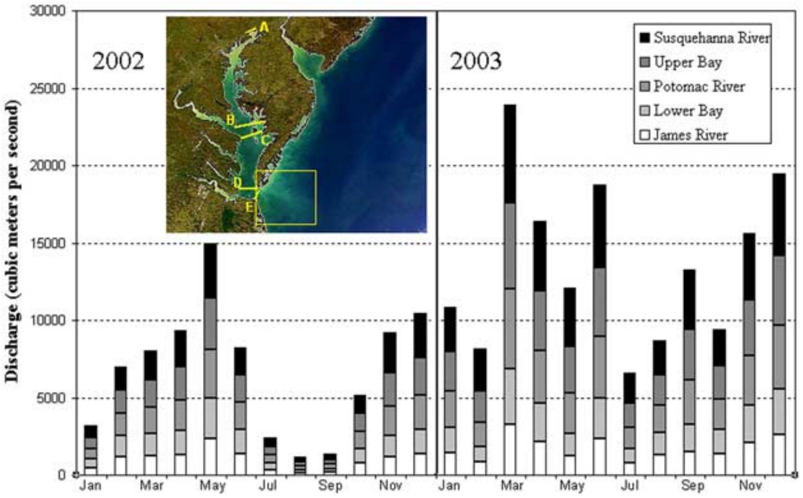


Figure 1. Estimated monthly freshwater flow to Chesapeake Bay in 2002 and 2003. The five sections correspond to regions A–E in the inset image, named here for clarity. During 2002, streamflow was significantly below average, and during 2003, streamflow was significantly above average. Streamflow data obtained from the USGS Water Resources Division MD-DE-DC; data for 2003 are preliminary. Inset: SeaWiFS image of the Chesapeake Bay region. The box designates the 1 × 1° study area defined for examination of monthly chl *a*, latitude 36.5–37.5°N and longitude 75.0–76.0°W. The sections designated by letter correspond to the areas used to estimate streamflow input to the Chesapeake Bay by the USGS: A, Susquehanna River; B, Upper Bay; C, Potomac River; D, Lower Bay; and E, James River.

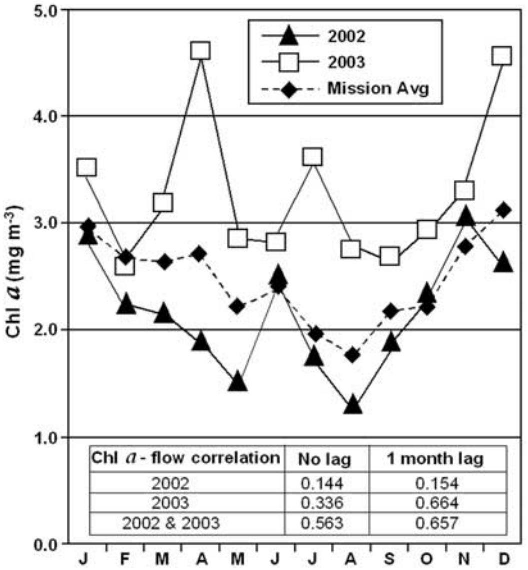
400% above average in September 2003 (USGS monthly water conditions, U.S. Geological Survey Water Resources Division MD-DE-DC, 2002, available at http://md.water.usgs.gov/publications/press_release/current/#archive).

3. Remotely-Sensed Chlorophyll Concentration Data

[8] We defined a 1 × 1° study region at the mouth of the Chesapeake Bay, 36.5–37.5°N latitude, 75.0–76.0°W longitude, for this study (Figure 1 inset). Chlorophyll (chl *a*) concentrations were retrieved from SeaWiFS Level 3 monthly Standard Mapped Image (SMI) data products with 9 km^2 spatial resolution. The monthly SMI data products were assimilated into Giovanni, using the Grid Analysis and Display System (GrADS) for data analysis. Giovanni was used to determine monthly mean chl *a* in the study area for 2002 and 2003 (Figure 2), and to generate Hovmöller longitude-time plots for each year (Figures 3a–3b). It was also used to generate maps of monthly chl *a* for April 2002 and April 2003 (Figures 3c–3d).

[9] Chl *a* retrievals derived from remotely-sensed radiances acquired by SeaWiFS and similar sensors are complicated by the bio-optical characteristics of coastal waters. Most coastal waters are classified optically as "Case 2", and are commonly turbid with higher chl *a* than open ocean, oligotrophic Case 1 waters [*Morel and Prieur*, 1977]. The influence of turbidity due to suspended sediments, and the reliability of algorithms in high chl *a* (>1 mg m^{-3}) as opposed to low chl *a* (<1 mg m^{-3}) waters, must be considered in evaluating data accuracy for coastal waters.

[10] The SeaWiFS Project goal is to achieve a global accuracy of ±35% for remotely-sensed chl *a* [*Hooker et al.*, 1992]. SeaWiFS data processing quality control (QC) tests for 15 different factors known to degrade data accuracy, and detection of any of these factors generates a QC "flag". All



Chl *a* - flow correlation	No lag	1 month lag
2002	0.144	0.154
2003	0.336	0.664
2002 & 2003	0.563	0.657

Figure 2. Mean chl *a* in the study area during 2002 (black triangles), 2003 (white squares), and for the SeaWiFS mission period of October 1997 to December 2003 (dashed line with black diamonds). Mean chl *a* during every month in 2003 was significantly higher than the corresponding month in 2002, and above the mission period mean every month except February. The highest mean chl *a* (April 2003) corresponds to the extremely high freshwater flow conditions occurring in March and April 2003 (Figure 1). The inset table shows the results of correlation analysis between chl *a* in the study area and freshwater flow to the Bay.

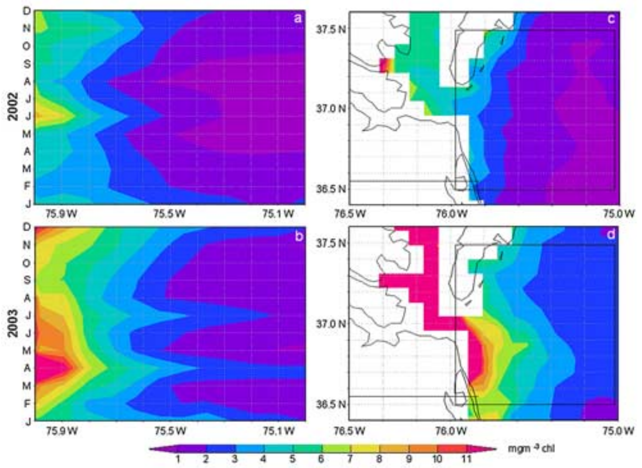


Figure 3. (a) Hovmöller longitude-time plot for the study area in 2002, showing that the highest chl *a* was isolated to a very small coastal region in June 2002. (b) Hovmöller longitude-time plot for the study area in 2003, showing significantly elevated chl *a* near the coast during the entire year, with higher chl *a* occurring further eastward in the Atlantic Ocean compared to 2002. (c) Chl *a* at the mouth of the Chesapeake Bay in April 2002. (d) Chl *a* at the mouth of the Chesapeake Bay in April 2003. Elevated chl *a* is evident within the Bay and extending south and east into the coastal Atlantic Ocean. The black box designates the study area boundaries.

flagged pixels (at 4 km^2 resolution, subsampled from the 1 km^2 nadir resolution data acquired by the sensor) are excluded in the creation of Level 3 data products (SeaWiFS archive product specifications, version 4.1, available at http://daac.gsfc.nasa.gov/oceancolor/PDFs/arch_prod_specs_v41.pdf). Thus, only data meeting QC standards contribute to the mean chl *a* in the SeaWiFS SMI data products that are used by Giovanni.

[11] The chl *a* images (Figures 3c–3d) demonstrate the effectiveness of the QC procedures, with exclusions primarily due to land mask (LAND) and high water-leaving radiance (HILT) flags. The land mask excludes pixels closest to shore, and the HILT flag excludes pixels with water-leaving radiance in any band that exceeds a threshold allowed for the low-gain setting of the SeaWiFS bilinear gain. The HILT flag thereby excludes pixels with significant bottom reflectance or high suspended sediment concentration. In Figures 3c–3d, it is evident that only the pixels in the central lower Chesapeake Bay (not in the study area) and east of the Bay mouth contributed to the 9 km^2 data. Overlap of small data areas onto the mapped land boundaries likely results from minor uncertainties in pixel location.

[12] The factors discussed above indicate that remotely-sensed chl *a* concentrations analyzed by this study are accurate for this region, despite being significantly higher than open ocean, Case 1 water concentrations. Chromophoric dissolved organic matter (CDOM) contributes significantly to absorption, complicating retrievals of chl *a* based on remote sensing reflectances. In-water bio-optical data for the region spanning years of variable freshwater flow, combined with QC flags, results in effective retrievals of chl *a*, despite the optically complex nature of these waters. Furthermore, confidence in the chl *a* data is supported by the results of *Magnuson et al.* [2004] and *Harding et al.* [2005] for remotely-sensed chl *a* concentrations in Chesapeake Bay and middle Atlantic bight.

4. Results

[13] Monthly mean chl *a* concentrations in the study area were higher for every month of 2003 compared to the corresponding month in 2002 (Figure 2). Monthly mean chl *a* in 2003 also exceeded the monthly mean chl *a* calculated using all SeaWiFS data available in Giovanni for October 1997–December 2003.

[14] Results of correlation analysis (Figure 2 inset table) indicated that mean chl *a* in the study area was not significantly correlated with flow to the Bay in 2002, but was correlated in 2003. The correlation in 2003 was observed with a one-month lag in chl *a*. For the two years combined, correlation was also significant with a one-month lag, suggesting that higher flow to the Bay influences chl *a* in the study area, but that there is no significant link of flow and chl *a* during extreme low-flow conditions.

[15] Hovmöller longitude-time plots showed contrasting spatial distributions of chl *a* in 2002 and 2003 (Figures 3a–3b). Figure 3a indicates that maximum chl $a > 8$ mg m^{-3} only occurred in the nearshore region (west of 75.8°W longitude) in June 2002. Figure 3b shows that chl *a* exceeded 11 mg m^{-3} in the nearshore region in April 2003, and was substantially higher through the spring and summer compared to 2002. In 2002, chl $a \geq 4$ mg m^{-3} was rarely found east of 75.7°W. In 2003, chl $a \approx 4$ mg m^{-3} occurred between 75.6–75.7°W, and extended further offshore in April and July. The most obvious difference in nearshore chl *a* occurred in spring of 2002 and 2003. In spring 2002, nearshore chl *a* was 3 to 4 mg m^{-3}, whereas in spring 2003 chl *a* was 7 to >11 mg m^{-3}. Chl $a > 7$ mg m^{-3} only occurred in June 2002, whereas high chl *a* occupied the entire nearshore region in every month of 2003.

[16] Figures 3c–3d compare monthly chl *a* in April 2002 and April 2003. Only a small section of the study area had chl $a > 4$ mg m^{-3} (Figure 3c) in April 2002. In contrast, data for April 2003 (Figure 3d) showed a large region southeast of the Chesapeake Bay mouth had elevated chl *a*, including values >11 mg m^{-3}. Highest chl *a* may indicate the approximate position of the Chesapeake Bay outflow plume during April. In April 2002, waters with chl *a* at 3–4 mg m^{-3} were observed at the Bay mouth (76°W) at 37°N, whereas in April 2003 waters of this concentration were shifted substantially offshore of the Bay mouth.

5. Discussion

[17] In this paper, we tested the hypothesis that increased freshwater flow to Chesapeake Bay in 2003 resulted in increased export of water from the Bay to the coastal Atlantic Ocean, leading to enhanced phytoplankton productivity observable as increased chl *a*. The cause of increased chl *a* could be either increased nutrient loading or export of high chl *a* water from the Bay to the coastal Atlantic. The effect of increased freshwater flow on the Bay itself must first be evaluated to determine if the Bay is a likely source of increased nutrients. Salinity measurements for 2003 indicated that increased freshwater flow lowered salinity

throughout the Bay. The Chesapeake Bay Program Office (CBPO) of the National Oceanic and Atmospheric Administration (NOAA) reported that low salinity waters (<10) were found approximately 150 km south of their normal extent in July. The increased volume of low-salinity water likely resulted in an increased transport from the Bay into the coastal Atlantic. In addition, CBPO also notes that the low precipitation and low freshwater flow in 2001 and 2002 likely resulted in increased terrestrial storage of nutrients, and a large amount of these "stored" nutrients subsequently entered the Bay in 2003 (Summer 2003 oxygen levels in the Chesapeake Bay report, Chesapeake Bay Program Office, 2003, available at http://www.chesapeakebay.net/pubs/low_do_backgrounder.pdf).

[18] Substantially elevated chl *a* in April 2003 (Figures 3a–3b) corresponded to a strong spring freshet in March 2003, the month with the highest flow in that year (Figure 1). However, because chl *a* was elevated throughout the Bay in 2003, we cannot discount that high chl *a* at the mouth of the Bay merely reflects an export of high chl *a* water from the Bay, rather than a local increase of phytoplankton productivity.

[19] Several factors, however, support the hypothesis that increased chl *a* was due in part to nutrient-enhanced phytoplankton productivity. Previous studies of Chesapeake Bay indicated that the seaward, polyhaline region (sections D and E in Figure 1 inset) is sensitive to variability of freshwater flow into the Bay. This region has shown the largest historical increase of chl *a* [*Harding*, 1994; *Harding and Perry*, 1997]. Furthermore, limitation of phytoplankton productivity by nitrogen availability in this region is substantially reduced during high flow conditions, resulting in higher-than-average chl *a* [*Harding et al.*, 2002]. Under the high flow conditions of 2003, Atlantic waters immediately adjacent to the Bay mouth would be expected to have similar characteristics to the estuarine waters in the lower Bay.

[20] Furthermore, chl *a* was elevated along the coast in the entire study area during 2003 (Figure 3b), not just in the outflow plume of the Bay (Figure 3d), and not only in the months with highest freshwater flow. This observation suggests that conditions evoking elevated chl *a* were not isolated to the outflow plume, i.e., increased nutrient loading in the Bay resulted in increased nutrient export to the adjacent coastal Atlantic. Several studies have shown that Chesapeake Bay is a net exporter of total nitrogen to the ocean [*Nixon*, 1987; *Boynton et al.*, 1995; *Cerco*, 2000; *Kelly et al.*, 2001], with much of the total nitrogen in particulate form, which could be remineralized by bacterial respiration at the Bay mouth.

[21] In summary, sequential years of low and high freshwater flow to Chesapeake Bay in 2002 and 2003 coincided with strongly contrasting chl *a* in the Atlantic Ocean adjacent to the Bay mouth. It is important to note that effects believed to contribute to the degradation of the Bay proper may also influence conditions in coastal waters adjacent to the estuary. Nitrogen limitation of phytoplankton productivity in the lower Bay, plume, and shelf waters makes this area particularly susceptible to climatic and anthropogenic influences. The availability of the rapid data analysis capabilities of Giovanni, in conjunction with the high-quality ocean color data from SeaWiFS, provides a new opportunity for researchers to monitor and evaluate the status of their unique coastal environments.

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