Large-scale forcing impact on biomass variability in the South Atlantic Bight

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[1] The Gulf Stream western front (GSF) follows the shelf slope topography for a great extent of the South Atlantic Bight (SAB). Sub-surface intrusions of the Gulf Stream are known to provide nutrient-rich waters to the outer shelf regions of the SAB and, consequently, promote phytoplankton growth. These intrusions are much more frequent during summer and are responsible for a significant portion of the annual SAB shelf carbon production. Based on the analysis of satellite ocean color data, sea surface temperature (SST), sea surface height (SSH), and climatologic data sets, we present evidence for a connection between these Gulf Stream intrusions and the seasonal variability of the size and strength of the North Atlantic Subtropical Gyre (NASG). The intensity and frequency of intrusions depend on the proximity of the GSF to the shelf, which is modulated by the seasonal expansion and contraction of the NASG. **Citation:** Signorini, S. R., and C. R. McClain (2007), Large-scale forcing impact on biomass variability in the South Atlantic Bight, *Geophys. Res. Lett.*, *34*, L21605, doi:10.1029/2007GL031121.

1. Introduction

[2] The connection between the NASG variability and the SAB shelf response is the Gulf Stream forcing, which is the western branch of the NASG. Therefore, the size and strength of the NASG, which is governed by the large-scale wind circulation and seasonal solar radiation, has an impact on the oceanographic processes of the SAB [*Signorini and McClain*, 2006]. Plankton productivity is highly affected by upwelling and onshore movement of nutrients driven by lateral excursions of the Gulf Stream front [*Lee and Atkinson*, 1983; *Martins and Pelegri*, 2006; *McClain et al.*, 1990]. These upwelling events, also called Gulf Stream intrusions, occur mostly during the summer [*Atkinson*, 1985] when the Gulf Stream has a more onshore position [*Olson et al.*, 1983]. The frequency and extent of cross-shelf penetration of summer, subsurface intrusions is controlled by interactions between Gulf Stream and wind forcing, density of shelf waters (lighter and more stratified during summer), and bottom topography [*Atkinson*, 1977; *Atkinson et al.*, 1982; *Blanton et al.*, 1981; *Janowitz and Pietrafesa*, 1982]. During spring-summer, the Gulf Stream intrusions, or so called Gulf Stream-induced upwelling [*Yoder*, 1985], are felt shoreward of the 40 m isobath in conjunction with northward wind stress and cold upwelled waters intrude across the shelf beneath warmer shelf waters [*Atkinson*, 1977]. Thus, upwelling at the shelf break is forced by the Gulf Stream, but northward wind stress is required to move upwelled waters across the shelf [*Atkinson*, 1977; *Atkinson et al.*, 1984; *Blanton et al.*, 1981; *Hofmann et al.*, 1981]. The frequency and intensity of intrusions are therefore a function of the Gulf Stream western front proximity to the shelf break and the wind direction and strength. Gulf Stream intrusions are the major supplier of nutrients to the outer and middle SAB shelves, which are more frequent during the summer [*Atkinson*, 1985]. Our study shows a strong annual east-west translation in the position of the Gulf Stream front modulated by the seasonality of the size of the NASG, which expands during spring-summer, pushing the Gulf Stream closer to the shelf break. This seasonal translation of the Gulf Stream front has been previously documented by *Olson et al.* [1983], who found the Gulf Stream front all along the U.S. east coast to be further offshore in the late winter and early spring, in agreement with our findings. The impact of these summer intrusions on the SAB shelf phytoplankton production is quite significant due to the 'new' nitrogen being pumped onto the shelf. Individual summer intrusion events advect 0.3 to 1.8×10^4 metric tons of NO_3-N onto the northeastern Florida and Georgia shelves [*Atkinson et al.*, 1982].

[3] Gulf Stream upwelling is the major process affecting rates and dynamics of outer shelf and slope (40 to 200m isobaths) primary production [*Atkinson et al.*, 1978; *Dunstan and Atkinson*, 1976; *Verity et al.*, 1993, 2002; *Yoder*, 1985; *Yoder et al.*, 1983]. Plankton densities may change 10-fold or more within days [*Yoder et al.*, 1985]. Subsurface intrusions of North Atlantic Central Water (NACW) occur mostly from May to August [*Yoder et al.*, 1985]. With regard to Chl-a concentration on the shelf, most of phytoplankton production resulting from Gulf Stream intrusions during high stratification (summer) occurs near the bottom and is below the depth sensed by ocean color sensors. Therefore it is not possible to use satellite ocean color algorithms to accurately estimate mean vertical chlorophyll concentrations and primary production when these subsurface blooms are present [*Signorini and McClain*, 2005].

[4] This study focuses on the influence of remote forcing on the seasonal and interannual variability of Chl-a in the SAB based on satellite-derived products. The major source of data for this study is the 9-year ocean color time series originating from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). A major conclusion from this study is that biomass variability in the SAB outer shelf and slope region is primarily governed by the size and strength of the NASG via Gulf Stream excursions on the shelf break. Excursions of the Gulf Stream on and off the outer shelf and slope are largely driven by the seasonal variability of the NASG, which expands in the summer and contracts in the winter.

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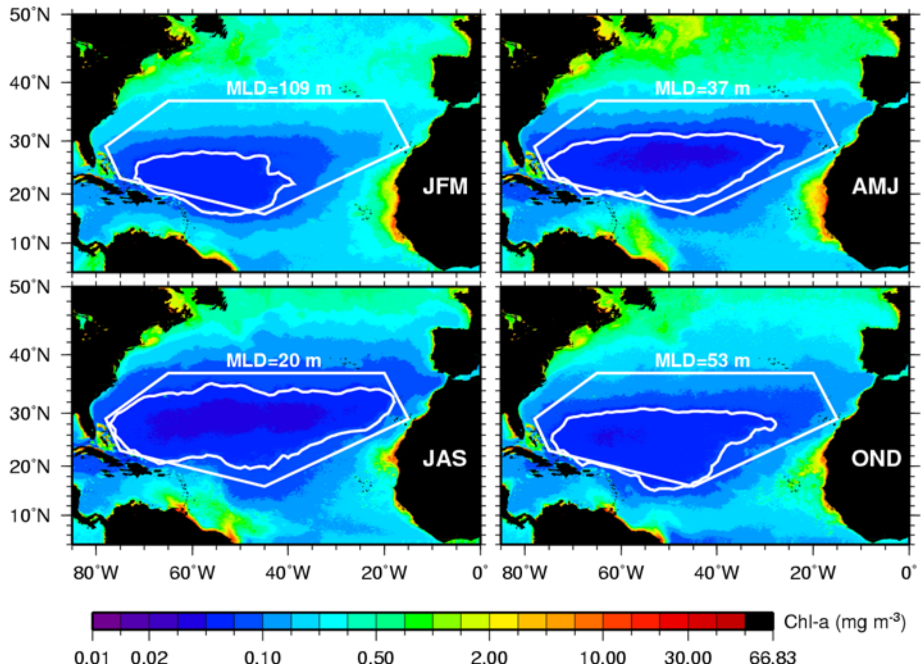

Figure 1. Seasonal composites of SeaWiFS-derived Chl-a. The white polygon delimits the control area of the NASG. The white contours are 0.07 mg m^{-3} Chl-a contours, and the mean MLD inside the polygon is shown for each season.

The size and strength of the NASG can be determined from ocean color data because changes in Chl-a within the NASG respond to local physical processes. Ekman drift is one such process, but vertical mixing also plays a major role. Although it is not always straightforward to separate cause and effect when several processes act simultaneously on the Chl-a concentration, the role of subtropical gyres on Chl-a variability and the various processes involved have been previously studied [*McClain et al.*, 2004; *Williams and Follows*, 1998].

2. Data Sources and Methods

[5] Data analyzed included a time series of sea surface height anomaly (SSHA) from TOPEX/POSEIDON, sea surface temperature (SST) from the Advanced Very High Resolution Radiometer (AVHRR), and chlorophyll-a (Chl-a) derived from SeaWiFS 9-km Standard Mapped Images (SMI) and 1-km Local Area Coverage (LAC) products. Global dynamic height (DHT) 1/3° grids were produced by **S**egment **S**ol multimissions d'ALTimétrie, d'Orbitographie et de localisation precise (SSALTO) and Data Unification and Altimeter Combination System (DUACS) and distributed by the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) with support from the Centre National d'Etudes Spatiales (CNES). We also used monthly mixed layer climatologic data provided by the National Oceanic and Atmospheric Administration (NOAA), Boulder, Colorado, USA, from their web site at http://www.cdc.noaa.gov/, and sea surface height anomaly (SSHA) from NASA GSFC Ocean Altimetry Pathfinder Project. The size of the NASG was calculated from the ratio between the total number of Chl-a pixels with concentration less than 0.07 mg/m^3 to the total number of pixels inside a polygon delimiting the gyre domain (Figure 1). This ratio is an indicator for the expansion and contraction of the oligotrophic region of the gyre and thus its size and strength [*McClain et al.*, 2004]. The shape and size of the polygon was chosen in such a way to minimize coastal influence and contain the expansion of the chosen contour. The 0.07 mg/m^3 value was chosen to provide a closed contour throughout the seasons.

3. Discussion and Results

[6] Figure 1 shows that the NASG is largest in the summer and smallest in winter, as indicated by the size of the oligotrophic region within the gyre. The variability is in phase opposition with the seasonal variability of the mixed layer depth (MLD), as shown by its seasonal mean values in Figure 1. The mean MLD values were calculated for the domain inside the polygon. They are 109, 37, 20, and 53 meters for winter, spring, summer, and autumn, respectively.

[7] The seasonal composites of Aviso DHT for the same North Atlantic region are shown in Figure 2. The seasonality of the DHT within the gyre indicates a contraction in winter and an expansion in summer, in phase with the size variability of the oligotrophic region inside the gyre. The common forcing factor in the Chl-a, DHT, and MLD (averaged within the polygon shown in Figure 1) variability within the gyre is the seasonal change in surface thermal forcing. The warming of surface waters promotes shallower mixed layers, higher DHT resulting from elevated sea level height (SLH), and lower Chl-a due to reduced vertical mixing. The opposite happens during the winter cooling period. The seasonal variability of the size of the oligotrophic region (size of the NASG), the climatologic seasonal MLD, SST, and DHT are plotted for the period of 1998–2005 in Figure 3a, while the effect of surface thermal expansion on DHT are clearly shown in Figure 3b. Note that DHT, SST, and the size of the NASG are all in phase (within ~1 month of each other), while the MLD is ~180°

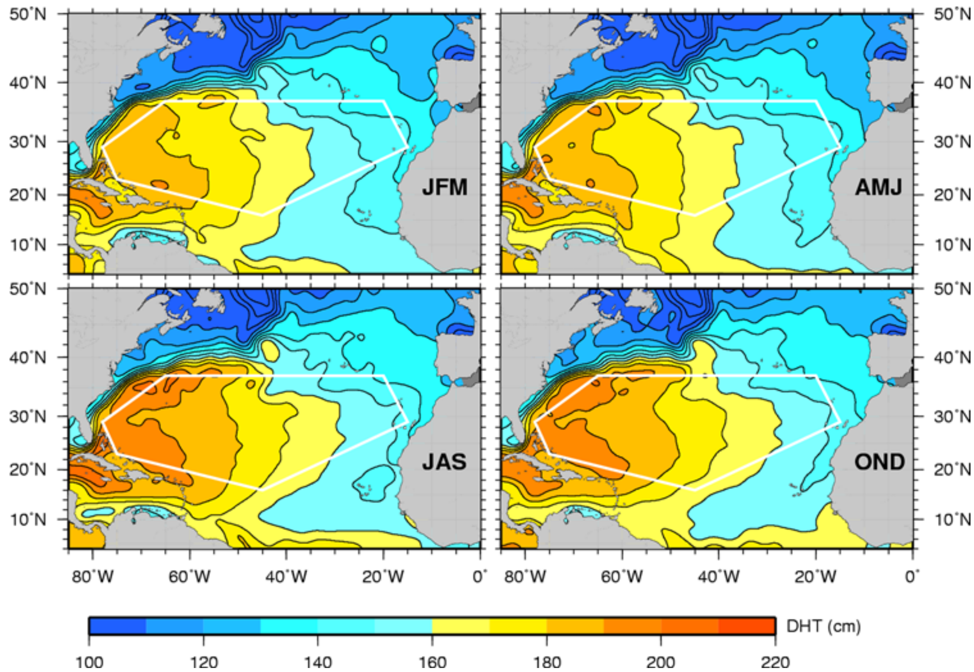

Figure 2. Seasonal composites of dynamic height (DHT) from Aviso data. Note the increase of dynamic height of ~20 cm from winter-spring to summer-autumn. The white polygon delimits the control area of the NASG.

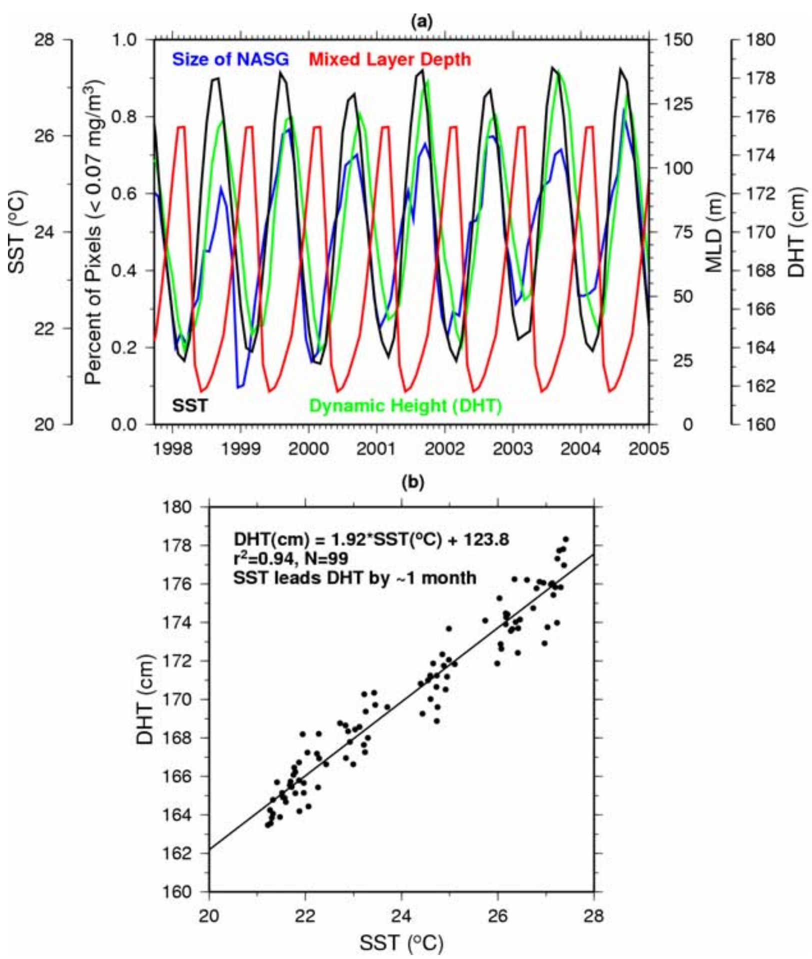

Figure 3. (a) Time series of NASG size, MLD, SST, and DHT for 1998–2005. (b) Scatter plot of DHT versus SST with corresponding regression equation.

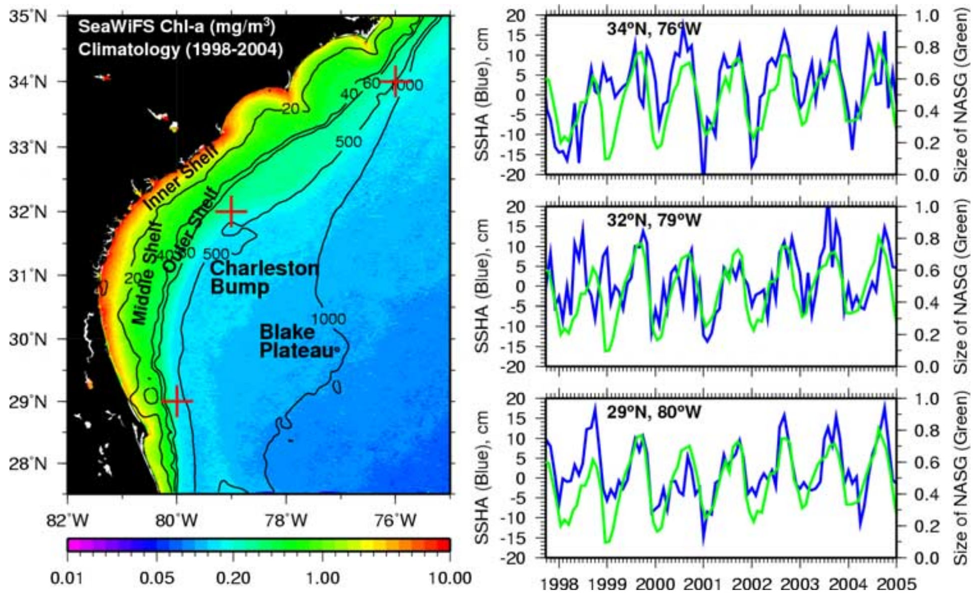

Figure 4. Time series of SSHA at three sites along the SAB shelf break. (left) SeaWiFS Chl-a climatology and the locations from which the three SSHA time series were extracted (red crosses). (right) The time series of SSHA at the three locations (blue lines) with the size of the NASG superimposed (green lines).

out of phase. The effect of surface thermal forcing on DHT is clearly shown in the DHT vs. SST regression ($r^2 = 0.94$) in Figure 3b. The SST time series was shifted forward by one month before the regression was made as the peak SST leads the peak DHT by ~1 month, presumably the time scale required for the NASG to respond to the thermal forcing. The regression in Figure 3b indicates that an increase of ~1°C is required to raise the DHT by 2 cm.

[8] Previous studies showed that a large portion of DHT changes in the ocean are related to steric effects [*Chambers*, 2006a, 2006b; *Kelly et al.*, 1999; *Mork and Skagseth*, 2005]. According to these references, the components of the total sea-surface height seasonal variability are: a steric component, a dynamically active component, and the barometric effect, which is negligible on a seasonal basis. The steric component is broken down into a buoyancy component (heat and freshwater fluxes), and contributions due to Ekman and geostrophic transports. According to *Ferry et al.* [2000], within the NASG domain, the Ekman and geostrophic transport components account for a seasonal amplitude of less than 1cm, while the total seasonal amplitude observed from satellite altimetry is ~5cm. They also determined that the buoyancy component due to freshwater fluxes is very small within the NASG. Therefore, the steric component is mainly due to thermal effects and is the major contributor to the total DHT seasonal change.

[9] Figure 4 shows time series of Pathfinder TOPEX/POSEIDON SSHA extracted from three locations along the SAB shelf slope between 100 and 500 m depth. The size of the NASG is superimposed on the three SSHA time series. There is a remarkable correlation between the SSHA and the size of the NASG, which indicates the strong influence of the gyre dynamics on the shelf slope SSHA variability via the Gulf Stream front displacement in response to the expansion and contraction of the NASG. This result is consistent with *Olson et al.* [1983], who showed a distinct seasonal cycle of the Gulf Stream front displacement using satellite SST data, offshore in spring and onshore in fall. Also, *Miller* [1994] identified an annual cycle in the fluctuations of the Gulf Stream frontal position between Cape Hatteras and the Straits of Florida using AVHRR SST data. He identified an annual mode for the Gulf Stream frontal position that accounted for 43% of the total variance, which was in phase along the entire SAB and exhibited a local increase of amplitude at and just north of the Charleston Bump (Figure 4). These findings are in agreement with our analysis.

[10] The high levels of subsurface Chl-a and primary production imparted by nutrient pumping via Gulf Stream summer intrusions on the SAB outer shelf is a well known process [*Yoder et al.*, 1985, 1983]. The unique contribution of our paper is the connection between these Gulf Stream summer intrusions and the seasonal variability of the size and strength of the NASG, as indicated by corresponding seasonal changes in size of the oligotrophic region as seen by the SeaWiFS Chl-a product (Figure 4). Although the effect of sub-surface Gulf Stream summer intrusions on biomass and primary production is not captured by ocean color satellites, the large-scale forcing that drives the Gulf Stream intrusions is clearly demonstrated by the remarkable coherence between the NASG size and the local SSHA variability. Summer cruises conducted during July–August 1981 [*Yoder et al.*, 1985] revealed elevated levels of Chl-a near the bottom (3 to 7 mg/m^3) with low concentrations at the surface. Our analysis of contemporaneous satellite ocean color data Chl-a from CZCS showed low values near the surface (~0.5 mg/m^3) similar to the observed surface values.

[11] Evidence of the seasonal displacement of the GSF was also obtained by using DHT and Chl-a horizontal gradients as indicators. The four lines representing the GSF seasonal variability were based both on the position of the 144 cm DHT contour and the position of the 0.25 mg/m^{-3} Chl-a contour (not shown). The contour

values appear to be good proxies for the GSF and were chosen within the region of sharpest gradients and based on the known position of the Gulf Stream axis with respect to bathymetry [*Bane*, 1983]. South of 32°N (Figure 4), the western edge of the Gulf Stream generally lies within ±15 km of the shelf break [*Bane and Brooks*, 1979]. The Chl-a contours seem to provide a more accurate representation of the seasonal GSF than DHT because they are based on higher resolution LAC data, e.g., 1 km versus 1/3° (~37 km) for the Aviso DHT data, which tend to be much smoother, especially north of the Charleston Bump. However, both representations of the GSF show that the front is closer to the shelf break in summer and moves offshore towards the winter. This seasonal behavior is consistent with our previous discussions regarding the expansion-contraction of the NASG. Also, the contours are farther apart immediately north of the Charleston Bump (Figure 4), a region of active eddy generation.

[12] We also mapped the spatial distribution of the linear correlation between the size of the NASG and Chl-a, which we omitted to present here for brevity. The highest correlation lies within the gyre itself and in the slope region north of the Charleston Bump where excursions of the Gulf Stream and frontal eddies are more frequent and energetic, acting as a nutrient pump to the outer shelf waters. There is also a narrow band of elevated correlation along the outer shelf south of the Charleston Bump to 28°S. This seems to be a result of Gulf Stream frontal excursions as well, but within a more confined range of distance.

4. Summary and Conclusions

[13] A study of the effects of local and remote forcing of the Chl-a variability was conducted for the SAB based on the analysis of satellite-derived products. The seasonal position of the GSF was obtained using Aviso DHT and SeaWiFS Chl-a as indicators. South of 32°N, the western edge of the Gulf Stream generally lies within ±15 km of the shelf break. The front is closer to the shelf break in summer and moves offshore towards the winter. Immediately north of the Charleston Bump, a region where the Gulf Stream is deflected eastward and eddy generation is very active, the seasonal location of the front is much more variable. These excursions of the Gulf Stream front have an impact on the observed surface Chl-a and the concentrations change according to which side of the front the observation is taken and on the structures associated with the frontal eddies. East of the front the thermocline and nutricline are deeper, DHT is high and Chl-a is low. West of the front the relationship between DHT and Chl-a reverses.

[14] There is a connection between the NASG variability and the SAB shelf response via Gulf Stream forcing, which is the western branch of the NASG. The size and strength of the NASG, which is governed by the large-scale wind circulation and seasonal solar radiation, has an impact on the oceanographic processes of the SAB as a result of seasonal Gulf Stream onshore/offshore motion. Our study shows that the GSF seasonal position can be detected by ocean color satellites and that it moves closer to the shelf break during summer when Gulf Stream subsurface intrusions are more frequent and intense, as demonstrated by numerous *in situ* studies. The intensity and frequency of intrusions depend on the proximity of the GSF to the shelf, which is modulated by the seasonal expansion and contraction of the NASG.

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