Influence of ocean freshening on shelf phytoplankton dynamics

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[1] Climate change-induced freshening of the ocean can enhance vertical stratification and alter circulation patterns in ways that influence phytoplankton dynamics. We examined the timing of spring phytoplankton blooms and the magnitude of net primary productivity in the Nova Scotian Shelf (NSS) - Gulf of Maine (GoM) region with respect to seasonal and interannual changes in surface water freshening from 1998 to 2006. The general pattern of temporal westward progression of the phytoplankton bloom corresponds with the gradient of increasing sea surface salinity from the NSS in the east to the western GoM. Increased freshening enhances the spatial gradients in bloom timing by stimulating earlier blooms upstream (NSS), but it has less impact downstream (the western GoM). Strong spatial gradients (increasing westward) of mean chlorophyll concentration and net primary productivity during post-bloom months (May–June) indicate that lower sea surface salinity upstream can likely impede nutrient fluxes from deep water and therefore affect overall productivity. **Citation:** Ji, R., C. S. Davis, C. Chen, D. W. Townsend, D. G. Mountain, and R. C. Beardsley (2007), Influence of ocean freshening on shelf phytoplankton dynamics, *Geophys. Res. Lett.*, *34*, LXXXXX, doi:10.1029/2007GL032010.

1. Introduction

[2] Continental shelf waters in the Northwest Atlantic from the Labrador Sea to the Mid-Atlantic Bight experienced significant freshening in the late 1990s [*Smith et al.*, 2001; *Mountain*, 2003; *Belkin*, 2004]. Mounting evidence suggests an upstream origin of lower salinity water, caused by increasing glacial melting and enhanced precipitation and river runoff at higher latitudes [*Curry and Mauritzen*, 2005; *Peterson et al.*, 2006]. These changes are accompanied by Arctic Oscillation-induced changes in the circulation pattern in the Arctic Ocean [*Proshutinsky et al.*, 2002; *Steele et al.*, 2004], which are thought to be associated with climate change. Freshening of shelf waters can alter circulation and stratification patterns and may induce significant changes in the ocean ecosystem at multiple trophic levels [*Durbin et al.*, 2003; *Pershing et al.*, 2005; *Greene and Pershing*, 2007]. Phytoplankton, at the base of the pelagic food web, plays a critical role in regulating the structure, function and productivity of shelf ecosystems and affecting fish recruitment success [e.g., *Cushing*, 1990]. Examining the response of phytoplankton dynamics to observed increases in freshening will be important to our understanding of how climate change can impact higher trophic levels and shelf ecosystem dynamics.

[3] The shelf region from the Nova Scotian Shelf (NSS) to the Gulf of Maine (GoM) is an ideal region within which to examine relationships between increased freshening and spring phytoplankton bloom (SPB) dynamics, and is supported by a wealth of available historical hydrographic and biological survey data and a long history of research on SPB in this region [e.g., *Riley*, 1942; *Townsend and Spinard*, 1986; *Townsend et al.*, 1992; *Platt et al.*, 2003; *Thomas et al.*, 2003; *Ji et al.*, 2006a]. The primary source of Scotian Shelf Water (SSW) is the West Greenland/Labrador Current system, with lesser input from the St. Lawrence system [*Smith et al.*, 2001]. Relatively cold, low salinity SSW enters the GoM in the surface layers around Cape Sable and meets warmer and more saline slope water that enters along the bottom through the Northeast Channel (NEC) (Figure 1). These two water masses progressively mix as they move in a general counter-clockwise pattern around the GoM, and then turn clockwise around GB with the major portion of the flow continuing westward into the Mid-Atlantic Bight [*Wiebe et al.*, 2002]. We present here the results of retrospective analyses to evaluate how variations in SSW inflow, influenced by large-scale changes in freshening, may impact the timing and spatial variability of the SPB and further influence system productivity at higher trophic levels.

2. Data and Methods

[4] We examined all available field data on hydrography and phytoplankton chlorophyll from ship surveys and satellite remote sensing (SeaWiFS). Our analyses of survey data and satellite data were performed for seven zones (Figure 1) (excluding areas shallower than 100 m in each zone to avoid more complex near-shore processes). Since the focus of this study is on the late winter/early spring period between 1998 and 2006 (after SeaWiFS data became available), most of the hydrographic data collected before 1998 were used solely to compute climatology and anomalies for the different years. The methodology for computing the sea surface salinity (SSS) anomaly is described in detail by *Mountain* [2003]. An integral depth-scale (also called trapping depth) method developed by *Price et al.* [1986] was used to compute the mixed layer depth (MLD) from CTD profiles.

[5] SeaWiFS Level-3 mapped daily chlorophyll (CHL) and photosynthetically active radiation (PAR) data with 9-

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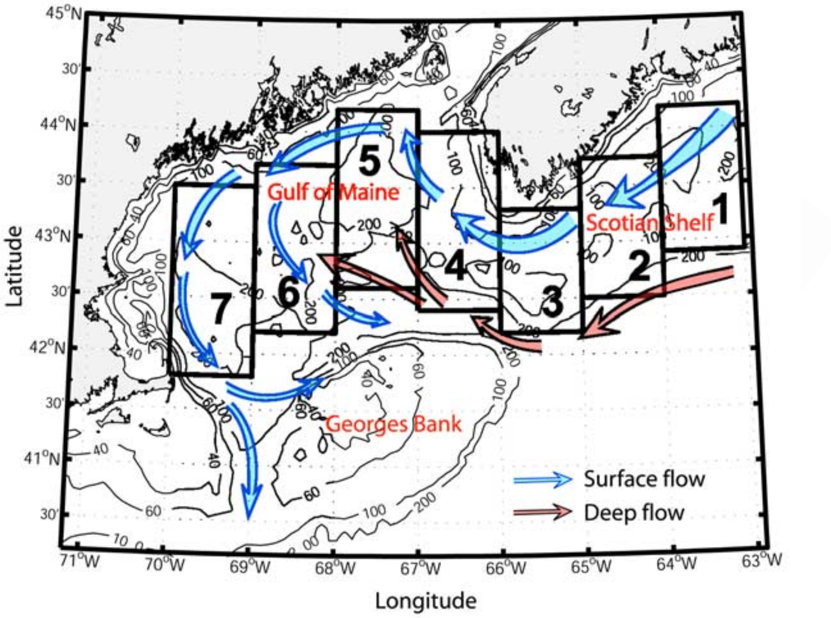

Figure 1. The map of study area and seven zones numbered from the Scotian Shelf to the western Gulf of Maine. The light blue and brown arrows indicate respectively the general circulation patterns of surface and deep waters in the domain.

km resolution were retrieved from the NASA ocean-color website (http://seadas.gsfc.nasa.gov). Automatic detection of the timing and magnitude of the spring phytoplankton bloom (T_{SPB}) was conducted as follows: a 5 × 5 pixel median filter in the spatial domain was used to reduce noise and fill small gaps (as given by *Yoder et al.* [2002] and *Thomas et al.* [2003]). Then a time series of CHL concentration at each pixel was formed for the first 4 months (January 1st to April 30th) of each year, followed by a Gaussian smoothing (with σ = 1 day) to remove noise in the time series. The first peak in the time series (considered here as the spring bloom) is defined by the CHL concentration exceeding 2 μg/l and also being greater than the mean value by two standard deviations of the whole (4-month) series. The time (year day) when such peaks occur is denoted as T_{SPB}. The monthly-average CHL concentrations were also computed for each zone. Additionally, monthly-averaged, gridded net primary production (NPP) data were retrieved from the Oregon State University Ocean Productivity website (http://web.science.oregonstate.edu/ocean.productivity/index.php). This dataset has a 10′ × 10′ resolution and was derived from a CHL-based model called the Vertically Generalized Production Model (VGPM) [*Behrenfeld and Falkowski*, 1997]. We averaged the NPP data for each of our seven zones from May to June of each year in order to determine the mean productivity of the post-bloom period.

3. Results and Discussion

[6] The general pattern of the westward progression of the SPB from NSS to the western GoM is presented in Figure 2 (top). Blooms occurred, on average, about 2 weeks later in Zone 7 than that in Zone 1, with a maximum delay of ~40 days in 1999; this pattern of westward progression is clear for most years (except for 2000). The time delay appears to be greater in some years (depicted as the solid lines in Figure 2) than others (dashed lines), which we believe is related to the intensity of freshening in different years (discussed below). The time scale for advective transport of surface water from Zone 1 on the Scotian Shelf

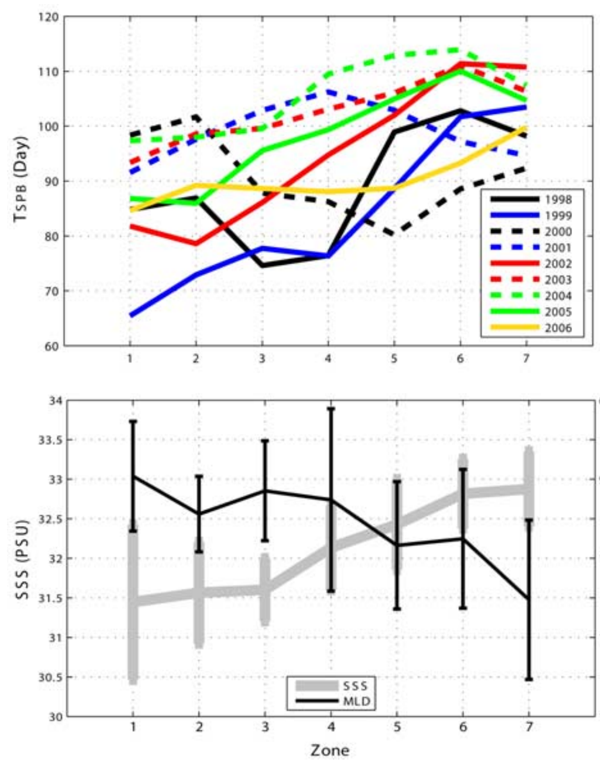

Figure 2. (top) Spatial gradients (from Zone 1 to 7) of T_{SPB} in years from 1998 to 2006. (bottom) SSS and MLD climatology from January to March (averaged over 1978–2006), with error bars indicating one standard deviation.

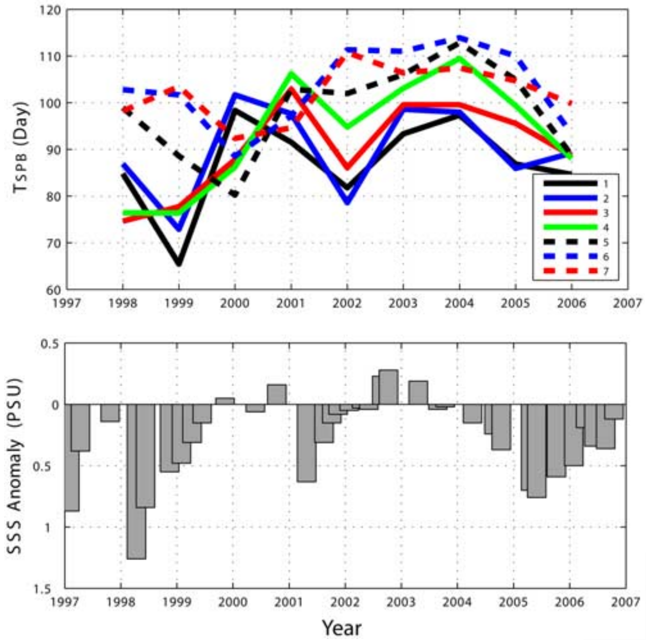

Figure 3. (top) Interannual variability of T_{SPB} in seven zones and (bottom) variability of SSS anomaly from 1998 to 2006.

to Zone 7 in the western GoM is greater than three months [*Mountain and Manning*, 1994], suggesting that it is the difference in timing of the blooms among the zones that causes the seeming progression in space.

[7] We maintain that the spatial gradient of SSS from the Scotian Shelf to the GoM (Figure 2, bottom) is responsible for the westward progression of the bloom. The classical theory of spring phytoplankton blooms holds that the timing of onset of the SPB is controlled primarily by changes in water column stability during the winter-spring period, as suggested by *Sverdrup* [1953] and the later-developed critical turbulence theory [e.g., *Townsend et al.*, 1992; *Huisman et al.*, 1999]. The former indicates that the bloom can only occur when the surface mixing layer is shallower than the critical depth, while the latter proposed that blooms can occur even in the absence of vertical stratification, as long as the vertical turbulent mixing rates are less than certain critical level. Both theories converge to the point that as the water column becomes more stabilized, phytoplankton blooms are more likely to develop.

[8] For the deeper parts of the NSS-GoM region (bottom depth >100 m), our analysis of the historical hydrographic data suggests that the variability of SSS can explain nearly all (~97%) the variability of surface water density in the NSS and the eastern GoM region during winter-spring time, and about 40–60% (zone-dependent) of the variability of MLD (which could be affected by many other factors including surface wind forcing, physical properties of the underlying water, and shelf-slope frontal dynamics). The statistical analysis suggests that, in general, the fresher surface water in the upstream zones is more vertically stable with shallower MLD (Figure 2, bottom, *t*-test for the slope of regression, $p < 0.001$). Here we used seasonal averaged MLD as an index for the spatial gradient of water column stability among the seven zones, with an assumption that waters with shallower average MLD are likely more stable during the bloom initiation period, since the time scale for freshening in the region is generally on the order of months. Given the fact that the surface PAR across the region does not vary significantly, the water column in upstream zones is likely to provide a more favorable condition for earlier blooms (e.g., shallower MLD relative to non-varying critical depths). This conclusion leads to the following discussion of whether more intensive surface freshening can result in changes in the SPB dynamics and primary productivity across the region.

[9] The interannual variation of T_{SPB} for seven zones is presented in Figure 3 (top). For Zones 1 to 4 (solid lines), the blooms occurred with a consistent zigzag pattern in T_{SPB}: relatively earlier in 1998–99, somewhat later in 2000 and 2001, earlier in the season again in 2002, followed by later blooms in 2003 and 2004, and then earlier again in 2005 and 2006. This pattern in timing is more obvious farther upstream (Zones 1 and 2). Such a temporal zigzag pattern appears to be consistent with the interannual variability of SSS anomalies computed for the eastern GoM (used as a proxy for the intensity of freshening throughout the study domain; Figure 3, bottom). The SSS anomaly is greater during the winter-spring of years 2000–2001 and 2003–2004, indicating a relatively weaker SSW influence, thus delaying the onset of the SPB. The waters farther downstream (Zones 5–7), however, did not show such a pattern. For instance, the blooms in 1998 and 1999 in Zones 5–7 appear to have been much later than that in 2000 and 2001. This observation seems counter-intuitive, since we would expect a shallower MLD when the freshening is more intensive in the region (M. H. Taylor and D. G. Mountain, unpublished manuscript, 2006), thus causing earlier blooms. One possible explanation is that the stability of the water column in these western zones is not controlled by SSS alone (although it is a very important factor). Rather, the variability of local wind forcing (hence heating) and deep water properties might contribute to the variability of water column stability, thus confounding the direct correlation between SSS and bloom timing. Another possible explanation is that prior to arriving in the western GoM, the surface water nutrients are already depleted as a result of the earlier blooms upstream in Zones 1 and 2 (Figure 3, top), leaving a nutrient-poor but vertically-stable water column in Zones 5–7. Either way, the SPB in the western GoM would be expected to show less interannual variability since the impact of external water inflows could be significantly damped. This appears to be the case; Figure 2 shows that T_{SPB} varied by <20 days in Zone 7, which is much smaller than that in the upstream zones (~30 days).

[10] Lower SSS in the upstream zones to the east is likely to impede mixing processes that can mix deep nutrient-rich water up to surface and therefore affect the overall primary productivity. From our examination of the spatial gradient in nitrate-nitrogen (from the historical survey data set) from Zone 1 to 7, we found that, in a climatological sense (averaging from 1978 to 2006), the mean nitrogen concentration during the winter-spring period (from January to March) in the upper 10 m is typically lower toward the upstream end of our sample domain (~5 μM) and increases to approximately 10 μM in the western GoM. Thus, increasing SSS from east to west corresponds to increasing

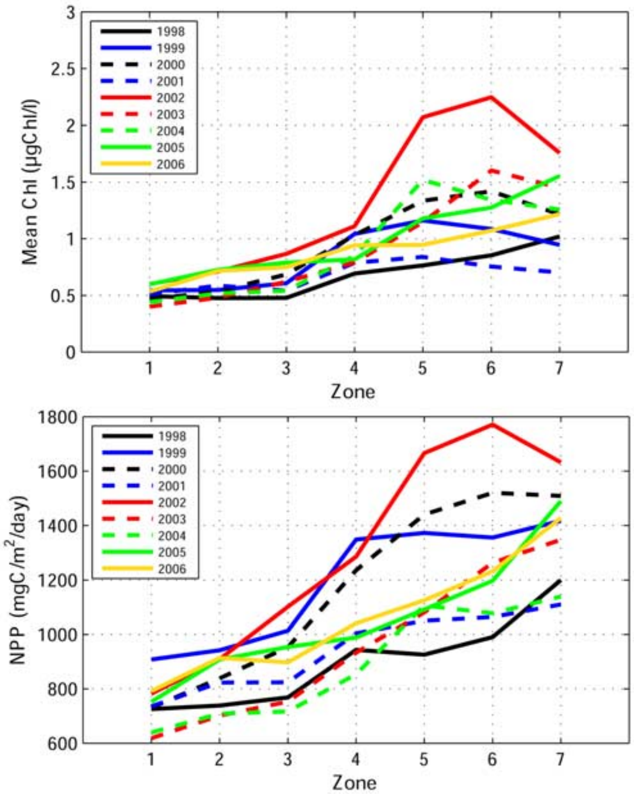

Figure 4. Spatial gradients (from Zone 1 to 7) of (top) CHL and (bottom) NPP averaged over May and June in years 1998–2006.

nutrient concentrations as well as the timing of bloom progression. The impact of freshening on nutrient replenishment and overall productivity would become more noticeable as nutrients become more limiting (lower than half-saturation constant) for photosynthesis during the post-bloom season. By examining the mean surface CHL and NPP in the seven zones in later spring (May–Jun) (Figure 4), it is clear that the mean surface phytoplankton biomass and productivity during the post-bloom season exhibit a general spatial gradient (Figure 4) similar to T_{SPB}, with both CHL and NPP almost doubled in the western GoM (downstream) compared to the areas further to the east and upstream. This pattern is consistent with the assumption that there is greater mixing of surface waters in the western zones with nutrient-rich deeper waters in the GoM, increasing the nutrient supply and thus enhancing the integrated productivity.

[11] It is worth noting here that although interannual variability in mean CHL and NPP is significant (one-way ANOVA, $p < 0.001$) across the seven zones (Figure 4), their correlation with interannual SSS anomalies is less clear and requires further investigation. We have not discussed in this short communication, the potential impact of other remote and local forcings on the SPB dynamics, but earlier studies [e.g., *Townsend and Spinard*, 1986; *Thomas et al.*, 2003] have suggested that bloom dynamics and primary productivity in the GoM could be influenced by the interannual variability of Warm Slope Water intrusions at depth and along the bottom (in response to North Atlantic Oscillation). Because freshwater intrusions into surface waters of shelf seas are likely to increase with global warming, we can expect to see altered patterns in both the timing and magnitude of the spring production cycle and higher trophic level dynamics [e.g., *Platt et al.*, 2003]. In order to understand better the underlying mechanisms and more clearly identify the role of freshening from a set of nonlinearly interacting remote and local forcings, further research with more sophisticated approaches are required, such as those possible with three-dimensional biological-physical models [e.g., *Ji et al.*, 2006b; *Ji et al.*, 2007].

4. Conclusions

[12] We examined the timing of spring phytoplankton blooms and their overall net primary productivity from east to west across the NSS and GoM region during the winter-spring period from 1998 to 2006, with respect to recent increased freshening of shelf waters. The freshening has likely enhanced the general pattern of westward progression of spring phytoplankton biomass by promoting earlier blooms in the upstream region where the influence of freshening is more significant compared to downstream regions in the GoM. Similarly, net primary productivity also appeared to have been influenced by freshening, with a general increase from east to west across the domain. We conclude that changes in freshwater fluxes to this important shelf region are important to the timing of phytoplankton blooms and ecosystem productivity, and that future research should focus on interactions between local and remote forcings, as they might influence overall plankton dynamics in continental shelf seas.

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