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Integrated impact of tropical cyclones on sea surface chlorophyll in the North Atlantic

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[1] Past studies have shown that surface chlorophyll-a concentrations increase in the wake of hurricanes. Given the reported increase in the intensity of North Atlantic hurricanes in recent years, increasing chlorophyll-a concentrations, perhaps an indication of increasing biological productivity, would be an expected consequence. However, in order to understand the impact of variable hurricane activity on ocean biology, the magnitude of the hurricane-induced chlorophyll increase relative to other events that stir or mix the upper ocean must be assessed. This study investigates the upper ocean biological response to tropical cyclones in the North Atlantic from 1997–2005. Specifically, we quantitatively compare the anomalous chlorophyll-a concentrations created by cyclone activity to the total distribution of anomalies in the subtropical waters. We show that the cyclone-induced chlorophyll-a increase has minimal impact on the integrated biomass budget, a result that holds even when taking into consideration the lagged and asymmetrical response of ocean color. **Citation:** Hanshaw, M. N., M. S. Lozier, and J. B. Palter (2008), Integrated impact of tropical cyclones on sea surface chlorophyll in the North Atlantic, *Geophys. Res. Lett.*, *35*, L01601, doi:10.1029/2007GL031862.

1. Introduction and Background

[2] It has recently been reported that the number of hurricanes and tropical cyclones (hereafter TCs), as well as the proportion of hurricanes reaching category 4 and 5 status, is increasing in the North Atlantic [*Webster et al.*, 2005], and may continue to increase further with global warming [*Emanuel*, 2005]. Though changes in frequency and intensity of TCs are of obvious interest due to their destructive impact upon landfall, the effect of such changes on ocean physics, biology, and chemistry is also of interest. The physical effects of hurricanes, including a decrease in sea surface temperature (SST), a deepening of the ocean mixed layer, and upwelling conditions in the wake of the passing hurricane, have been well documented in recent decades [*Jacob et al.*, 2000; *Price*, 1981; *Sanford et al.*, 1987; *Shay et al.*, 1992]. Additionally, hurricanes have been shown to influence CO_2 exchange between the ocean and the atmosphere, as strong winds can dramatically increase the efflux from the ocean of this climatically important gas [*Bates et al.*, 1998]. Studies of the biological effects of hurricanes, facilitated by SeaWiFS (Sea-viewing Wide Field-of-view Sensor) ocean color data, have shown surface chlorophyll (chl-a) increases in the wake of hurricanes [*Babin et al.*, 2004; *Davis and Yan*, 2004; *Walker et al.*, 2005].

[3] Past studies using SeaWiFS have revealed hurricane-induced chl-a increases in the Atlantic [*Babin et al.*, 2004], along the northeastern coast of the U.S. [*Davis and Yan*, 2004] and in the Gulf of Mexico [*Walker et al.*, 2005]. These increases have been hypothesized to result from upwelling or entrainment of subsurface, chlorophyll-rich waters to within the penetration depth of the SeaWiFS sensor (the upper tens of meters of the water column in this region of the ocean [*Gordon and McCluney*, 1975]) and/or new production of phytoplankton due to an influx of nutrients. One of the most comprehensive studies [*Babin et al.*, 2004] investigated thirteen hurricanes passing through a region of the subtropical North Atlantic. *Babin et al.* [2004] reported chl-a increases ranging from 5% to 91% in the wake of these hurricanes, with elevated levels typically lasting 2–3 weeks before returning to pre-hurricane concentrations. The study also noted that the strength of the chl-a increase varied in proportion to the wind strength and that response was greatest on the right-hand side of the storms, consistent with a known asymmetrical physical response to hurricanes [*Price et al.*, 1994].

[4] Considering that phytoplankton consume carbon dioxide and play a vital role in the air-sea exchange of this important greenhouse gas, research into hurricane-induced impacts on phytoplankton is important for understanding our climate system and the possible consequences of increased atmospheric CO_2 levels, which may include more frequent and intense hurricanes. However, though past studies have documented a measurable increase in chl-a concentrations as a result of hurricanes, the magnitude of this increase relative to other processes that impact ocean chl-a must be assessed to determine the consequence of increasing hurricane frequency and/or intensity for ocean biology and chemistry. Other processes that could impact the local chl-a include wind events that are not categorized as TCs, wintertime convective mixing, eddy-induced upwelling, and advection of chl-a anomalies. Thus, the aim of this study is to assess the integrated impact of TCs on sea surface chl-a in the North Atlantic relative to other perturbations. Specifically, we investigate the upper ocean chl-a response to TCs and quantitatively determine their contribution to the integrated surface chl-a budget of a North Atlantic study region over the period 1997–2005.

2. Data and Methods

[5] To investigate the impact of tropical cyclones on the biomass budget of the subtropical North Atlantic, we

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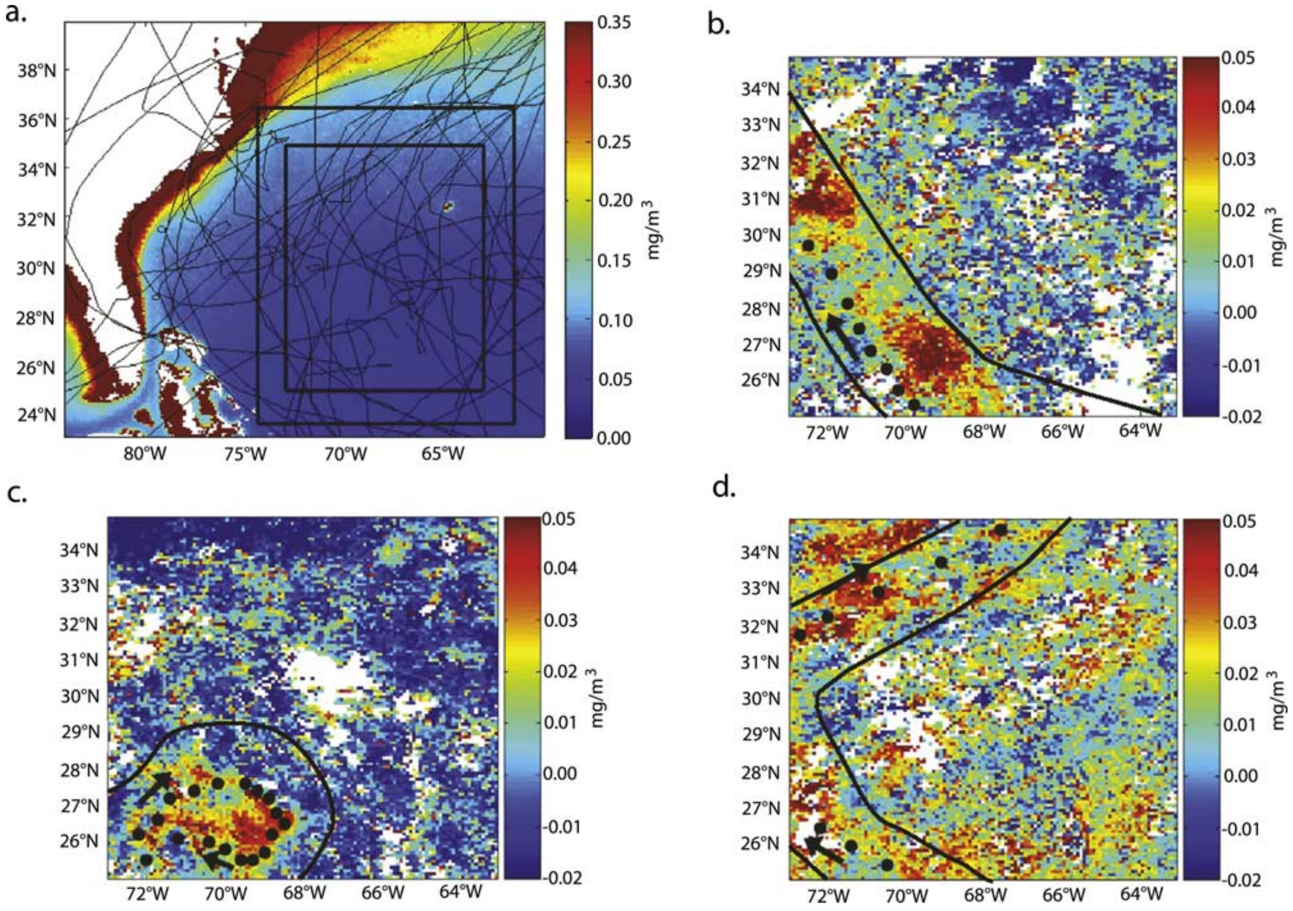

Figure 1. (a) Study domain showing mean SeaWiFS chl-a concentration for the 1997–2005 hurricane seasons. The inner box is the study area for which ocean color data was obtained. The outer box marks the buffer zone. TC data was obtained for all TCs passing within the outer box. Tracks indicate all TCs (45) in the domain from 14 Sep 1997 through 2005. (b) Chl-a anomaly plot for Hurricane Isabel–Cat. 3; chl-a composite image from 14 Sep 2003 to 21 Sep 2003. Circles represent the TC center locations at 6-hourly intervals, the direction of the TC is indicated by arrows and approximate impact swath is outlined in black, using 1° to the left, 2° to the right criteria. (c) As for Figure 1b, but for Hurricane Jeanne–Cat. 1; chl-a composite image from 21 Sep 2004 to 28 Sep 2004. (d) As for Figure 1b, but for Hurricane Danielle–Cat. 1; chl-a composite image from 29 Aug 1998 to 05 Sep 1998. Note that Danielle exits and reenters the box.

selected a region within the basin frequented by TCs, calculated the chl-a anomalies associated with the passage of TCs, and then compared these anomalies to the total distribution of anomalies over the spatial and temporal domain of our study. Comparisons of the TC-induced chl-a anomalies to the total distribution of anomalies for the region were made for the hurricane season and for the entire year. The study area (Figure 1a) encompasses a 10° by 10° box in relatively oligotrophic waters surrounding Bermuda, which was influenced by 45 TCs between 1997 and 2005. Chl-a concentrations for this region between the inception of the SeaWiFS data, September 14th, 1997 and December 2005 were obtained from the 8-day, 9-km, level-3 SeaWiFS data. TC data, including the storms' center locations and maximum sustained winds for 6-hourly periods were taken from the National Hurricane Center (NHC) archives. Unless otherwise mentioned (see Table 1), only those hurricanes occurring within hurricane season (June 1st–November 30th) have been included in this study.

Table 1. Average Chl-a Concentrations for the Entire Year, Hurricane Season, and Non-Hurricane Season, With and Without Impacted Cells Included[a]

Cells Used	Average Chl-a, mg m^{-3}	Standard Deviation, mg m^{-3}	Standard Error, mg m^{-3}
Annual Totals:			
all cells	0.08582	0.04896	2.30×10^{-5}
non−impacted cells	0.08621	0.04930	2.35×10^{-5}
impacted cells	0.07164	0.03050	8.63×10^{-5}
Hurricane Season:			
all cells	0.06632	0.02898	1.87×10^{-5}
non-impacted cells	0.06613	0.02898	1.91×10^{-5}
impacted cells	0.06997	0.02853	8.31×10^{-5}
Non-Hurricane Season:			
all cells	0.10826	0.05808	3.98×10^{-5}
non-impacted cells	0.10828	0.05811	3.99×10^{-5}
impacted cells	0.09933	0.04588	5.44×10^{-4}

[a] Three TCs (3) occurred outside of hurricane season; these are included in the impacted categories in the annual means and the non-hurricane season means. Impacted cells also include the +1 octave lagged cells for category 2 and 3 hurricanes.

[6] Our decision to use the 8-day, 9-km, level-3 SeaWiFS data rather than the 1-km and daily images was based on two main factors. First, the high winds of a hurricane typically span 150–250 km in diameter, and impact ocean currents, surface temperatures, and chl-a at comparable spatial scales [*Price et al.*, 1994; *Babin et al.*, 2004]. Thus, the 9-km data resolve not only a hurricane's impact swath, but also the variability within that swath. Sampling the satellite chl-a data at ever-smaller spatial scales would certainly resolve increasingly smaller scale variability [*Mahadevan and Campbell*, 2002]; however, characterizing such sub-mesoscale variability does not contribute to the goal of this study which is to assess hurricanes' integrated impact on chl-a relative to other perturbations studied at the same scale. Secondly, 8-day composite chl-a images have been shown to resolve the impact of hurricanes, as well as the slow return to equilibrium after their passage [*Babin et al.*, 2004]. It should also be noted that although the satellite has a nominal return time of one day, the ocean surface chl-a concentrations are computed for cloud-free pixels during daylight hours. For work with hurricanes, which are characterized by large convective clouds, the 8-day data is the shortest temporal resolution available that can consistently resolve the region of interest during and after the storms. The limitations of dealing with daily images as well as the appropriateness of using 8-day images are illustrated by *Davis and Yan* [2004], in which daily SeaWiFS images are used to compare chl-a concentrations before and after the passage of various hurricanes. Due to cloudiness, for 2 of 7 storms, the study region could not be resolved until 6 and 10 days following the storm. Despite the lag between the storm's passage and the first view of its impact, the impact of these 2 storms was among the strongest studied. In sum, the 8-day, 9-km, level-3 SeaWiFS data is appropriate and sufficient for our study.

[7] We computed local mean chl-a concentrations for every 9-km grid cell and every 8-day composite image (octave). Chl-a anomalies were then calculated for each octave of each 9-km grid cell by subtracting this local mean: a positive chl-a anomaly for a particular cell would indicate that the measure of chl-a for that particular octave is higher than the chl-a averaged for that same octave over the study period.

[8] All octaves of all cells were designated as either TC-impacted or non-impacted. TC-impacted cells are those found inside the area of influence for the TC. The area of influence includes cells within a specific distance to the left and right of the TC track created by linearly interpolating between the reported center locations. We investigated the impact of right-handed asymmetry, and concluded that an impact swath of 1° to the left and 2° to the right of the TC track produced the greatest chl-a response. Thus, all impacted cells are defined as those that fall within the 1°L, 2°R swath; non-impacted cells encompass all remaining cells in that particular octave. TC strength was designated with one discrete category, i.e. each cyclone was categorized as either a tropical depression (9 occurrences), tropical storm (23), or as a category 1 (7), category 2 (2) or category 3 (4) hurricane. This designation was determined by averaging the maximum sustained winds for all 6-hourly measurements during which the hurricane was within the study domain. If a TC spanned more than one octave, an average was computed for each octave. The categorization for the TC was then based on this collective mean wind. There were no category 4 or 5 hurricanes in the study region during 1997–2005.

3. Results

[9] Three representative chl-a anomaly plots for the TCs in this study area reveal that while some cyclones produce a significant impact that is clearly strongest on the right-hand side of the storm, others show either a weak or non-localized response along the cyclone track (Figures 1b, 1c and 1d). Hurricanes Isabel (Figure 1b) and Jeanne (Figure 1c) produced significant chl-a responses on the right-hand side of the TC tracks, while Danielle (Figure 1d) produced a less localized and relatively weak response along its track.

[10] To ascertain whether TC category affects the strength of the chl-a response, chl-a anomalies for all impacted cells were grouped by TC category. As seen in Figure 2a, a shift in the chl-a anomaly distribution to increasingly positive values is evident as the storm category increases. The positive correlation between wind strength and chl-a anomaly strength is consistent with the results of *Babin et al.*'s [2004] study: stronger winds are likely to induce greater mixing of the upper ocean, bringing larger amounts of subsurface chl-a and/or nutrients to the surface. Their study indicates that an increase in wind speed, from 40 to 60 ms^{-1}, corresponds with a 20% greater chl-a response. Our analysis shows that the shift from a category 1 to a category 3 hurricane (a difference in mean wind speed of 16 ms^{-1}, from 38 to 54 ms^{-1}) results in a 15% increase in the chl-a concentration. Scaling this to a comparable change in wind strength of 20 ms^{-1}, our study results in a 19% increase in the chl-a concentration. (Note that the anomaly strength almost doubles, as can be seen from the inset in Figure 2a, but the actual concentration change is much smaller.)

[11] The distributions in Figure 2a illustrate that a wide range of chl-a anomalies are contained within the impact swaths of TCs. As determined by standard error calculations, all reported means, though small relative to the total range, are significantly greater than zero (Table 1). To investigate the integrated impact of the storms, the distribution of all TC-impacted anomalies is compared to the distribution of anomalies from all non-impacted cells during hurricane season and non-hurricane season (Figure 2b). As is evident from these distributions, TC-impacted cells account for only a small percentage (4.9%) of all cells within hurricane season. Notably, the non-impacted cells within the hurricane season have a wider distribution of chl-a anomalies than the impacted cells. In other words, the variability in the chl-a response induced by TCs is completely subsumed by the larger variability that characterizes the spatial domain. The chl-a response to TCs is apparently no more or no less than that produced by other events or processes that act to elevate or depress the local chl-a concentration. The relative insignificance of the TC-induced anomalies is even starker when compared to the anomaly distribution from the non-hurricane season (Figure 3). Events during non-hurricane season produce larger positive and negative anomalies than those found within hurricane season and certainly larger than those produced by TCs, as would be expected

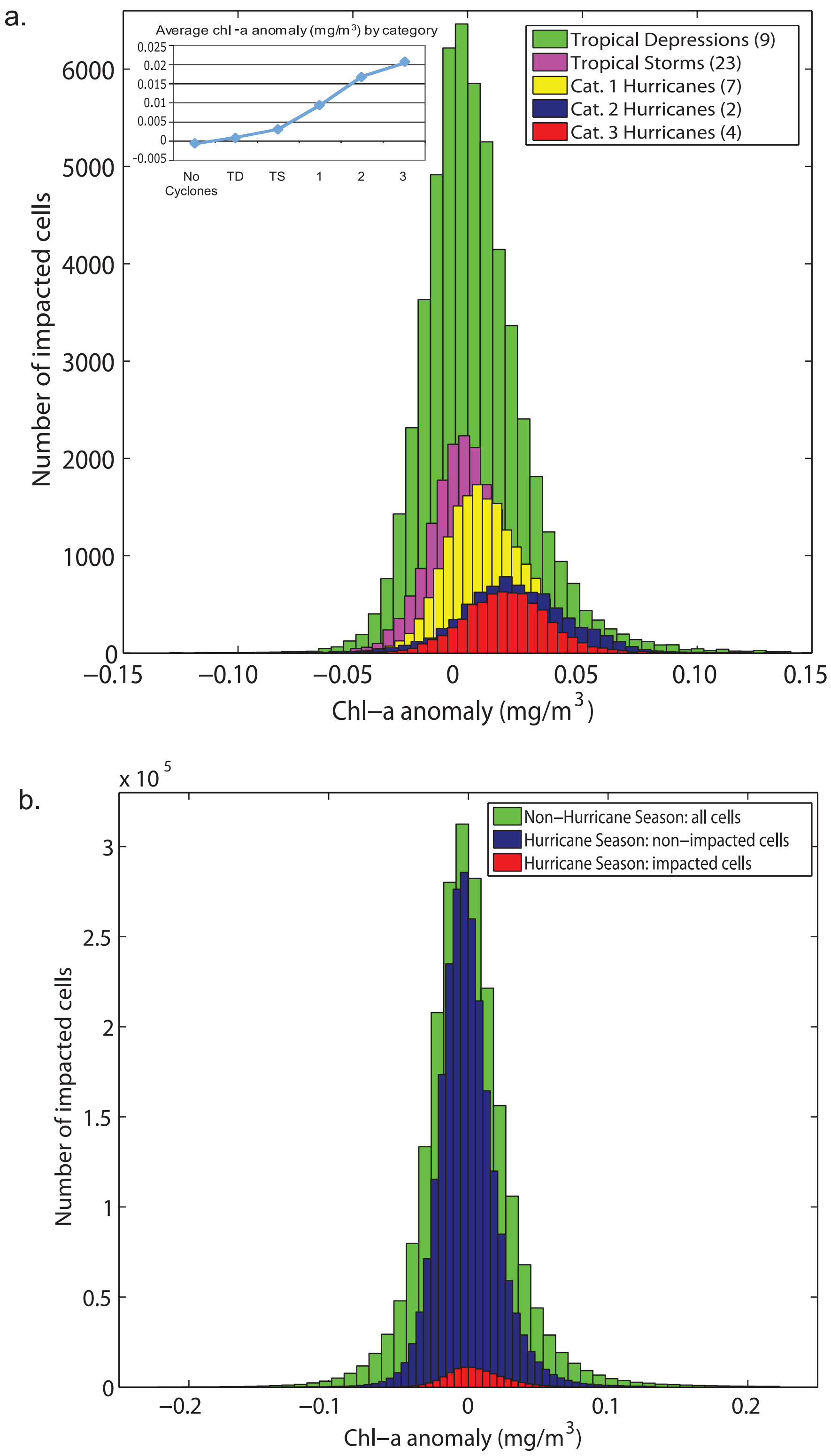

Figure 2. (a) Histogram of chl-a anomalies for all impacted cells in each TC category. The differing number of impacted cells for each TC category is a reflection of the number of TCs in each category. Inset shows the average chl-a anomaly for each TC category, with the No Cyclones category representing all the non-impacted cells within hurricane season. Standard error bars are included, but are so small that they are obscured by the series markers. (b) Chl-a anomalies for non-hurricane season (green), hurricane season non-impacted cells (blue), and impacted cells (red).

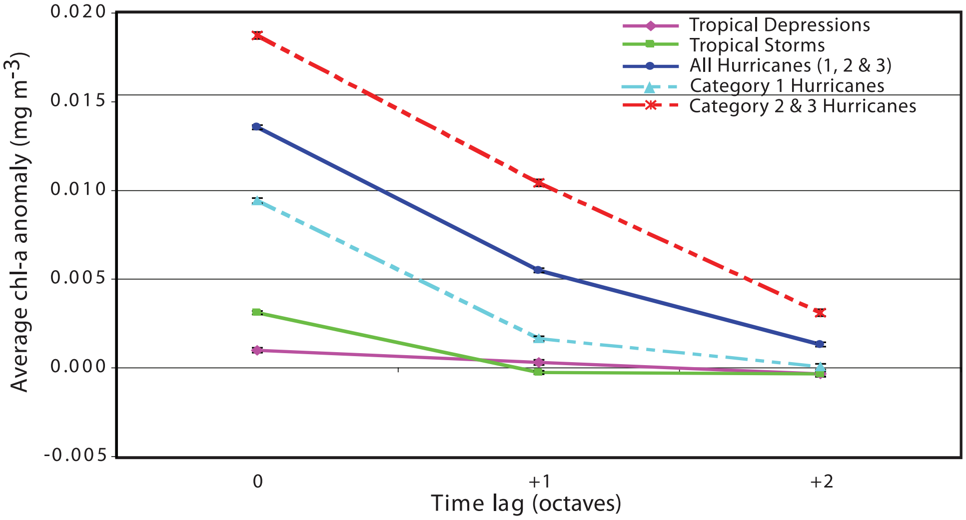

Figure 3. Average chl-a anomalies by category, for varying time lag (0 = no lag, 1 = the first lagged octave, 2 = the second lagged octave). If a new TC passed through the impact-swath of a lagged TC, any overlapping cells were only counted for the most recent TC. Due to the fact that there were so few hurricanes in categories 2 and 3, their means are reported together. Standard errors, which are included as vertical bars at each data point, are often small enough to be obscured by the data point itself.

due to winter storminess and the impact of the winter/spring bloom in this region.

[12] It is possible that our measure of the TC-impacted anomalies is underestimated since it considers anomalies only within the octave that the hurricane occupies the box. As mentioned earlier, *Babin et al.* [2004] observed that chl-a concentrations remained elevated over pre-hurricane concentrations for 2–3 weeks. To assess the importance of this lagged response, mean chl-a anomalies within the impact swath for each of the two octaves following the passage of a TC were calculated and compared to the mean chl-a anomaly during the initial octave. Average chl-a anomalies for the two octaves following the initial impact (Figure 3) indicate that the greatest impact of a TC occurs during the octave for which the TC is in the study area (octave 0). For tropical depressions and tropical storms, mean chl-a anomalies return to zero by the first lagged octave (+1). In contrast, a measurable response remains in the first lagged octave for the category 2 and 3 hurricanes; however, this response converges to zero by the second lagged octave (+2). Figure 2 incorporates the lagged response for category 2 & 3 hurricanes in the +1 octave; results are similar to the distributions calculated without the lagged impact. The strong initial response, followed by a relatively rapid decay of the elevated positive anomaly (Figure 3) leads us to hypothesize that the increased chl-a concentrations are caused primarily by the upward mixing of chl-a to the SeaWiFS penetration depth. In this region of the ocean, the deep chl-a maximum resides between 50 m and 120 m throughout the hurricane season, with the top of the nutricline found just below this depth [*Michaels and Knap*, 1996]. That the chl-a response to a passing hurricane is strongest in the same octave during which the hurricane passes through the study region may indicate that the signal is primarily caused by the upward flux of chl-a from the deep chl-a maximum. A biological response to a vertical nutrient flux is expected to occur only after some lag. The correspondence of TC strength to the size of the chl-a response suggests that the stronger storms mix this deep chl-a maximum more effectively and/or that the stronger storms also bring nutrients from below the chl-a maximum to excite a bloom that persists after a lag.

[13] To summarize and quantify the impact of TCs on annual chl-a concentrations and variability, chl-a averages for the entire year, for the hurricane season and for the non-hurricane season are compared (Table 1). As expected, non-hurricane season averages in all categories are elevated over those for the hurricane season and for the entire year. In all three categories (annual, hurricane season, and non-hurricane season) the average chl-a concentrations for all cells and non-impacted cells are quite similar, reflecting the small contribution of the cells impacted by TCs. Although average chl-a in the impacted cells is 5.8% higher than in the non-impacted cells during hurricane season, including impacted cells in the mean chl-a concentration creates an increase of only 0.29% over the non-impacted cells. Inclusion of lagged weeks in the calculation of chl-a concentration contributes only 1.1% of the positive chl-a anomaly within the hurricane season.

4. Summary

[14] This study has confirmed that surface chl-a increases in response to passing TCs, that the increase is larger on the right-hand side of the TC and that the magnitude of the response is dependent upon the strength of the TC. Additionally, we have found the duration of the response to be shorter than reported by previous studies, with a negligible lagged response for tropical depressions, tropical storms and category 1 hurricanes, and only a minimal lagged response for category 2 and 3 hurricanes. The main contribution of this study is the evaluation of the TC response relative to the total variability of the chl-a field during hurricane season and to the total annual variability. While the biological

response to the TCs is significant, with this significance manifest qualitatively (as in Figures 1b–1d) and quantitatively (Figure 2), the TC-induced chl-a response relative to the total chl-variability is minimal for two main reasons. First, TCs are simply too small and infrequent to be of much consequence: the cells impacted by TCs represent a paltry fraction of the total cells within a year or even within a hurricane season, accounting for only 2.8% of all cells within the study area over a year. Secondly, there are numerous other events and processes that produce anomalies just as large and, often, even larger than those produced by the cyclones. This is particularly true during the non-hurricane season, which includes the winter/spring bloom. Concentrations during non-hurricane season are on average 0.022 mg m^{-3} greater than the annual all-cell average, and 0.042 mg m^{-3} greater than the hurricane season all-cell average (26% and 63% greater, respectively). Finally, though we have provided a quantification of the ocean color anomalies, our study does not hinge on the absolute value of the ocean color anomalies, an estimate that is likely scale-dependent. Rather, our study is focused on the contribution of TCs to ocean color anomalies relative to other events that mix or stir the ocean to create ocean color anomalies.

[15] In summary, if TC intensities increase over time, it is likely that phytoplankton in the immediate aftermath of the cyclones will be affected to a slightly greater extent, exhibiting an observable immediate local response that rapidly decays. However, over the course of the hurricane season and certainly over the course of the year, the integrated response due to these TCs will likely remain minimal. It is unlikely that an increase in cyclone frequency, within the bounds predicted, would change this conclusion.

[16] **Acknowledgments.** The authors gratefully acknowledge the SeaWiFS Project, NASA/Goddard Space Flight Center and support from the National Science Foundation.

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