

RESEARCH ARTICLE

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Key Points:

- Lagged physical data are used to predict spring chlorophyll *a* variability
- Winter surface nitrate was not a robust correlate to chlorophyll *a* in all cases
- Models resolve up to 88% of chlorophyll *a* variability in Georges Bank

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Physical associations to spring phytoplankton biomass interannual variability in the U.S. Northeast Continental Shelf

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Abstract The continental shelf of the Northeast United States and Nova Scotia is a productive marine ecosystem that supports a robust biomass of living marine resources. Understanding marine ecosystem sensitivity to changes in the physical environment can start with the first-order response of phytoplankton (i.e., chlorophyll *a*), the base of the marine food web. However, the primary physical associations to the interannual variability of chlorophyll *a* in these waters are unclear. Here we used ocean color satellite measurements and identified the local and remote physical associations to interannual variability of spring surface chlorophyll *a* from 1998 to 2013. The highest interannual variability of chlorophyll *a* occurred in March and April on the northern flank of Georges Bank, the western Gulf of Maine, and Nantucket Shoals. Complex interactions between winter wind speed over the Shelf, local winter water levels, and the relative proportions of Atlantic versus Labrador Sea source waters entering the Gulf of Maine from the previous summer/fall were associated with the variability of March/April chlorophyll *a* in Georges Bank and the Gulf of Maine. Sea surface temperature and sea surface salinity were not robust correlates to spring chlorophyll *a*. Surface nitrate in the winter was not a robust correlate to chlorophyll *a* or the physical variables in every case suggesting that nitrate limitation may not be the primary constraint on the interannual variability of the spring bloom throughout all regions. Generalized linear models suggest that we can resolve 88% of March chlorophyll *a* interannual variability in Georges Bank using lagged physical data.

1. Introduction

The continental shelf of the Northeast United States and Nova Scotia is a western boundary ecosystem characterized by multiple basins in the north and a broad shelf in the middle that narrows considerably toward Cape Hatteras, North Carolina, in the south (Figure 1). Phytoplankton biomass (chlorophyll *a*) in this shelf ecosystem is typically highest in the spring with the exception of the Middle-Atlantic Bight (Figure 1), which can sometimes have a higher biomass in the fall/winter [Xu *et al.*, 2011; *Northeast Fisheries Science Center (NEFSC)*, 2012]. Throughout the shelf, biomass in the fall is also considerable, and thus, both a spring and fall bloom can sometimes occur each year. Although phytoplankton biomass is typically lowest in the summer, primary productivity (rate of photosynthesis) is highest in the summer when light levels, temperature, and stratification are also at peak levels [NEFSC, 2012]. Variability in the phenology, duration, and magnitude of phytoplankton blooms is also high in this region [Song *et al.*, 2010, 2011].

With the exception of riverine and estuarine sources of nutrients in coastal waters, the majority of external nutrient input to this shelf system derives from along-shelf flow from the north and deep off-shelf sources [Townsend *et al.*, 2006]. The deep Northeast Channel in the Gulf of Maine (tan arrow in Figure 1) connects the shelf to off-shelf waters and is thus the major thoroughway by which deep water enters the ecosystem [Townsend *et al.*, 2006]. The major deep water sources derive from slope waters of the Labrador Current (from the north) the Gulf Stream (from the south) [Townsend *et al.*, 2006] (Figure 1). Nitrate concentrations are higher (>24 μM) in the warmer, saltier slope water associated with the Gulf Stream than in the colder,

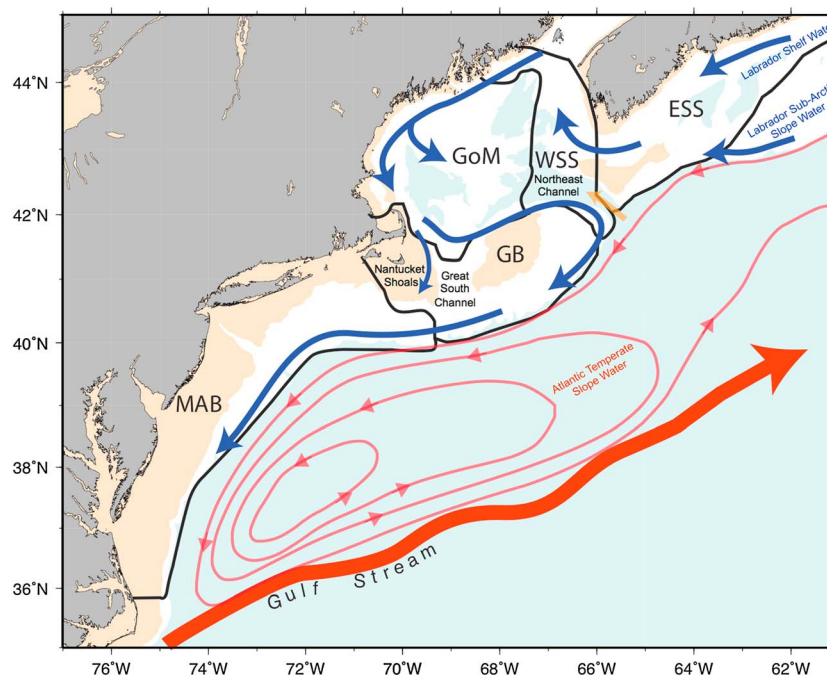


Figure 1. Source waters, ecological production units, and bathymetry within the U.S. Northeast and Scotian Shelf. Based on physical features, biological community composition, and political boundaries, this shelf region can be broken down into five distinct subregions termed ecological production units [NEFSC, 2012] consisting of the Eastern Scotian Shelf (ESS), Western Scotian Shelf (WSS), Gulf of Maine (GoM), Georges Bank (GB), and the Middle-Atlantic Bight (MAB). Enclosed in the western side of Georges Bank, Nantucket Shoals is a shallow region extending southeast of Nantucket Island. Blue arrows represent waters originating from the Labrador Current (colder, fresher, and lower NO_3), and red arrows represent waters originating from the Gulf Stream (warmer, saltier, higher NO_3). Atlantic Temperate Slope Water (associated with the Gulf Stream) and Labrador Subarctic Slope Water (associated with the Labrador Current) enter the Gulf of Maine at depth via the Northeast Channel. The thicker red arrow represents the mean position of the Gulf Stream Northern Wall. The ecological production units are outlined in solid black lines: Eastern Scotian Shelf (ESS), Western Scotian Shelf (WSS), Gulf of Maine (GoM), Georges Bank (GB), and Mid-Atlantic Bight (MAB). Water depths shallower than 50 m are shaded in tan, and those deeper than 200 m are shaded in light blue. The 200 m isobath roughly approximates the shelf break.

fresher slope water associated with the Labrador Current (15 to 17 μM) [Townsend *et al.*, 2010]. Additionally, there are injections of fresh, nutrient-poor water into the Gulf of Maine through the Eastern Scotian Shelf [Townsend *et al.*, 2014]. Observations show that the relative proportions of these source waters vary on interannual time scales [Townsend *et al.*, 2010, 2014; Han and Tang, 1999; Lillibridge and Mariano, 2013].

In the Northwest Atlantic, wind stress is highest during the winter, weakest in the summer, and is typically directed toward the southeast with the exception of summer when winds are toward the northeast [Saunders, 1977]. Cross-isobath fluxes and convective mixing are the primary mechanisms that transport nutrient-rich waters into the euphotic zone [Townsend *et al.*, 2006]. Winter mixing replenishes nutrients in surface waters that fuel the spring bloom [Townsend *et al.*, 2006]. Tidal pumping due to the robust M_2 tide is the primary factor that drives relatively high phytoplankton biomass throughout the year in shallow regions such as Georges Bank and Nantucket Shoals [Franks and Chen, 1996; Hu *et al.*, 2008]. Salinity-driven changes in stratification due to changes in the proportions of source waters could also influence phytoplankton bloom variability [Ji *et al.*, 2008; Song *et al.*, 2010, 2011]. However, empirical and modeling analyses focused on source water contributions on both lower and upper trophic levels in this shelf region suggest that the relationship may not simply be this straight forward and is much more complex [Hare and Kane, 2012; Mountain, 2012]. To help reduce this uncertainty, we analyzed the associations, both individually and interactively, among a suite of local and remote physical variables to phytoplankton biomass in the spring using 16 years of high-resolution, satellite-derived ocean color data.

2. Data and Methods

To estimate spring (March, April, May) phytoplankton biomass in the near-surface ocean layers, we used daily satellite-derived chlorophyll *a* data (1 km resolution, processed with SeaDAS v6.4) from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors (oceancolor.gsfc.nasa.gov) and produced monthly composites. We used chlorophyll *a* as a proxy for phytoplankton biomass, and we note that carbon to chlorophyll *a* ratios can change based on environmental factors such as temperature, nutrients, and light levels [Wang *et al.*, 2009]. The SeaWiFS time series spanned from March 1998 to May 2010 with the exception of two spring months that were missing due to sensor malfunction (March 2008 and May 2009). The MODIS time series spanned from March 2003 to May 2013. Therefore, MODIS data were used for March 2008, May 2009, and spring 2011–2013 while SeaWiFS data was used for the remainder of the 1998 to 2010 time series. Each monthly composite of chlorophyll *a* was calculated using a regionally tuned algorithm [Pan *et al.*, 2010] that reduces satellite measurement error in optically complex Case-2 coastal waters. The regional algorithm is based on in situ chlorophyll *a* data collected at various locations within U.S. Northeast Continental Shelf waters.

For each spring month analyzed, we calculated climatological monthly means, which were used to calculate monthly anomalies (proportional changes). An empirical orthogonal function (EOF) analysis was applied to March and April anomalies (in waters 0 to 250 m) to produce the leading three spatial modes of chlorophyll *a* variability for each month.

To determine remote and local physical associations to chlorophyll *a*, we compared monthly anomalies in chlorophyll *a* to ocean circulation indices composed of the Labrador Current Transport Volume [Han and Tang, 1999], annual proportions of deep Atlantic Temperate Slope Water and Labrador Subarctic Slope Water entering the Northeast Channel [Mountain, 2012], and the Gulf Stream Northern Wall position [Taylor, 1996]: monthly north-south and east-west wind speed data [Kalnay *et al.*, 1996] averaged over the entire shelf region, monthly 4 km sea surface temperature data, monthly in situ sea surface salinity from the Gulf of Maine and Western Scotian Shelf, and monthly water level data from Nantucket Island. We chose these physical variables based on previous research in these waters, and in other regions, that have explored models and empirical data regarding the physical constraints on phytoplankton biomass. Finally, we compared both chlorophyll *a* and the physical variables to winter surface (0–39 m) nitrate concentrations [Rebuck and Townsend, 2014] in Georges Bank and Gulf of Maine waters (where the majority of these measurements were taken) to understand winter nitrate limitation on the magnitude of spring phytoplankton biomass in these waters. All correlations were computed with and without time lags (monthly, seasonal, and annual). Monthly anomalies of chlorophyll *a* were statistically compared to various remote and local physical time series data using the Pearson correlation coefficient. The correlation coefficients were calculated for each 1 km pixel of chlorophyll *a* compared to a time series of physical data such that only statistically significant correlations were presented ($p < 0.05$). Physical data were lagged (or not) by various time steps, and the most robust correlations for the shelf waters were presented.

Monthly ocean surface wind speed data (1998–2013) were derived from the National Center for Environmental Prediction (NCEP) Reanalysis [Kalnay *et al.*, 1996] ($2.5^\circ \times 2.5^\circ$ resolution). We used surface ocean wind speed (m s^{-1}) in the *u* (zonal) and *v* (meridional) vectors. Monthly values of the Gulf Stream Northern Wall position were based on the first principal component of the latitude of the northern wall at six different latitudes [Taylor, 1996] and were available through 2013. The Labrador Current Transport Volume (Sv) through 2012 was provided by the Canadian Department of Fisheries and Oceans; this metric is based on satellite altimetry data from the Newfoundland Basin (Grand Banks area) [Han and Tang, 1999]. The annual proportions of Atlantic Temperate Slope Water and Labrador Subarctic Slope Water entering the Northeast Channel were derived from hydrographic observations in the deep region of the channel (150–200 m) following previously defined methods [Mountain, 2012]. Sea surface temperature data were from the Pathfinder (1998–2012) and MODIS (2013) satellite sensors at a 4 km resolution (<http://www.nodc.noaa.gov> and <http://oceancolor.gsfc.nasa.gov>). Sea surface salinity (SSS) from 1998 to 2013 in the Western Scotian Shelf and Eastern Gulf of Maine derived from the Bedford Institute of Oceanography (<http://www.bio.gc.ca>) and composed of ship-based, ocean float, and moored buoy measurements of sea surface salinity (0 to 5 m). We used monthly SSS averaged in a grid (42° to 44°N , 66° to 69°W) encompassing the Western Scotian Shelf and Eastern Gulf of Maine where the influence of salinity anomalies on spring phytoplankton bloom dynamics has been

Table 1. Generalized Linear Model and Stepwise Regression Statistics^a

Region	Month	Chlorophyll <i>a</i> Linear Model	Adjusted R ²	F Statistic Versus Constant Model	p Value	Root-Mean-Squared Error	t Statistics (Absolute Value)
Georges Bank	March	2559.4 – 15.488(ATSW) – 4579.3(MHW) – 292.45(v-wind) + 311.1(MHW)(v-wind) + 0.09683(ATSW ²) + 2641.1(MHW ²)	0.879	19.1	0.0001	10.2	Intercept = 3.4, ATSW = 7.6, MHW = 3.0, v-wind = 3.9, MHW:v-wind = 4.1, ATSW ² = 7.7, MHW ² = 3.2
Gulf of Maine	March	–302.24 + 1.7499(ATSW) + 379.84(MHW) – 1980.5(MLW) – 45.115(u-wind) + 431.82(MLW)(u-wind)	0.715	8.51	0.0022	15.3	Intercept = 2.8, ATSW = 5.2, MHW = 3.2, MLW = 4.8, u-wind = 4.8, MLW:u-wind = 4.5
Georges Bank	April	–61.931 – 11.053(v-wind) + 10.903(u-wind)	0.612	12.8	0.0008	15.8	Intercept = 4.7, v-wind = 3.4, u-wind = 3.6
Gulf of Maine	April	–110.84 – 44.694(LCVT) + 169.44(MHW) – 17.311(u-wind) + 13.339(LCVT)(u-wind)	0.396	3.46	0.046	13.7	Intercept = 1.6, LCVT = 2.7, MHW = 2.6, u-wind = 2.4, LCVT:u-wind = 3.1

^aDescriptive statistics for each of the four linear models shown in Figure 8a. Larger absolute values of the t statistic indicate a larger influence a predictor variable (either alone or as an interaction of two variables) has on the dependent variable (anomalies of chlorophyll *a*).

suggested to be the highest [Ji *et al.*, 2007, 2008]. Monthly mean high and low water measurements through 2013 were from Nantucket Island, Massachusetts (station 8449130; <http://tidesandcurrents.noaa.gov>).

Surface nitrate data (0 to 39 m) for Georges Bank and the Gulf of Maine derived from a nutrient database compiled from many historical sources (<http://grampus.umeoce.maine.edu/nutrients>). Seasonal climatological means (1998 to 2012) were produced using a kriging method that resulted in a ~2.75 km spatial resolution [Rebeck and Townsend, 2014]. Seasonal anomalies of surface nitrate (0–39 m) were calculated using the seasonal climatological means. Refer to Rebeck and Townsend [2014] for details regarding the historical nitrate measurements and kriging methodology.

The stepwise regression of generalized linear models of chlorophyll *a* in Georges Bank and the Gulf of Maine used both a forward and backward selection process (Table 1). Three tests, the Jarque-Bera, Lilliefors, and chi-square goodness of fit using a 95% confidence interval, were used to confirm a normal distribution of chlorophyll *a* in Georges Bank and the Gulf of Maine in March and April. The linear models tested were quadratic, pure quadratic, linear, constant, and interactions.

Model selection was based on the corrected Akaike Information Criterion (AIC_c), which is used for low sample sizes and considers the number of predictor variables used in each model. Models with the lowest AIC_c were considered to be the best models of chlorophyll *a* (Table 1). Additionally, to confirm that the linear relationships between the predictor variables and chlorophyll *a* anomaly estimates were not influenced by outliers in the predictor variables, we applied the same three tests of normal distribution to the residuals between modeled and observed chlorophyll *a* anomalies.

Multicollinearity, the condition where two or more predictor variables in a multiple regression model are highly correlated, can reduce the ability to detect reliable effects of correlated variables. To assess how much the variance of the coefficient estimates were being inflated by multicollinearity in the chlorophyll *a* models for Georges Bank and the Gulf of Maine, we calculated the variance inflation factors (VIFs) for each predictor variable used in each of the four models (Table 2). The typical rule of thumb is that multicollinearity can be ignored for a particular predictor variable if its VIF is less than 4 [O'Brien, 2007]. To determine if the residuals between modeled and observed chlorophyll *a* were autocorrelated (serial correlation), we used the Durbin-Watson test at a 95% confidence interval (Table 2).

Finally, we conducted a the stepwise regression based on data only up to 2010 but using the same predictor variables used in the regression results based on data up to 2013

Table 2. Autocorrelation and Multicollinearity Tests for Each of the Four Generalized Linear Models^a

Region	Month	Durbin-Watson Statistic	<i>p</i> Value	Variance Inflation Factors
Georges Bank	March	2.43	0.52	$v_wind = 2.3$ ATSW = 1.4 MHW = 3.6
Gulf of Maine	March	2.53	0.38	$u_wind = 1.3$ MLW = 1.8 MHW = 1.9
Georges Bank	April	1.45	0.14	$u_wind = 1.6$ $v_wind = 1.5$
Gulf of Maine	April	2.24	0.81	$u_wind = 1.0$ LCVT = 1.0 MHW = 1.0

^aIf the Durbin-Watson statistic is less than 1 and the *p* value less than 0.05, then autocorrelation (serial correlation) among the residuals between the model fit and observed is likely. The variance inflation factor (VIF) measures the amount of multicollinearity among predictor variables such that a VIF greater than 4 suggests considerable multicollinearity.

(Table 1). This allowed us to assess experimental forecast models for the years 2011, 2012, and 2013 along with testing the consistency of the physical predictor variables identified in the stepwise regression of the entire time series.

3. Results and Discussion

3.1. Spring Chlorophyll *a* Mean and Variability

We found considerable variability in the magnitude of spring surface phytoplankton biomass from 1998 to 2013 (Figure 2). Among all subregions during the spring months, phytoplankton biomass was highest in April

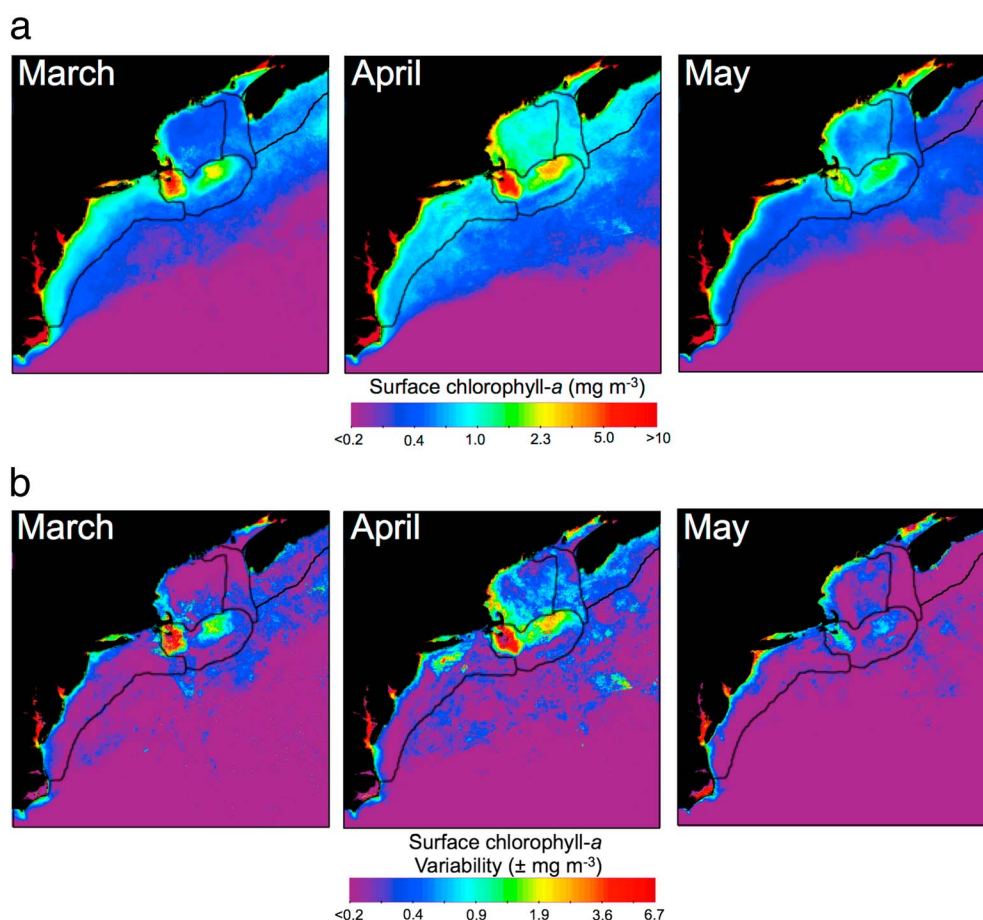


Figure 2. Spring surface chlorophyll *a* mean and variability in the U.S. Northeast and Scotian Shelf from 1998 to 2013. (a) Monthly climatologies of mean surface chlorophyll *a* concentration (phytoplankton biomass) in the spring (March, April, May). (b) Monthly climatologies of mean surface chlorophyll *a* concentration interannual variability. Color bars are on a log scale and the ecological production units are outlined within the solid black lines.

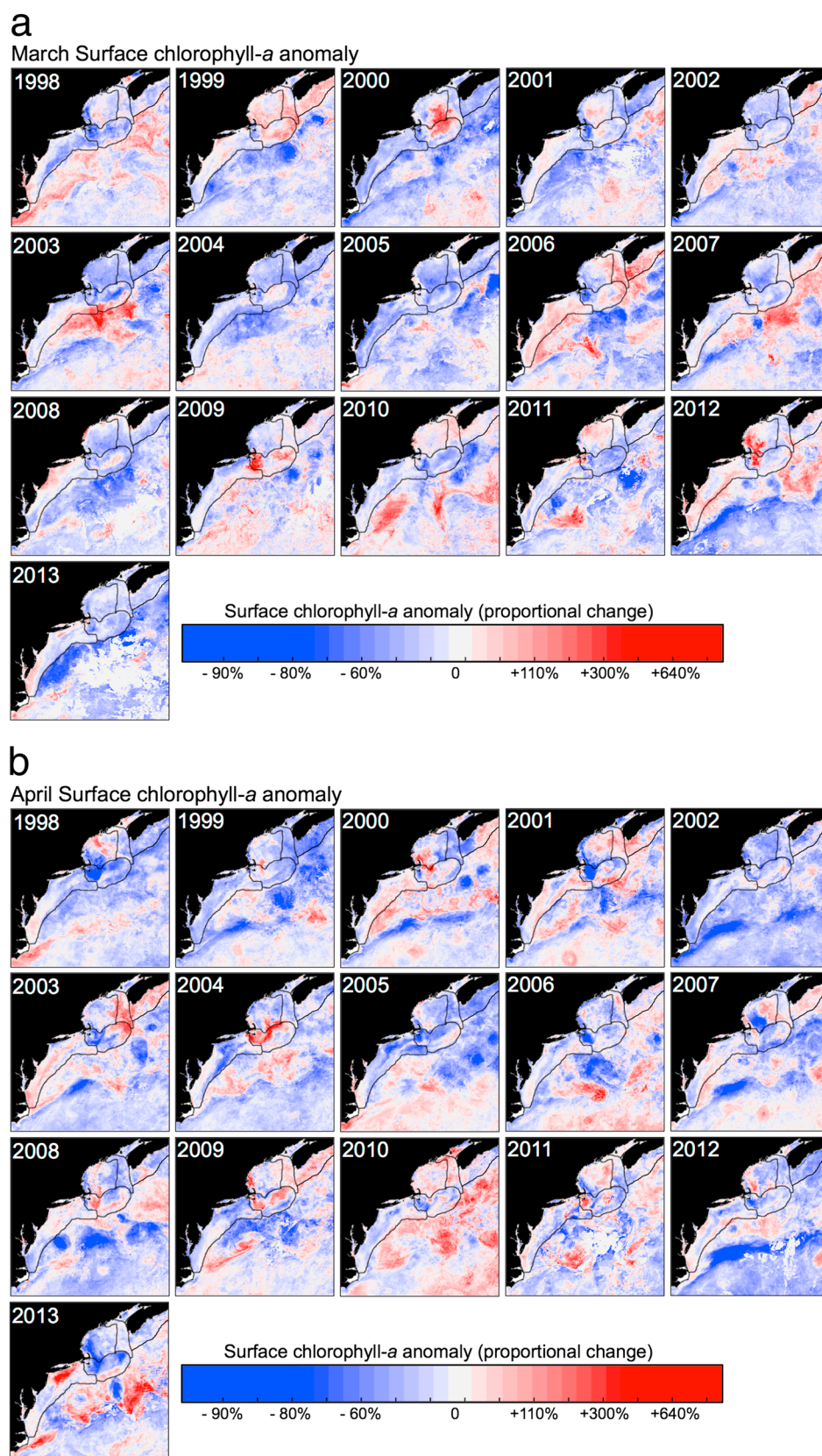


Figure 3. Spring surface chlorophyll *a* anomalies. Proportional changes are based on the (a) March, (b) April, and (c) May climatologies from 1998 to 2013. Ecological production units are outlined within the solid black lines.

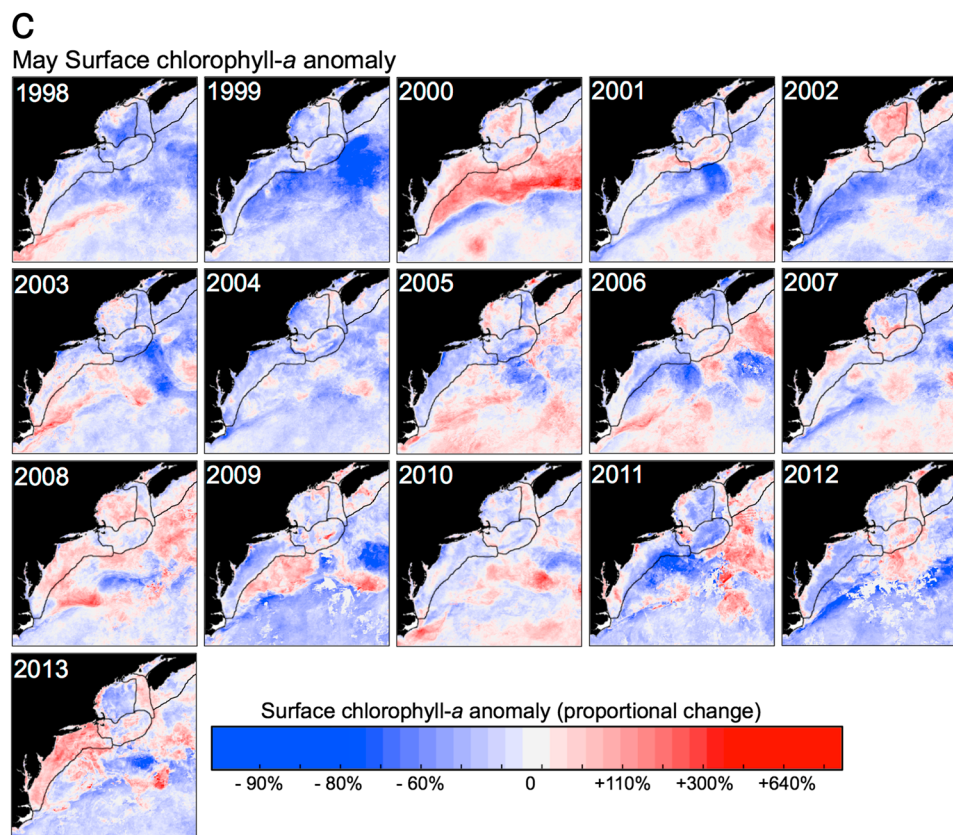


Figure 3. (continued)

(Figure 2a). In particular, the northern flank of Georges Bank and Nantucket Shoals had the highest biomass in all spring months (Figure 2a). The largest variability in surface chlorophyll *a* for all the subregions was in March and April, especially in the northern flank of Georges Bank, Nantucket Shoals, and the western Gulf of Maine (Figure 2b). Mean surface chlorophyll *a* anomalies were not proportionally synchronous throughout most of the subregions in March, April, and May (Figures 3 and 4). For example, mean surface chlorophyll *a* concentrations in the northern flank of Georges Bank and in Nantucket Shoals were $\sim 300\%$ higher than average in April of 2004, whereas the other subregions were either close to or below average during the same month and year (Figure 3). Moreover, March of 2004 was not an anomalously high month for chlorophyll *a* in the northern flank of Georges Bank and in Nantucket Shoals (Figure 3a). Therefore, for each spring season of each year, all the subregions had high month-to-month variability in the proportional change in chlorophyll *a* with the exception of the Middle-Atlantic Bight where the proportional changes were more synchronous (Figure 4).

An empirical orthogonal function (EOF) analysis of March and April chlorophyll *a* anomalies in waters 0 to 250 m (restricted to shelf waters) confirmed that the leading spatial modes of interannual variability were in the northern flank of Georges Bank, Nantucket Shoals, and the western Gulf of Maine (Figures 5a and 5b). A recent study by Tian *et al.* [2014] conducted an EOF analysis of modeled primary production in the region encompassing the Gulf of Maine, Georges Bank, and Nantucket Shoals on an annual cycle and found that the first mode of variability represented tidal forcing in the shallow regions. The EOF analysis in Tian *et al.* [2014] resulted in strong seasonal variability in the eigenvalue time series throughout the year, whereas our analysis resulted in strong interannual variability in the spring (Figures 5c and 5d). These differences suggest that tidal forcing is linked to the seasonal variability, not the interannual variability, of spring phytoplankton biomass in the U.S. Northeast Shelf (NES).

Although the Georges Bank subregion includes Nantucket Shoals in the U.S. Northeast Shelf ecosystem management framework (Figure 1), we separated these waters in our analysis from here forward because

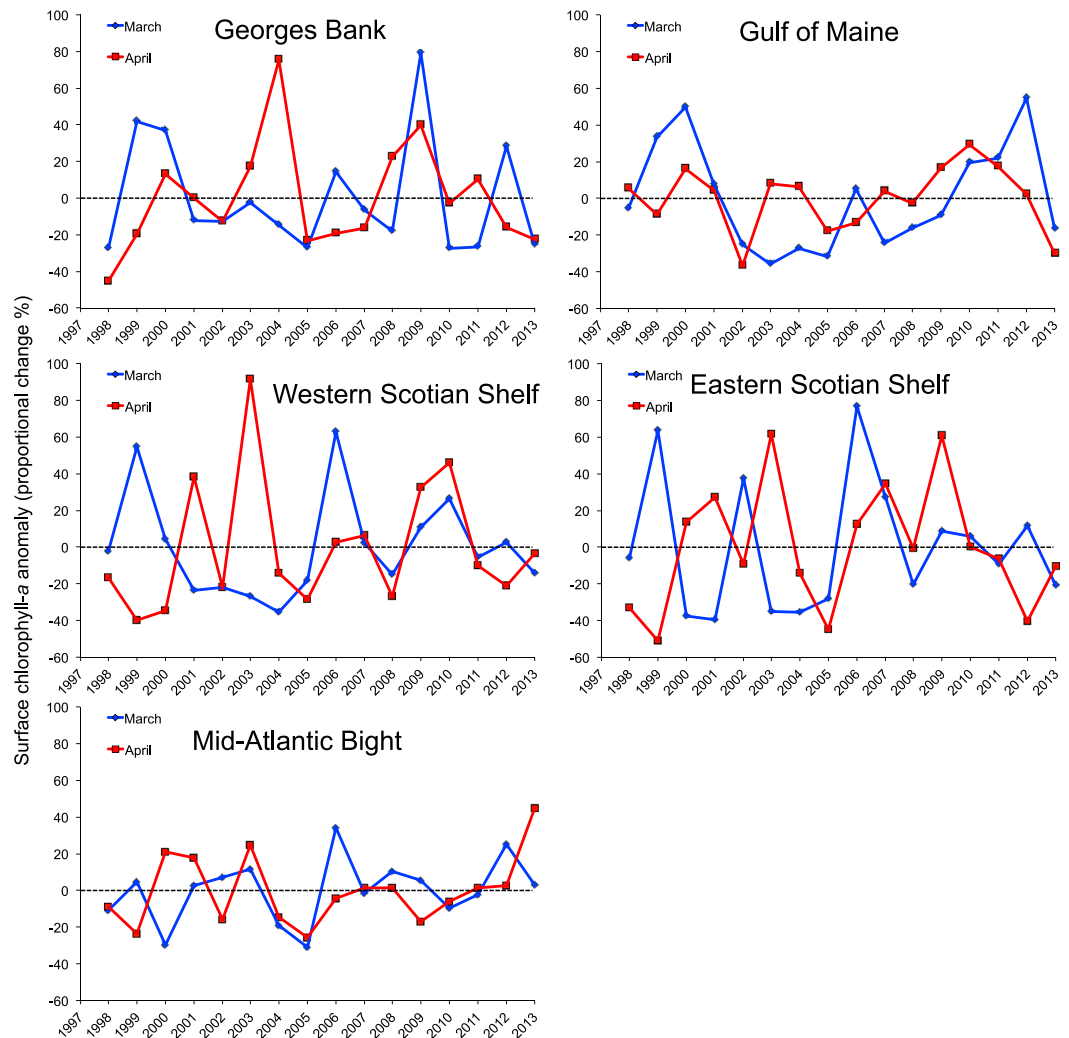


Figure 4. March and April surface chlorophyll *a* anomalies from 1998 to 2013. Time series of proportional change in chlorophyll *a* averaged for each ecological production unit.

the EOF results suggest that chlorophyll *a* variability is not always synchronous between these two areas (Figures 5a and 5b). Because the majority of chlorophyll *a* variability occurred in Georges Bank, Nantucket Shoals, and Gulf of Maine waters, we now predominantly focus on these subregions.

3.2. Physical Associations to Chlorophyll *a* Variability

Among all of the physical data analyzed, those with the most statistically robust relationships to anomalies in chlorophyll *a* within the shelf subregions were north-south (*v*-wind), east-west (*u*-wind) wind speeds over the Shelf, the mean high water (MHW) and mean low water (MLW) at Nantucket Island averaged in the previous January to each March and April, the Northeast Channel Atlantic Temperate Slope Water (ATSW) proportion and Labrador Current Transport Volume (LCVT) averaged over the previous summer and fall to each March and April, and the position of the Gulf Stream Northern Wall in winter and spring (Figure 6).

3.2.1. Sea Surface Salinity

We did not find robust correlations between sea surface salinity (lagged or not) and chlorophyll *a* in either Georges Bank or the Gulf of Maine (Figure 6). However, there were some positive correlations in the shelf break of the Middle-Atlantic Bight (winter sea surface salinity) and in the Eastern Scotian Shelf (April sea surface salinity). Previous research based on models and ocean color data [Ji *et al.*, 2007, 2008; Song *et al.*, 2010, 2011] suggests that surface salinity anomalies are related to the timing (phenology), and in some cases, the magnitude of the spring bloom in the Eastern Scotian Shelf and Western Scotian Shelf (or Eastern Gulf of Maine).

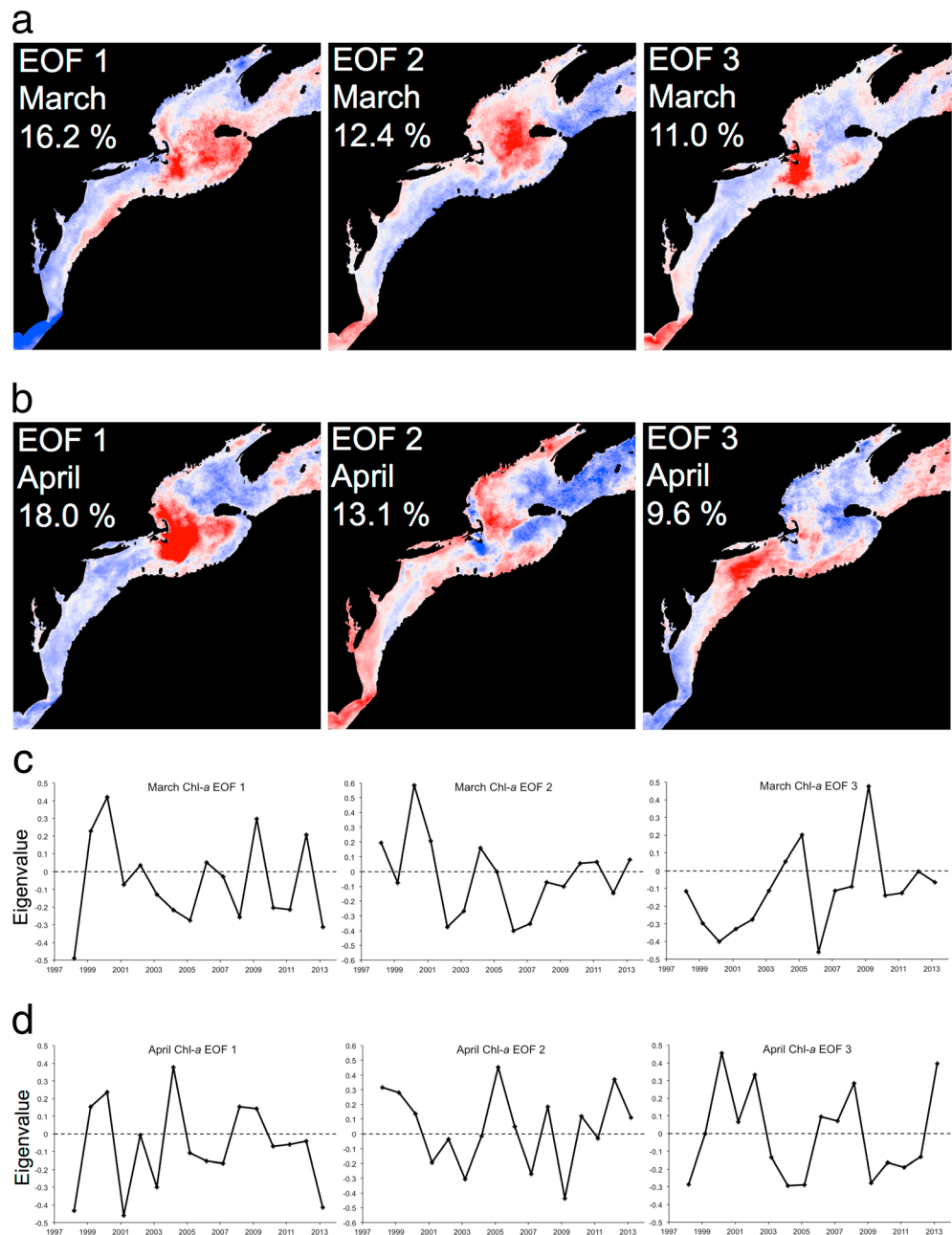


Figure 5. First three EOF spatial modes of surface chlorophyll *a* interannual variability. (a) First three spatial modes of surface chlorophyll *a* interannual variability in March representing 40% of the total variability. (b) First three spatial modes of surface chlorophyll *a* interannual variability in April representing 41% of the total variability. The red and blue colors represent spatial mode strength derived from eigenvalues, which are unitless and thus no color bar is shown. Deeper colors represent stronger interannual variability and consistent colors (within a spatial mode) represent variability that is directionally in sync. (c) Time series of eigenvalues from the first three spatial modes of surface chlorophyll *a* in March. (d) Time series of eigenvalues from the first three spatial modes of surface chlorophyll *a* in April.

One must note that bloom magnitude is not the same metric as our monthly chlorophyll *a* anomalies. Our results agree with the studies that have suggested a positive relationship between spring sea surface salinity anomalies and spring chlorophyll *a* magnitude in the upstream waters of the Eastern Scotian Shelf (Figure 6b). However, the correlations between surface salinity (winter or spring) and spring chlorophyll *a* was weak or even nonexistent in the Gulf of Maine and Georges Bank (Figure 6). This gives further support to the hypothesis

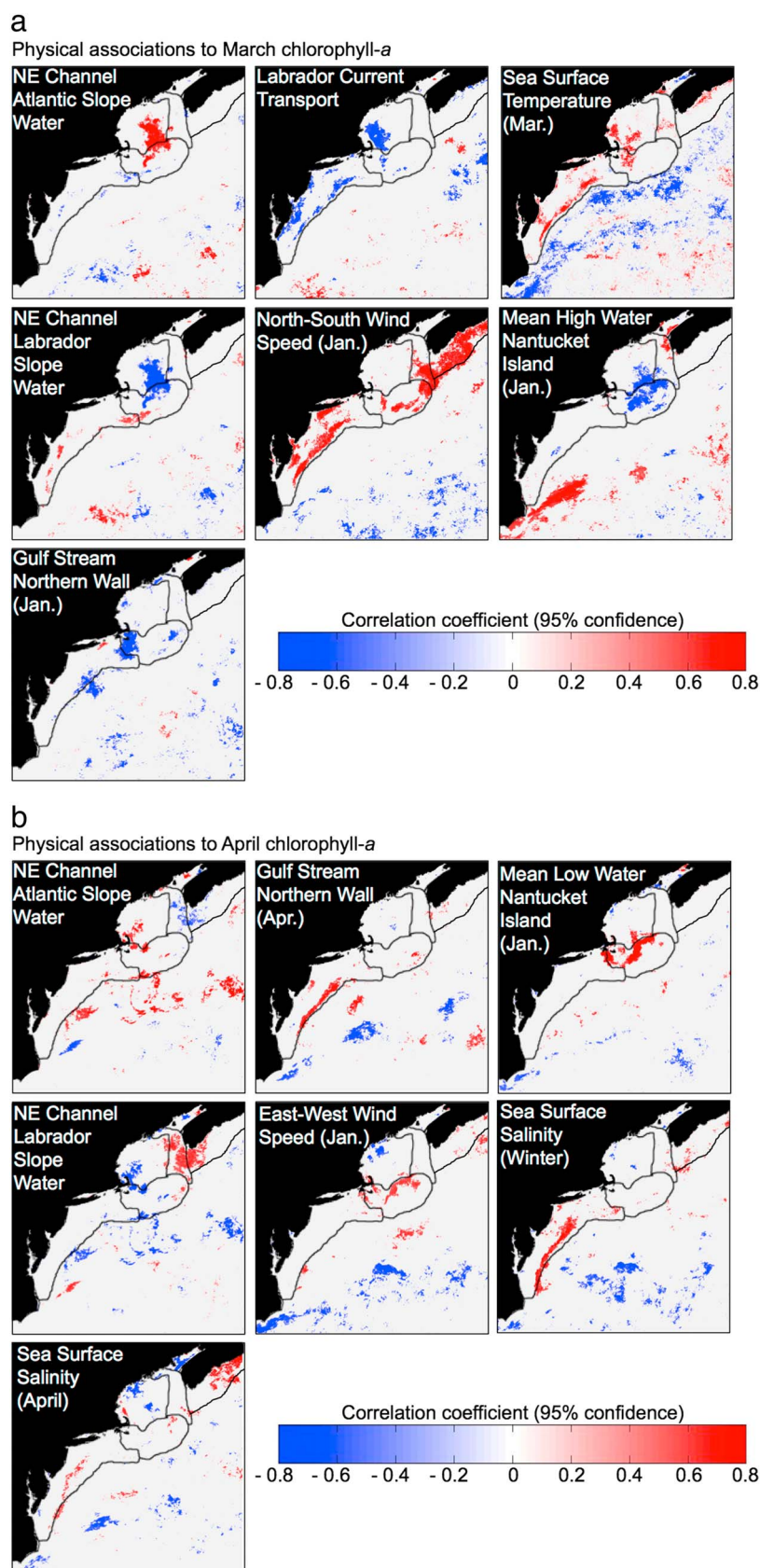


Figure 6

that salinity anomalies in this shelf region are more related to chlorophyll *a* anomalies in the upstream waters of the Eastern Scotian Shelf as opposed to those waters downstream. Moreover, sea surface salinity anomalies in the Western Scotian Shelf and eastern Gulf of Maine may be more related to spring phytoplankton bloom phenology [Ji *et al.*, 2007, 2008] as opposed to interannual variability in spring phytoplankton biomass.

3.2.2. Sea Surface Temperature

With the exception of a few subregions in March, sea surface temperature (SST) was not a predominant correlate to chlorophyll *a* anomalies within the entire shelf region (Figure 6). Sea surface temperature was more related to anomalies in the pelagic, shelf slope, and off-shelf regions (Figure 6). Previous studies have identified robust correlations between SST and surface chlorophyll *a* [Irwin and Finkel, 2008] and between SST and modeled net primary productivity (NPP) [Behrenfeld *et al.*, 2006]. However, these correlations and models were based on basin-scale [Irwin and Finkel, 2008] and global-scale [Behrenfeld *et al.*, 2006] analyses. Moreover, the robust relationship between SST and NPP on a global-scale is restricted to the permanently stratified ocean and does not include the U.S. NES and other high-latitude waters [Behrenfeld *et al.*, 2006], which have strong seasonal stratification. However, even when the seasonal signal is removed as was done in our analysis, interannual variability of SST was not strongly related to the interannual variability of spring chlorophyll *a* in most waters of the U.S. NES. This may be attributed to the highly variable and complex nature of the waters that enter and mix within the U.S. NES from the north (surface; coldest and freshest) and via the Northeast Channel (deep waters; mix of cold-fresh from north and warm-salty from south).

3.2.3. Gulf Stream Northern Wall

The position of the Gulf Stream Northern Wall (GSNW) was associated with chlorophyll *a* anomalies in both Nantucket Shoals (March) and along the shelf break of the Middle-Atlantic Bight (April). There was an inverse relationship between the position of the GSNW in January and Nantucket Shoals chlorophyll *a* in March such that a more southerly GSNW was associated with higher phytoplankton biomass (Figure 6a). This is an indirect association due to the decoupled nature of the waters between Nantucket Shoals and the GSNW (Figure 1). Therefore, the GSNW must be a proxy for another physical variable not explored in this analysis.

Schollaert *et al.* [2004] showed that the relationship between the position of the GSNW and interannual variability of spring surface chlorophyll *a* in the Shelf Slope waters off the Middle-Atlantic Bight is positive (more northern GSNW = higher spring chlorophyll *a*). Our analysis agrees with this study and can be visualized in Figure 6b, which shows a positive correlation between the position of the GSNW in April and chlorophyll *a* in the Shelf Break and Slope waters of the Middle-Atlantic Bight in April. A similar pattern can be observed between SSS anomalies in the winter Eastern Gulf of Maine/Western Scotian Shelf and Shelf Break/Slope waters of the Middle-Atlantic Bight (Figure 6b). This indirect relationship may be an artifact of a more northern GSNW causing a greater proportion of saltier Atlantic Temperate Slope Water entering the Northeast Channel, mixing to surface waters in the winter, and thus showing the direct influence farther south in the Middle-Atlantic Bight Shelf Break and Slope waters where the Gulf Stream is directly influencing chlorophyll *a* [Schollaert *et al.*, 2004]. The proposed mechanism is that the subsurface waters of the Gulf Stream have a higher nutrient content compared to the subsurface waters of the Labrador Current and thus a more northern GSNW results in a greater penetration of higher-nutrient subsurface waters into the euphotic zone of the Middle-Atlantic Bight Shelf and Slope seas [Schollaert *et al.*, 2004].

Figure 6. Primary correlations to physical variables from 1998 to 2013. (a) Leading spatial correlations between physical variables and surface chlorophyll *a* anomalies in March. The NE Channel Slope Water proportions and Labrador Current Transport Volume are the average measured during the previous summer and fall; sea surface temperature is the average for March, and north-south wind speed over the Northwest Atlantic Shelf (more positive (negative) = stronger southerly (northerly)), mean high water at Nantucket Island, and the Gulf Stream Northern Wall position are the average for the previous January. The Pearson correlation coefficient is calculated for each 1 km pixel of chlorophyll *a*, and only values that are statistically significant ($p < 0.05$) are shown. Red values are positive correlations, and blue values are negative correlations. Solid black lines are the ecological production units. (b) Leading spatial correlations between physical variables and surface chlorophyll *a* anomalies in April. The NE Channel Slope Water proportions and Labrador Current Transport Volume are the average from the previous summer and fall; east-west wind speed over the Northwest Atlantic Shelf (more positive (negative) = stronger westerly (easterly)) and mean low water at Nantucket Island are the average from the previous January; the Gulf Stream Northern Wall position is the average for April.

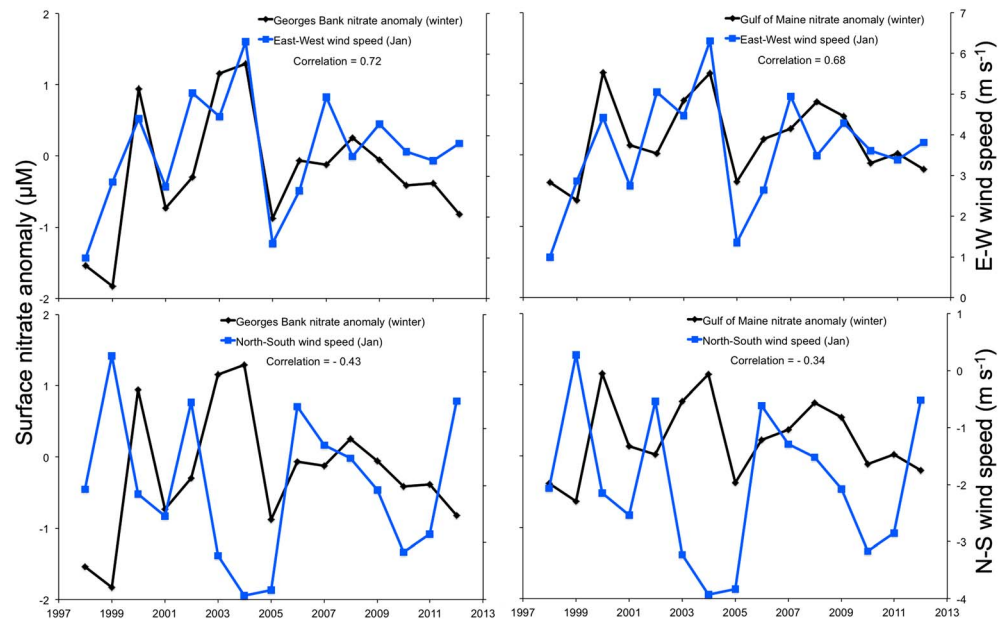


Figure 7. Winter surface nitrate (0–39 m) in Georges Bank and the Gulf of Maine compared to January surface wind speed over the Northwest Atlantic Shelf. Pearson correlation coefficients are shown within each panel. In the east-west direction, more positive (negative) wind speeds are stronger winds deriving from the west (east); in the north-south direction, more positive (negative) wind speeds are stronger winds deriving from the south (north).

3.2.4. Surface Nitrate

The most robust physical association to winter surface nitrate concentrations in the Gulf of Maine and Georges Bank were east-west wind speed in January such that stronger winds deriving from the west were associated with a higher concentration of surface nitrate (Figure 7 and Table 3). Interestingly, Georges Bank chlorophyll *a* in April was the only strong association to winter surface nitrate in Georges Bank (Pearson = 0.80; $p < 0.05$) and the Gulf of Maine (Pearson = 0.77; $p < 0.05$). This suggests that winter surface nitrate may not be the primary constraint on both March and April chlorophyll *a* interannual variability in these waters. A primary example of this mismatch was in 2004 when winter surface nitrate in both Georges Bank and the Gulf of Maine was at a peak or near-peak concentration (Figure 7), yet March and April chlorophyll *a* was well below average in the Gulf of Maine (Figures 3a, 3b, and 4). Nitrate concentrations in the surface waters of the Gulf of Maine and Georges Bank are at peak levels in the winter [Rebeck and Townsend, 2014] and are often a primary constraint on the seasonal variability of chlorophyll *a* resulting in peak phytoplankton biomass in the spring resulting in nitrate drawdown.

Table 3. Correlation Between Georges Bank/Gulf of Maine Winter Surface Nitrate and the Physical Predictor Variables From 1998 to 2012^a

	<i>u</i> -wind	<i>v</i> -wind	Physical Predictor Variables			
			MHW	MLW	LCVT	ATSW
			<i>Winter Surface Nitrate</i>			
Georges Bank	0.72	−0.43	−0.28	−0.03	0.32	0.31
Gulf of Maine	0.68	−0.34	−0.39	−0.12	0.34	0.36

^aPearson correlation coefficients are listed for each relationship between winter surface nitrate (0–39 m) and the various predictor variables using the lags reported in the main text. North-south (*v*-wind) and east-west (*u*-wind) wind speeds over the Northwest Atlantic Shelf and the mean high (MHW) and low (MLW) water at Nantucket Island are the average from each January. The NE Channel Atlantic Temperate Slope Water (ATSW) proportion and Labrador Current Transport Volume (LCVT) are the average measured over the previous summer and fall to each winter. For example, the winter surface nitrate in 1999 (average of December 1998, January 1999, February 1999) was compared to *u*-wind, *v*-wind, MHW, and MLW averaged in January 1999; winter surface nitrate in 1999 was compared to the average ATSW and LCVT in the summer and fall of 1998.

However, our analysis of interannual variability suggests that winter surface nitrate concentration was only correlated to the interannual variability of chlorophyll *a* in Georges Bank in April.

Diatoms are the predominant phytoplankton during the spring bloom in both Georges Bank and Gulf of Maine [Townsend *et al.*, 2006]. These large phytoplankton cells take up nitrate and silicate at equal proportions, yet the source waters that enter the U.S. NES through the Gulf of Maine have higher concentrations of nitrate relative to silicate [Townsend *et al.*, 2006]. Therefore, it appears that the spring bloom in both the Gulf of Maine and Georges Bank is first limited by silicate until the concentration is drawn down and is then limited by nitrate [Townsend *et al.*, 2006, and references therein].

3.3. Generalized Linear Models

The models of Georges Bank and Gulf of Maine chlorophyll *a* using lagged physical variables resolved 88% and 72% (respectively) of interannual variability in March and 61% and 40% of interannual variability in April (Figure 8a and Tables 1 and 2). The residuals of the model fits were not autocorrelated, and all of the Variable Inflation Factors (VIFs) were much less than 4, suggesting that multicollinearity did not affect the stepwise regression coefficient estimates or standard errors (Table 2). Moreover, the residuals for the model fits in both Georges Bank and the Gulf of Maine were from a normal distribution and thus not influenced by outliers or highly skewed predictor variables. Anomalies of chlorophyll *a* in Nantucket Shoals were not normally distributed (numerically transformed or not), and thus, we did not conduct a regression analysis due to the potential influence of outliers or highly skewed data.

3.4. March Chlorophyll *a* Models

In March, the proportion of Atlantic Temperate Slope Water entering the Gulf of Maine via the Northeast Channel (proportional to Labrador Subarctic Slope Water) averaged over the previous summer and fall was the primary predictor variable for chlorophyll *a* interannual variability in both Georges Bank and the Gulf of Maine (Table 1; refer to *t* statistics). Whereas Labrador Current source waters (Shelf and Slope) and chlorophyll *a* had an inverse association, Atlantic Temperate Slope Water had a positive association, particularly on the northern flank of Georges Bank and where the Northeast Channel enters the Gulf of Maine (Figure 6a). These results are consistent with prior studies [Thomas *et al.*, 2003; Townsend *et al.*, 2010, 2014] suggesting that more Labrador Sea source waters present in the Gulf of Maine and Georges Bank region would lead to reduced phytoplankton biomass in these waters. However, the mechanism is not entirely clear with regard to the nitrate concentrations associated with Atlantic (higher nitrate) versus Labrador (lower nitrate) source waters. Winter surface nitrate in these two subregions was only weakly correlated (positively) to the proportion of Atlantic Temperate Slope entering the Gulf of Maine (Table 3). Conversely, Labrador Current Transport Volume from the north in the previous summer/fall was positively associated with winter surface nitrate (Table 3). Moreover, January wind speed over the Northwest Atlantic Shelf and water level data from Nantucket Island were also predictor variables for March chlorophyll *a* suggesting complex interactions between deep source water intrusions into the Gulf of Maine, winter winds, and winter tidal currents/fluxes in the region. In both Georges Bank and the Gulf of Maine, weaker January winds from the north (i.e., more positive *v*-wind) were associated with increased chlorophyll *a*. This relationship was relatively robust throughout a large portion of shelf waters, particularly in the Eastern Scotian Shelf, as shown in Figure 6a. A recent analysis by Li *et al.* [2014] found that stronger southwesterly (northeastward) winds tended to weaken the prevailing southwestward flow over the shelf, whereas weaker southwesterly winds were associated with stronger southwestward flow and thus increasing sea level in the Gulf of Maine. Therefore, it appears that less flow from the north resulting from weaker winds from the north (i.e., stronger southerly winds) was associated with increased chlorophyll *a* in March throughout a large portion of shelf waters, particularly those in the Eastern Scotian Shelf.

We note that high and low water level data measured at Nantucket Island reflect a complex synergy of tidal currents, winds, heat content, along-shelf flow, storminess, etc., and thus, we cannot attribute the predominant influence the water level measurements have on chlorophyll *a*. Moreover, the Nantucket Island water level measurements occur downstream of the current flow from Georges Bank and the Gulf of Maine (Figure 1) but may serve as a proxy for along-shelf flow for these waters. Negative anomalies in the January mean high water level at Nantucket Island were associated with negative chlorophyll *a* anomalies on the northern flank of Georges Bank in March (Figure 6a). The specific mechanism linked to the interannual variability of chlorophyll *a*

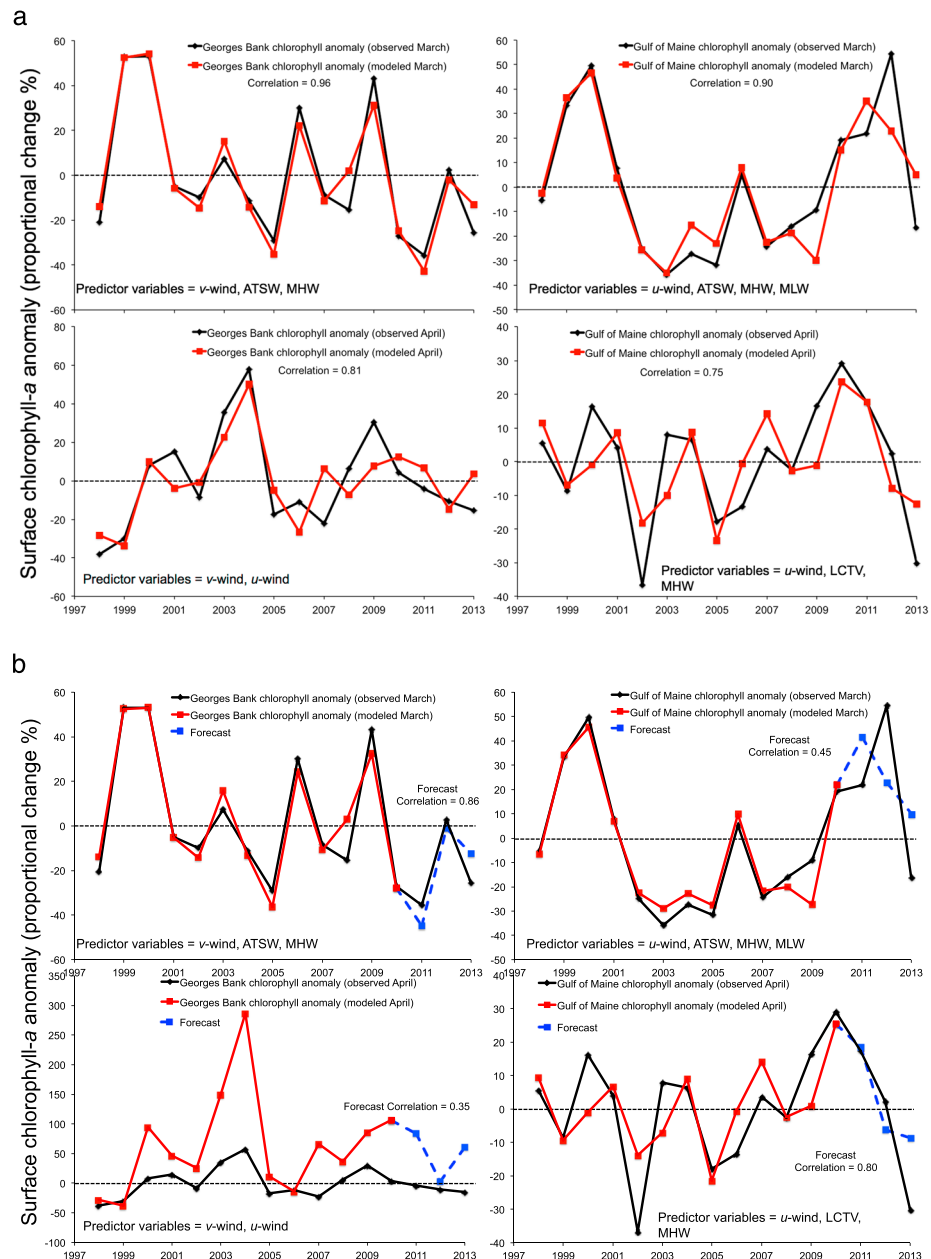


Figure 8. Generalized linear models of chlorophyll *a* anomalies in Georges Bank and the Gulf of Maine. (a) Generalized linear model fits of Georges Bank (not including Nantucket Shoals) and Gulf of Maine chlorophyll *a* anomalies in March and April based on stepwise regression (Tables 1 and 2). The predictor variables used in each linear model are shown in each panel. North-south (*v*-wind) and east-west (*u*-wind) wind speeds over the Northwest Atlantic Shelf and the mean high (MHW) and low (MLW) water at Nantucket Island are the average in the previous January to each March and April. The NE Channel Atlantic Temperate Slope Water (ATSW) proportion and Labrador Current Transport Volume (LCTV) are the average measured over the previous summer and fall to each March and April. (b) Forecasts of chlorophyll *a* in Georges Bank and the Gulf of Maine using general linear models parameterized with data only up to 2010. The forecast correlation is the Pearson coefficient between each model's forecast and the observed proportional change in chlorophyll *a*.

is unclear, but our analysis does show that January water levels were the stronger predictor variables, just as January winter winds, suggesting winter controls on spring phytoplankton biomass variability.

Interannual variations in winter convection in the western Gulf of Maine are linked to variations in surface layer salinity and correlated with variations in the inflowing shelf water from the north [Taylor and Mountain, 2009]. More shelf water inflow is correlated with fresher surface water, stronger stratification, and weaker convection

(and visa versa). These dynamics may explain why the Labrador Current Volume Transport (LCVT) from the previous summer/fall was negatively correlated with chlorophyll *a* phytoplankton variability in the western Gulf of Maine in March (Figure 3a). However, the LCVT was not a significant predictor variable for Gulf of Maine chlorophyll *a* in March (Figure 8a), suggesting that winter wind convection and Slope Water proportions entering the Northeast Channel may be the stronger constraints on phytoplankton biomass. Finally, the experimental forecasts of proportional changes in March chlorophyll *a* in 2011, 2012, and 2013 had much higher skill in Georges Bank than in the Gulf of Maine (Figure 8b).

3.5. April Chlorophyll *a* Models

In April, the models resolved less interannual variability of chlorophyll *a* relative to March, possibly due to a stronger decoupling from previous physical forcing due to the slightly longer time lag. The more robust model in April was for Georges Bank where wind speeds (both directions) in January were the only predictor variables (Figure 8a and Table 1). Stronger westerly and stronger northerly winds (i.e., stronger southeastern winds) in January were associated with higher April chlorophyll *a* in Georges Bank (Figure 8a and Table 1). The spatial correlations in Figure 6b show that the westerly wind is strongly associated with chlorophyll *a* on the northern flank of Georges Bank.

We suggest that stronger southeastern winds across Georges Bank in January increase the rate of deep water intrusion from slope water that enters the Gulf of Maine through the Northeast Channel. Indeed, cross-isobath fluxes of nutrients onto Georges Bank have been suggested to be most influential on the northern edge due to its close proximity to slope waters [Townsend *et al.*, 2006] where *f* ratios (the fraction of primary productivity fueled by NO_3) have been measured to be as high as 0.7 [Loder *et al.*, 1992]. While tidal pumping is a primary mechanism for nutrient delivery that keeps phytoplankton biomass relatively high on the northern flank of Georges Bank year-round [Chen and Beardsley, 1998], variations in winter wind stress over this region along with variations in the nutrients in off-bank waters can constrain spring phytoplankton biomass variability [Hu *et al.*, 2008]. Additionally, persistent winds also force near-surface Ekman currents that can overwhelm the tide-driven circulation, transporting surface waters across Georges Bank from north to south. Therefore, during strong southeastward wind events that are typical of winter, the wind-driven Ekman flow will enhance on-bank advection of nutrient rich water that has been mixed upward along the northern flank [Brink, 2003].

Both the experimental forecast and the regression of the entire time series showed that the models performed poorly toward the end of the time series, whereas the Gulf of Maine April forecast had a more robust correlation to observations. However, it is clear that the models resolved chlorophyll *a* variability to a higher extent in March as opposed to April.

4. Summary

Interannual variability of spring phytoplankton biomass in the Northwest Atlantic Shelf is confined to smaller subregions within the shelf. We caution the evaluation of the spring bloom as a single event over the entire spring and suggest that monthly or even weekly data (if possible) be evaluated due to the lack of synchrony in March and April variability and due to the complex associations with lagged physical variables. However, we have confidence in our monthly composites based on a companion study showing that monthly averages of low-resolution (9 km, satellite-derived) surface chlorophyll *a* data in the spring was positively associated to spring zooplankton biovolume in both Georges Bank and the Gulf of Maine (Friedland *et al.*, in review).

Our regression models and correlation analyses agree with a recent study by Mountain [2012] suggesting that, in addition to nitrate, a variety of biophysical processes and parameters including stratification and mixing (light limitation) influence the interannual variability of spring phytoplankton biomass in these waters. The most compelling example of this was the inconsistent correlation between the interannual variability of winter surface nitrate and the interannual variability of spring chlorophyll *a* in Georges Bank and the Gulf of Maine. Other wintertime surface nutrients such as phosphate, silicate, and iron may be additional constraints on the interannual variability of spring phytoplankton biomass.

The Georges Bank and Gulf of Maine experimental forecasts in this study can be tested each year to assess their forecasting ability and to learn if these models need to be substantially reparameterized as new time series data

become available. The relatively short time series of satellite data limits our forecasting ability, but improvements can only be made if existing satellite missions continue and new missions are planned and funded.

Our study focused on physical associations to chlorophyll *a* variability, and many of the mechanisms that we discussed or that were implied by the models still require more in situ time series data to confirm the major constraints on the interannual variability of phytoplankton biomass in these shelf waters. This calls for an expansion of ecosystem surveys at greater temporal and spatial scales that measure physical, biological, and biogeochemical properties.

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