AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL063222

Key Points:
- Integrated impact of tropical cyclones on chl a is similar to that of the NAO
- Cyclones affect interannual chl a through changes in mixed layer depth
- Previous techniques likely underestimate impact of cyclones on integrated chl a

Supporting Information:
- Text S1
- Figure S1

Correspondence to:
G. R. Foltz,
gregory.foltz@noaa.gov

Citation:
Foltz, G. R., K. Balaguru, and L. R. Leung (2015), A reassessment of the integrated impact of tropical cyclones on surface chlorophyll in the western subtropical North Atlantic, *Geophys. Res. Lett.*, *42*, 1158–1164, doi:10.1002/2015GL063222.

Received 22 JAN 2015
Accepted 27 JAN 2015
Accepted article online 5 FEB 2015
Published online 27 FEB 2015

A reassessment of the integrated impact of tropical cyclones on surface chlorophyll in the western subtropical North Atlantic

Gregory R. Foltz[1], Karthik Balaguru[2], and L. Ruby Leung[3]

[1]Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami, Florida, USA, [2]Marine Sciences Laboratory, Pacific Northwest National Laboratory, Seattle, Washington, USA, [3]Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, Richland, Washington, USA

Abstract The impact of tropical cyclones on surface chlorophyll concentration is assessed in the western subtropical North Atlantic Ocean during 1998–2011. Previous studies in this area focused on individual cyclones and gave mixed results regarding the importance of tropical cyclone-induced mixing for changes in surface chlorophyll. Using a more integrated and comprehensive approach that includes quantification of cyclone-induced changes in mixed layer depth, here it is shown that accumulated cyclone energy explains 22% of the interannual variability in seasonally averaged (June–November) chlorophyll concentration in the western subtropical North Atlantic, after removing the influence of the North Atlantic Oscillation (NAO). The variance explained by tropical cyclones is thus about 70% of that explained by the NAO, which has well-known impacts in this region. It is therefore likely that tropical cyclones contribute significantly to interannual variations of primary productivity in the western subtropical North Atlantic during the hurricane season.

1. Introduction

Phytoplankton consume CO_2, affecting its air-sea exchange rate and the efficiency with which carbon is sequestered in the deep ocean. The intense vertical mixing induced by some tropical cyclones has been shown to enhance surface chlorophyll *a* (chl *a*) concentration significantly [*Lin et al.*, 2003; *Babin et al.*, 2004; *Sun et al.*, 2010; *Lin*, 2012]. The effect is especially apparent in the subtropics, where the seasonal thermocline and nutricline are strong but shallow, and the mean chl *a* concentration is low (Figure 1a) [*Siegel et al.*, 1990; *Babin et al.*, 2004]. When the subtropical mixed layer shoals in boreal spring, prior to the start of the hurricane season, phytoplankton multiply and deplete nutrients from the mixed layer, creating a chlorophyll maximum in the seasonal thermocline during boreal summer and fall [*Siegel et al.*, 1990]. The stratification in the thermocline prevents nutrients from entering the mixed layer except for the case of strong turbulent mixing, as often occurs during the passage of a tropical cyclone.

Previous studies have identified the North Atlantic Oscillation (NAO) [*Hurrell et al.*, 2003] as an important driver of sea surface temperature (SST), mixed layer depth (MLD), and chl *a* in the subtropical North Atlantic on interannual time scales [*Cayan*, 1992; *Bates*, 2001; *Follows and Dutkiewicz*, 2002; *Hurrell and Deser*, 2009; *Cianca et al.*, 2012]. A reduction in surface wind speed in the subtropics associated with positive phases of the NAO tends to force warmer SSTs, a reduction in vertical turbulent mixing and hence a thinner MLD, and a resultant decrease in chl *a* concentration. Connections between chl *a* and El Niño–Southern Oscillation (ENSO) are less well established, though *Cianca et al.* [2012] show a significant negative correlation near the Canary Islands during January–April with ENSO leading by 1 year. The main focus of most previous studies was the boreal winter and spring seasons, when atmospheric forcing from the NAO and ENSO are strongest [*Wallace et al.*, 1992].

There is debate over whether tropical cyclone-induced mixing has a significant impact on chl *a* in the subtropical Atlantic over the course of the hurricane season (June–November) relative to other larger-scale atmospheric forcing from phenomena such as ENSO and the NAO. On the one hand, individual cyclones have been shown to enhance chl *a* concentration through the mixing of nutrients and phytoplankton into the surface layer [*Babin et al.*, 2004]. During 1998–2001, every hurricane that passed through the subtropical North Atlantic (55°W–78°W, 20°N–32°N) caused an increase in surface chl *a* concentration along its track

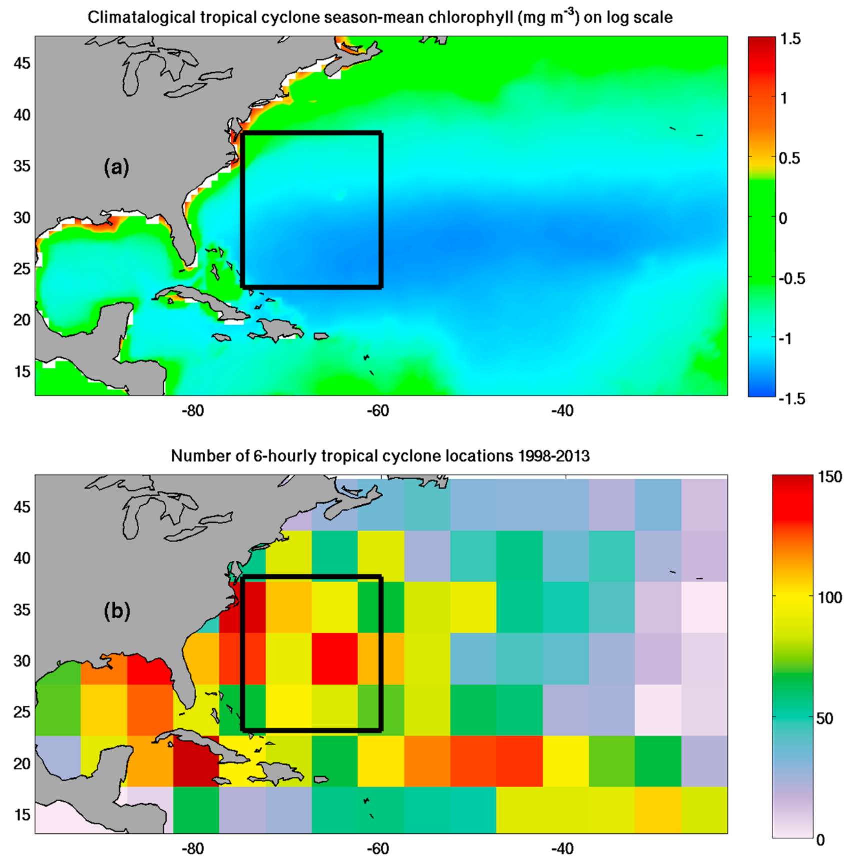

Figure 1. (a) Climatological hurricane season (June–November) mean chlorophyll *a*. (b) Number of six-hourly tropical cyclone locations during 1998–2013. Black boxes in Figures 1a and 1b enclose the region used for our analysis.

that persisted for 2 to 3 weeks. Based on these observations, cyclone-induced mixing would appear to make an important contribution to seasonal primary productivity in the subtropical North Atlantic. On the other hand, *Hanshaw et al.* [2008] argue that tropical cyclones are too small and occur too infrequently to induce significant changes in chl *a* in the subtropical North Atlantic on a seasonal mean basis.

Here we address the apparent inconsistency between previous analyses of tropical cyclone-induced chl *a* enhancement in the subtropical North Atlantic. In contrast to previous analyses, which attempted to quantify the chl *a* response to each cyclone separately, here we assess tropical cyclone activity and chl *a* variability averaged for the entire hurricane season and integrated over a larger region in the western subtropical North Atlantic. This technique avoids assumptions about the spatial scale of the storm-induced chl *a* response and the relaxation time scale for chl *a* after a cyclone passes. It is shown that tropical cyclones exert a significant influence on the spatially and seasonally integrated chl *a* concentration independent of large-scale forcing of the NAO and ENSO.

2. Data and Methods

Monthly chl *a* concentration during 1998–2011 was obtained from the Ocean Color Climate Change Initiative project (http://www.esa-oceancolour-cci.org) on a ~4 km grid. The data set merges satellite measurements from the Medium Resolution Imaging Spectrometer (MERIS), Moderate Resolution Imaging Spectroradiometer (MODIS), and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) after band-shifting and bias-correcting MERIS and MODIS data to match SeaWiFS data. Cyclone track data for the period 1998–2013, obtained from http://www.aoml.noaa.gov/hrd/hurdat/hurdat2.html [*Landsea and Franklin*, 2013], are used to identify cyclone track locations and maximum wind speed at 10 m. The accumulated cyclone energy (ACE) is calculated as the sum of the squares of the six-hourly 10 m maximum wind speed from each tropical cyclone (maximum wind speed >17 m s^{-1}) in a given hurricane season (June–November).

We use monthly 1°×1° maps of temperature and salinity from Argo profiles for the period 2004–2013, available from http://www.argo.ucsd.edu/Gridded_fields.html [*Roemmich and Gilson*, 2009]. The MLD is calculated from the gridded temperature and salinity products using the criterion of the density equivalent of a 0.2°C decrease in temperature from a depth of 10 m, following *de Boyer Montégut et al.* [2007]. Monthly SST was obtained from the Hadley Centre SST data set (HadSST2) and is available on a 5°×5° grid for the period 1850–2014. The NAO index is calculated using rotated principal component analysis on monthly standardized 500 hPa height anomalies in the region 20°N–90°N. The Niño3.4 index, defined as monthly SST averaged in the region 5°S–5°N, 120°W–170°W, is used as a measure of ENSO variability. Both indices are available from http://www.esrl.noaa.gov/psd/data/climateindices/list.

We calculate chl *a*, ACE, and MLD averaged during June–November in a region where the highest cyclone track density is observed and where the mean chl *a* concentration is very low (23°N–38°N, 60°W–75°W; Figures 1a and 1b). The NAO and Niño3.4 indices are averaged during July–October of each year. These months coincide with the period of highest ACE and strongest interannual variability of ACE in the western subtropical North Atlantic.

Note that because we use monthly chl *a* data, we cannot unambiguously distinguish the before-cyclone chl *a* signal from the after-cyclone signal. As a result, a significant correlation between observed chl *a* and ACE by itself, for example, is inadequate to conclude that cyclones have a strong influence on chl *a*. For this reason, we conducted additional analyses, including (1) examination of Hybrid Coordinate Ocean Model (HYCOM) data to determine the typical magnitude and time scale of the mixed layer depth response to tropical cyclones (described later in this section) and (2) statistical analyses with observed mixed layer depth, chl *a*, NAO and Niño3.4 indices, and ACE (described in the following section).

In addition to the observational data described above, we use daily output from a $\frac{1}{12}^\circ$ HYCOM global assimilative run covering the period 8 May 2008 to 31 December 2013. The HYCOM data are used only to estimate the impact of tropical cyclones on MLD for an independent comparison to the observed impact. The model has 10 levels in the upper 200 m and assimilates subsurface temperature and salinity from various platforms, including Argo. Full details are given at hycom.org and in *Chassignet et al.* [2007]. Daily subsurface temperature and salinity from the model were used to calculate MLD using the same density-based criterion as we used for Argo data, which was described previously in this section. The daily MLD fields were then high-pass filtered with a cutoff period of 90 days in order to remove seasonal and longer time scale variability unrelated to forcing from tropical cyclones. The cyclone track data were used to identify the six-hourly positions of each storm that passed through the region 23°N–38°N, 60°W–75°W (hereafter “Sargasso Sea”) during 2008–2013. Any cyclone located outside of this region was excluded from the analysis. In addition, only cyclones for which the maximum wind speed exceeded 17 m s^{-1} were considered.

For each cyclone location that fits these criteria, the high-passed daily MLD from HYCOM was averaged in a 4° × 4° box centered on the storm. The area-average was calculated for the period from 10 days before to 20 days after the storm’s arrival, and only locations within the Sargasso Sea region were included in the area average. The MLD anomaly averaged over the 10 days before the storm’s arrival was then subtracted from the 30 day time series of MLD anomalies at each location in order to calculate the MLD response to each cyclone. We then calculated the mean MLD response to all tropical cyclones during 2008–2013 (a total of 32) based on the 30 day time series from each storm location. This methodology is used to estimate the typical maximum MLD anomaly caused by a cyclone and the average damping time scale of the MLD anomaly (Figure 2).

To determine the large-scale and time-integrated impact of tropical cyclones on HYCOM MLD in the Sargasso Sea, the days of each cyclone’s entry into and exit from the region were first identified. For each cyclone that passed through the Sargasso Sea, the high-pass-filtered MLD anomaly field from HYCOM was then averaged over the entire region, and the area average was summed from 1 day before the cyclone’s entry until 20 days after the cyclone’s exit from the region. The time periods of 1 day before and 20 days after were chosen based on the composite of cyclone-induced MLD anomaly (Figure 2). Results are similar for time periods ranging from 10 to 30 days. Duplicate days (i.e., when two or more cyclones’ MLD wakes are present in the region) were removed before the sum was computed. The result of this calculation is a MLD anomaly, area averaged in the Sargasso Sea, on each day during 2008–2013 when a cyclone’s MLD wake is expected to be present. Summing these values and dividing by 1080 days (6 years, each with 180 days

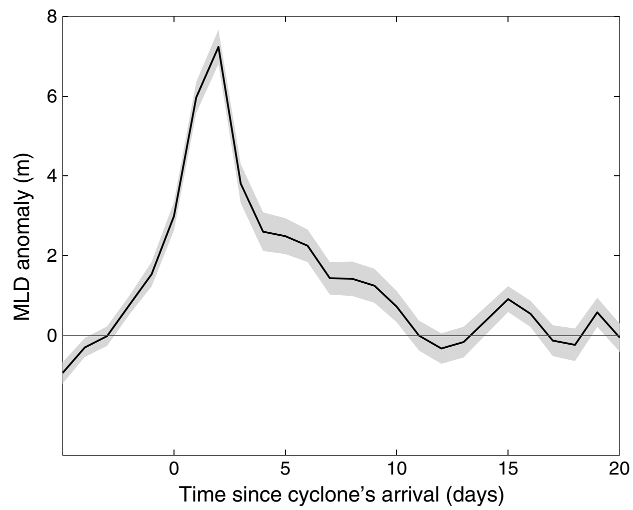

Figure 2. Mean temporal evolution of mixed layer depth in response to tropical cyclones during 2008–2013 from a HYCOM data assimilative run. Only hurricanes within the 15°×15° region shown in Figure 1 were considered. Grey shading indicates one standard error.

during the hurricane season) gives the seasonal mean cyclone-induced MLD response in the Sargasso Sea. For assessing the large-scale impact of tropical cyclones on MLD, this technique is preferred over the calculation following each storm (described in the previous paragraph) since no assumption about the spatial scale of the MLD response is needed.

In summary, we use similar methods to calculate chl *a*, ACE, and MLD in the Sargasso Sea region. The observed chl *a* and MLD are simply averaged across the Sargasso Sea and over the hurricane season (June–November), and ACE is based on all cyclones in the same region for the same period of time. Because other factors besides ACE are likely to affect MLD, and MLD itself can affect ACE through its effect on upper ocean heat content, we also estimate the impact of tropical cyclones on MLD independently, using output from a high-resolution HYCOM run. The method used to calculate the cyclone-induced MLD response consists of a large-scale spatial and temporal integration across the Sargasso Sea region, consistent with the method used for the observational analysis. Because of the strong link between MLD and chl *a* [*Follows and Dutkiewicz*, 2002], in the following section we first quantify the impacts of tropical cyclones on MLD before interpreting observed statistical relationships between ACE and chl *a*.

3. Results and Discussion

Tropical cyclones are expected to increase surface chl *a* concentration primarily through enhanced vertical turbulent mixing, which tends to thicken the surface mixed layer, bringing the base of the mixed layer closer to the top of the nutricline and the subsurface chlorophyll maximum. In the absence of large-scale and direct measurements of turbulent mixing, we therefore consider MLD as an indicator of the strength of cyclone-induced mixing. Previous observational analyses in the western subtropical North Atlantic indicate that the mixed layer deepens by ∼30 m during a hurricane's passage, with the anomaly persisting for at least 1 week [*Dickey et al.*, 1998; *Zedler et al.*, 2002]. However, these studies are based on measurements at a single location during the passage of one storm.

In order to quantify the MLD response to tropical cyclones in the western subtropical North Atlantic on broader spatial and temporal scales, we consider the temporal evolution of the cyclone-induced MLD anomaly from HYCOM, following each storm in the Sargasso Sea. During and immediately following a cyclone's passage, MLD increases sharply by 7 m on average (Figure 2). The positive anomaly rapidly diminishes during the following several days but remains positive on average until about 20 days after the cyclone's passage. Note that because we averaged the MLD anomaly over a 4° box centered on each storm and averaged across all storms during a 6 year period, the maximum MLD response is considerably lower than that observed directly at a single location for one storm.

The persistence of a significant MLD anomaly for 2 to 3 weeks after a tropical cyclone's passage suggests that the seasonal mean MLD in the Sargasso Sea may be altered substantially by cyclone-induced mixing. We find a mean cyclone-induced mixed layer deepening of 0.34 m during 2008–2013, integrated in the Sargasso Sea and over the hurricane season, and an interannual standard deviation of 0.21 m. For comparison, the total interannual standard deviation of June–November mean MLD in the Sargasso Sea is 1.70 m. Cyclone-induced variations in MLD therefore account for 12% of the total interannual variability of MLD in the Sargasso Sea during June–November. The same value of 12% is obtained when using the "storm-following" methodology described in the previous section, indicating that the cyclone-induced MLD signal is robust and is not contaminated by forcing from other large-scale phenomena such as the NAO.

Consistent with our analysis using HYCOM, observed MLD is positively correlated with ACE when averaged during June–November in the Sargasso Sea (Figures 3a and S1 in the supporting information). The correlation of 0.46 implies that ACE explains 21% of the year-to-year MLD variance, a value that is larger than the 12% result obtained from the HYCOM analysis. The larger percentage of the variance explained based on the ACE-MLD correlation likely results from the well-known influence of the NAO on MLD, and the impact of MLD on ACE through changes in upper ocean heat content. We found that the NAO is significantly correlated with MLD (−0.50) in the Sargasso Sea, consistent with a positive NAO phase leading to weaker surface winds, warmer SST, increased upper ocean stratification, and a thinner mixed layer [*Follows and Dutkiewicz*, 2002; *Hurrell and Deser*, 2009]. The partial correlation between ACE and MLD, after removing the influence of the NAO, is 0.33, indicating that ACE explains 8% of the MLD interannual variance independent from the NAO (since 75% of the MLD variability is independent of the NAO, and ACE explains $0.33^2 = 11\%$ of it). This value is closer to the 12% obtained from the HYCOM analysis, further indicating that our calculation of tropical cyclones' impact on MLD is robust.

Because vertical mixing during the passage of a tropical cyclone can extend at least 80 m below the base of the mixed layer in the subtropical North Atlantic [*Zedler et al.*, 2002] and the observed mean MLD in the Sargasso Sea during June–November 2004–2013 is 27 m, cyclone-induced mixing can reach the nutricline and deep chlorophyll maximum, located at depths of 50–100 m in the Sargasso Sea [*Siegel et al.*, 1990]. Since vertical mixing and associated deepening of the mixed layer are the primary mechanisms through which nutrients and chl *a* are brought to the surface in the oligotrophic subtropical North Atlantic, cyclone-induced mixing in theory should contribute to year-to-year changes in chl *a* concentration in the Sargasso Sea. We find a correlation of 0.44 between ACE and chl *a* in the Sargasso Sea, which is significant at the 10% level (Figures 3b and S1). The partial correlation between ACE and chl *a*, after removing the influence of the NAO, is 0.57, which is significant at the 5% level. Thus, during the years with enhanced tropical cyclone activity, stronger vertical mixing increases the average MLD, resulting in an anomalous upward flux of nutrients and chl *a* into the mixed layer.

Based on a correlation of −0.56 between the NAO and chl *a*, we find that the NAO is the main driver of chl *a* variability, explaining 31% of the variance, while ACE explains 22% of the variance after accounting for the NAO's influence. These results are consistent with those of *Follows and Dutkiewicz* [2002], which show a strong impact of the NAO on chl *a*. Over half of the chl *a* variance in the Sargasso Sea during June–November can therefore be recovered if the NAO and ACE are known. Note that the NAO and ACE consistently explain a smaller portion of the MLD variance compared to the chl *a* variance (25% and 31% of the MLD and chl *a* variance, respectively, are explained by the NAO; 12% and 22%, respectively, by ACE). These relationships suggest that the connection between MLD and chl *a* may be nonlinear and dependent on the vertical distribution of nutrients and chl *a*. We found a weak correlation between the Niño3.4 index and chl *a* (−0.16), suggesting that the NAO is the main large-scale climate signal to impact chl *a* in the subtropical North Atlantic.

Our results are consistent with those of *Babin et al.* [2004], who showed significant enhancement of surface chl *a* concentration following the passage of several hurricanes in the subtropical North Atlantic but did not consider the integrated impact of tropical cyclones on chl *a* concentration. *Babin et al.* [2004] found changes in chl *a* of 5–91% for each of 13 hurricanes that they tracked, compared to only −1 to −9% for SST. The larger percentage change for chl *a* on average can be attributed to very low prestorm values combined with a shallow nutricline that readily provides nutrients to the mixed layer during strong-mixing events. In contrast

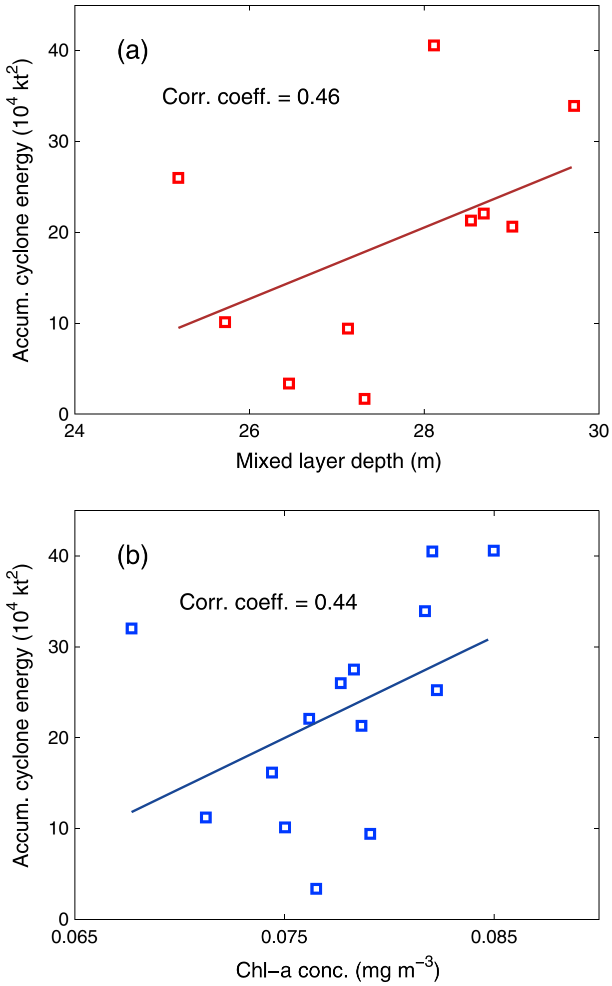

Figure 3. (a) Scatter between mixed layer depth, averaged in the box shown in Figure 1 during June–November for each of the years 2004–2013, and accumulated cyclone energy in the same box for the same period. (b) Same as Figure 3a except *x* axis is chlorophyll *a* concentration and time period is 1998–2011.

to the results of *Babin et al.* [2004] and our findings, *Hanshaw et al.* [2008] argued that tropical cyclones are too small and infrequent to contribute significantly to chl *a* concentration in the western subtropical North Atlantic. They concluded that cyclones contribute only ∼1% to chl *a* anomalies within a hurricane season.

There are several possible reasons for the discrepancy between our results and those of *Hanshaw et al.* [2008]. In contrast to our integrated analysis, which compares chl *a*, ACE, and MLD averaged over a 15° region for the entire hurricane season, *Hanshaw et al.* [2008] tracked individual cyclones and compared the chl *a* response to the chl *a* anomalies in the region that were not impacted by the cyclone. This approach requires some assumptions to be made, such as the spatial extent of a cyclone's impact and the duration of the cyclone-induced chl *a* wake. *Hanshaw et al.* [2008] assumed that the chl *a* response is contained within a swath from 1° to the left of the cyclone's center to 2° to the right, which is likely an underestimate of the spatial extent of the average cyclone's wind forcing [*Chavas and Emanuel*, 2010]. They used a relaxation time for the chl *a* wake of 2 weeks, whereas *Babin et al.* [2004] show that for some storms the wake can persist for a month. By excluding the chl *a* response outside of a narrow 3° swath and a time period of two weeks, it is possible that *Hanshaw et al.* [2008] failed to capture the full extent of the cyclone-induced chl *a* anomalies. Finally, we use a chl *a* product that combines measurements from three different satellite sensors and covers 14 years, whereas *Hanshaw et al.* [2008] relied entirely on retrievals from SeaWiFS for an 8 year period. It is unclear whether the 8 day averaged data from SeaWiFS are adequate for quantifying the chl *a* response to individual cyclones, given the spike in chl *a* that normally follows immediately after a cyclone's passage and the contamination of SeaWiFS retrievals by clouds.

4. Conclusions

We investigated the large-scale impact of tropical cyclones on chl *a* in the western subtropical North Atlantic and found that the accumulated cyclone energy explains 22% of the interannual chl *a* variance during the hurricane season (June–November). This value is consistent with the large changes in chl *a* reported by *Babin et al.* [2004] for individual hurricanes and is much larger than the 1% reported by *Hanshaw et al.* [2008] in a similar region. Our results suggest that enhancement of chl *a* by tropical cyclones in the subtropical North Atlantic is large enough to cause a significant change in the seasonal mean (June–November) chl *a* concentration integrated over an area stretching from 60°W to 75°W and from 23°N to 38°N. Tropical cyclone-induced changes in chl *a* concentration may also affect the survival rates of fish larvae and their recruitment to adulthood. *Bonhommeau et al.* [2008] show that fluctuations of European eel recruitment, for example, are closely linked to primary productivity in the Sargasso Sea.

Further analysis is therefore needed to assess the basin-wide and global impacts of tropical cyclones on chl *a* and to examine the specific mechanisms through which tropical cyclones enhance surface chl *a*. As the lengths of the satellite chl *a* records grow, further refinements to the cyclone-induced chl *a* response in the North Atlantic will also be possible, as will global analyses of the chl *a* response to tropical cyclones.

Acknowledgments
G.F. was supported by base funds to NOAA/AOML. K.B. and L.R.L. were supported by the U.S. Department of Energy (DOE) Office of Science Biological and Environmental Research as part of the Regional and Global Climate Modeling program. The Pacific Northwest National Laboratory is operated for DOE by Battelle Memorial Institute under contract DE-AC05-76RL01830. We thank two anonymous reviewers for their helpful suggestions. All data used to produce the results of this paper are freely available from the URLs supplied in section 2.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Babin, S. M., J. A. Carton, T. D. Dickey, and J. D. Wiggert (2004), Satellite evidence of hurricane-induced phytoplankton blooms in an oceanic desert, *J. Geophys. Res.*, *109*, C03043, doi:10.1029/2003JC001938.

Bates, N. R. (2001), Interannual variability of oceanic CO_2 and biogeochemical properties in the Western North Atlantic subtropical gyre, *Deep Sea Res., Part II*, *48*, 1507–1528.

Bonhommeau, S., E. Chassot, and E. Rivot (2008), Fluctuations in European eel (*Anguilla anguilla*) recruitment resulting from environmental changes in the Sargasso Sea, *Fish. Oceanogr.*, *17*, 32–44.

Cayan, D. R. (1992), Latent and sensible heat flux anomalies over the northern oceans: Driving the sea surface temperature, *J. Phys. Oceanogr.*, *22*, 859–881.

Chassignet, E. P., et al. (2007), The HYCOM (Hybrid Coordinate Ocean Model) data assimilative system, *J. Mar. Syst.*, *65*, 60–83.

Chavas, D. R., and K. A. Emanuel (2010), A QuikSCAT climatology of tropical cyclone size, *Geophys. Res. Lett.*, *37*, L18816, doi:10.1029/2010GL044558.

Cianca, A., J. M. Godoy, J. M. Martin, J. Perez-Marrero, M. J. Rueda, O. Llinàs, and S. Neuer (2012), Interannual variability of chlorophyll and the influence of low-frequency climate modes in the North Atlantic subtropical gyre, *Global Biogeochem. Cycles*, *26*, GB2002, doi:10.1029/2010GB004022.

de Boyer Montégut, C., J. Mignot, A. Lazar, and S. Cravatte (2007), Control of salinity on the mixed layer depth in the world ocean: 1. General description, *J. Geophys. Res.*, *112*, C06011, doi:10.1029/2006JC003953.

Dickey, T. D., D. Frye, J. McNeil, D. Manov, N. Nelson, D. Sigurdson, H. Jannasch, D. Siegel, A. Michaels, and R. Johnson (1998), Upper ocean temperature response to Hurricane Felix as measured by the Bermuda testbed mooring, *Mon. Weather Rev.*, *126*, 1195–1201.

Follows, M., and S. Dutkiewicz (2002), Meteorological modulation of the North Atlantic spring bloom, *Deep Sea Res., Part II*, *49*, 321–344.

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.

Hurrell, J. W., and C. Deser (2009), North Atlantic climate variability: The role of the North Atlantic Oscillation, *J. Mar. Syst.*, *78*, 28–41, doi:10.1016/j.jmarsys.2008.11.026.

Hurrell, J. W., Y. Kushnir, M. Visbeck, and G. Ottersen (2003), An overview of the North Atlantic Oscillation, in *The North Atlantic Oscillation, Climatic Significance and Environmental Impact, Geophys. Monogr. Ser.*, vol. 134, edited by J. W. Hurrell et al., pp. 1–35, AGU, Washington, D. C.

Landsea, C. W., and J. L. Franklin (2013), Atlantic Hurricane database uncertainty and presentation of a new database format, *Mon. Weather Rev.*, *141*, 3576–3592.

Lin, I.-I. (2012), Typhoon-induced phytoplankton blooms and primary productivity increase in the western North Pacific subtropical ocean, *J. Geophys. Res.*, *117*, C03039, doi:10.1029/2011JC007626.

Lin, I.-I., W. T. Liu, C.-C. Wu, G. T. F. Wong, C. Hu, Z. Chen, W.-D. Liang, Y. Yang, and K.-K. Liu (2003), New evidence for enhanced ocean primary production triggered by tropical cyclone, *Geophys. Res. Lett.*, *30*(13), 1718, doi:10.1029/2003GL017141.

Roemmich, D., and J. Gilson (2009), The 2004–2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program, *Prog. Oceanogr.*, *82*, 81–100.

Siegel, D. A., R. Iturriaga, R. R. Bidigare, R. C. Smith, H. Pak, T. D. Dickey, J. Marra, and K. S. Baker (1990), Meridional variations of the springtime phytoplankton community in the Sargasso Sea, *J. Mar. Res.*, *48*, 379–412.

Sun, L., Y. J. Yang, T. Xian, Z. M. Lu, and Y. F. Fu (2010), Strong enhancement of chlorophyll a concentration by a weak typhoon, *Mar. Ecol. Prog. Ser.*, *404*, 39–50.

Wallace, J. M., C. Smith, and C. S. Bretherton (1992), Singular value decomposition of wintertime sea surface temperature and 500 mb height anomalies, *J. Clim.*, *5*, 561–576.

Zedler, S. E., T. D. Dickey, S. C. Doney, J. F. Price, X. Yu, and G. L. Mellor (2002), Analyses and simulations of the upper ocean's response to Hurricane Felix at the Bermuda testbed mooring site: 13–23 August 1995, *J. Geophys. Res.*, *107*(C12), 3232, doi:10.1029/2001JC000969.