

**CHLOROPHYLL *A* VARIABILITY DUE TO LARGE-SCALE NORTH
ATLANTIC CIRCULATION CHANGES**

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ABSTRACT

The North Atlantic Ocean is one of the strongest oceanic carbon sinks and is heavily influenced by biological uptake. Satellite-observed chlorophyll concentrations, a proxy for phytoplankton biomass, declined by 14% in the North Atlantic inter-gyre region (defined in this study as 40-60 °N, 20-40 °W) over 1998-2006. This study examines the drivers behind satellite chlorophyll *a* concentration changes over 1998-2006 in this North Atlantic inter-gyre region using a regional biogeochemical model of the North Atlantic basin. Light impacts phytoplankton growth seasonally, but nitrate concentrations drive chlorophyll concentrations on interannual timescales. A nitrate budget of the inter-gyre region finds that along-isopycnal horizontal mixing dominates on the mean and is also a first-order control of interannual variability from 1998-2000 to 2004-2006. Horizontal advection of nutrients is on the same order of magnitude as vertical nitrate advection, and horizontal advection is dominated by advection of nitrate by the North Atlantic nutrient stream. All nitrate transfer processes weaken over time, which is connected to a wind-driven spin-down of the North Atlantic gyres that weakens the nutrient stream and shoals the isopycnals. The implications of this study are three-

fold: a three-dimensional paradigm is needed to fully understand nutrient transport; isopycnal processes may be just as important as vertical processes to supply nutrients to the mixed layer, and thus need continual improvement in their representation in biogeochemical models; and changes in the large-scale physics can impact chlorophyll concentrations, particularly in the inter-gyre region.

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1. INTRODUCTION

The oceanic carbon sink is a significant sink for carbon dioxide, taking up to 27% of anthropogenic carbon dioxide emitted into the atmosphere each year [Sabine *et al.*, 2004; Le Quéré *et al.*, 2012]. This significant uptake is aided by biological processes that transport carbon out of surface waters. At higher latitudes, much of the sinking, biologically-fixed carbon is due to large cells produced by phytoplankton blooms in the spring. In the more nutrient-poor lower latitudes, efficient ecosystem recycling means that less biologically-fixed carbon is able to escape the surface ocean. Although photosynthesizing phytoplankton require carbon dioxide, the abundance of light and nutrients are often the limiting factors to phytoplankton growth in the ocean.

Many studies have examined the constraints behind oceanic phytoplankton growth. Sverdrup [1953] used observations from a weather ship in the Norwegian Sea to propose the notion of a “critical depth”, where a phytoplankton bloom can occur only if the mixed layer base is shallower than the euphotic zone depth. When the mixed layer, which is assumed to have a well-mixed distribution of phytoplankton, reaches below the critical depth, both increased respiration and lower light levels decrease production. To understand Sverdrup’s hypothesis, Dutkiewicz *et al.* [2001] and Follows and Dutkiewicz [2002] investigated regions of the North Atlantic characterized by the ratio of the spring critical depth to the winter mixed layer depth through *in situ* measurements, satellite observations, and a simple biogeochemical model. Models utilize the Michaelis-Menton term (Eq. 1) to quantify how ambient light and nutrient concentrations impact phytoplankton growth rates. The most limiting term is multiplied by the maximum possible growth rate to calculate local

phytoplankton growth. Each term describes the limitation by light or nutrient availability, with a half-saturation constant in the denominator being the level of nutrients or light at which growth is cut in half. The Michaelis-Menton terms for nitrate and light, or photosynthetically active radiation (PAR), are defined as

$$\frac{[NO_3]}{[NO_3] + k_N} \text{ or } \frac{I}{I + k_I} \quad (1)$$

where $[NO_3]$ is the concentration of nitrate, I is PAR, and k_N and k_I are half-saturation constants. By using this limitation parameterization, Dutkiewicz *et al.* [2001] and Follows and Dutkiewicz [2002] found that the subtropics have a high ratio of critical depth to mixed layer depth, where an enhanced bloom occurs due to enhanced mixing. Subpolar regions have a low ratio, where deep mixing slows the phytoplankton bloom by pulling the phytoplankton below the critical depth. Thus, in a region with abundant light (subtropical region), deeper mixing does not remove phytoplankton from the deep euphotic zone but does bring more nutrients to the phytoplankton. However, in a region where there is less light (subpolar region), the deeper mixing brings more nutrients to the phytoplankton, but the phytoplankton are pulled out of the shallow euphotic zone. These results are consistent with the hypothesis proposed by Sverdrup [1953].

In the past two decades, phytoplankton biomass changes have been studied through ocean color satellites that utilize the optical properties of the chlorophyll in phytoplankton [McClain *et al.*, 2004; Siegel *et al.*, 2005]. For example, Siegel *et al.* [2002] used the satellite Sea-viewing Wide Field-of-view Sensor (SeaWiFS), which measured chlorophyll *a* over the global oceans during its run from 1997-2010, and found evidence in support of the Sverdrup hypothesis in the North Atlantic. Similarly, Venables and Moore [2010] used SeaWiFS to

understand phytoplankton growth in the Southern Ocean in response to light and nutrient limitations. The Southern Ocean has low chlorophyll concentrations despite being an area of macro-nutrient upwelling (high macro-nutrients, low chlorophyll; “HNLC”), but there are areas in the Southern Ocean downstream of islands that are considered high nutrients, high chlorophyll (HNHC). Because the same chlorophyll concentrations were not found in both HNLC and HNHC areas when the light hit a certain level, they concluded that a trace element, iron, must be the limiting factor in this HNLC region.

Nutrients are moved through both biological and physical (vertical and horizontal) processes back and forth between the deep ocean and surface layer [Sverdrup, 1953; Dutkiewicz *et al.*, 2001; Palter *et al.*, 2005; Pelegrí *et al.*, 1996; Williams *et al.*, 2006]. Thus, changes in the physics controlling nutrient movement may contribute to variations in chlorophyll concentrations. The dominant theory behind productivity trends is based on the Sverdrup hypothesis and only considers the impact of increased stratification due to ocean warming on the vertical supply of nutrients into the mixed layer.

Studies such as Behrenfeld *et al.* [2006], Martinez *et al.* [2009], Polovina *et al.* [2008], and Yoder and Kennelly [2003] suggest that increasing sea surface temperatures (SSTs) are an indicator of increasing stratification of the water column, which inhibits mixing and prevents nutrients from being upwelled to the euphotic zone. Both Behrenfeld *et al.* [2006] and Martinez *et al.* [2009] found used satellite-derived observations and models and discovered that a negative relationship between SSTs (used as a proxy for stratification) and chlorophyll concentrations appears to be the dominant relationship over the global oceans (particularly over the SeaWiFS period). Thus, increasing SSTs (and presumably

increasing stratification) correlates with decreasing chlorophyll concentrations. The hypothesis that stratification is the dominant control behind chlorophyll concentrations strongly suggests that the vertical component of nutrient advection drives chlorophyll changes.

A schematic from Doney [2006] illustrates how increasing SSTs decreases mixing in subtropical and subpolar regions in accordance with the stratification hypothesis (Figure 1). Decreased vertical mixing in both the subtropical and subpolar gyres will bring fewer nutrients up from the deep ocean. According to the Sverdrup hypothesis, phytoplankton growth should decrease in the nutrient-limited subtropics and increase in the light-limited subpolar region. Decreased mixing will cause phytoplankton to stay in or closer to the euphotic zone in the subpolar regions while still maintaining a flux of nutrients to the phytoplankton, thus causing phytoplankton growth to increase. However, SSTs cannot be assumed to increase everywhere. Despite global warming, Lozier *et al.* [2008] suggest that the subpolar North Atlantic has exhibited trends toward less buoyancy from 1950 to 2000. According to the Sverdrup hypothesis, this could reduce phytoplankton productivity by increasingly pulling the phytoplankton cells out of the euphotic zone in an already light-limited region.

In the subtropics, a controversy exists with respect to the full applicability of the Sverdrup hypothesis. According to Behrenfeld *et al.* [2006] and Martinez *et al.* [2009], the subtropics have been dominated by inverse relationships between SSTs and chlorophyll concentrations trends from the 1980s to the 2000s, in support of the stratification hypothesis. However, these studies imply correlation by causation, do not demonstrate any connection

between SSTs and stratification, and neglect to explicitly examine how limiting factors of phytoplankton growth are affected by increasing SSTs. In contrast, Lozier *et al.* [2011] and Dave and Lozier [2010] show that locally increasing stratification in the subtropical gyre—though correlated with decreasing ocean color and increasing sea surface temperatures seasonally— is not correlated with reduced productivity on interannual timescales in either the North Atlantic or the North Pacific. Particularly, the Lozier *et al.* [2011] study revealed that the kinetic energy imparted to the surface by the winds at the Bermuda Area Time Series (BATS) was more than the energy required to overturn the water column from 200 m to the surface, indicating that surface warming alone is unlikely to be the dominant mechanism to modify surface chlorophyll concentrations.

Horizontal nutrient advective processes include lateral mixing, induction and subduction, and lateral advection (Figure 2) [Palter *et al.*, 2005; Pelegrí *et al.*, 1996; Williams *et al.*, 2006]. Williams *et al.* [2006] compared the magnitude of Ekman upwelling to induction, which is the three-dimensional movement per unit area of water or nutrients from the permanent thermocline to the mixed layer along isopycnals. Climatologically, induction accounts for up to six times as much volume transport to and from the surface as vertical Ekman processes. Furthermore, the horizontal components of induction are three times larger in magnitude than the vertical component. Large-scale lateral advection and mixing is accomplished by nutrient streams, which are subsurface nutrient conduits that moves nutrients from subtropical gyres, through intense western boundary currents, to subpolar gyres (green arrow, Figure 2) [Pelegrí and Csanady, 1991; Pelegrí *et al.*, 1996; Palter *et al.*, 2005; Williams *et al.*, 2006]. The nutrient stream is a below-surface phenomena because

phytoplankton efficiently utilize and remove nutrients from the surface. The North Atlantic nutrient stream, which transports nutrients through the Gulf Stream, supplies nutrients to subsurface euphotic layers via diapycnal mixing and is a significant contributor to the productivity in the North Atlantic subpolar gyre [Pelegri and Csanady, 1991; Pelegri *et al.*, 1996; Palter *et al.*, 2005; Williams *et al.*, 2006]. Considering both horizontal and vertical processes not only fully close nutrient budgets, but also is more accurate mechanistically.

Changing oceanic circulation influences both horizontal and vertical advective transports. A wind-driven spin-down (slow down) of the gyres relaxes isopycnal slopes and decreases advection along isopycnals as well as upwelling and downwelling [Häkkinen and Rhines, 2004; Hátún *et al.*, 2005; Lozier *et al.*, 2008]. Wind-driven spin-downs of gyres are driven by wind stress declines in response to atmospheric oscillations or long-term trends associated with climate change [Häkkinen and Rhines, 2004; Hátún *et al.*, 2005; Lozier *et al.*, 2008]. Additionally, buoyancy fluxes contribute to density variations within a basin and may contribute to mixed layer depth changes, which can influence bloom timing and strength [Lozier *et al.*, 2008]. Oceanic physical changes in gyre structures, isopycnal slopes, and mixed layer depths likely redistribute nutrients and modify productivity at the surface.

In inter-gyre regions, horizontal advective processes have been noted to dominate at the surface and the base of the mixed layer [Dutkiewicz *et al.*, 2001; Follows and Dutkiewicz, 2002; Williams and Follows, 1998; Williams *et al.*, 2006]. Furthermore, the inter-gyre region is an area of transition between the nutrient-limited subtropics and light-limited subpolar gyre; thus, the influence of light and nutrients in inter-gyre regions are not

well-diagnosed due to the complicated nature of the dynamics [Dutkiewicz *et al.*, 2001; Follows and Dutkiewicz, 2002; Letelier *et al.*, 2004; Venables and Moore, 2010].

The North Atlantic Ocean stores 23% of the atmospheric carbon dioxide taken up by the ocean, making it the strongest oceanic carbon sink [Sabine *et al.*, 2004]. The strength of the North Atlantic carbon sink is partially derived from the biological pump [Takahashi *et al.*, 2002]. Thus, understanding changes in phytoplankton populations and growth in the North Atlantic, especially in highly dynamic regions, is vital for comprehending how ocean carbon uptake may change in the future.

In order to investigate the cause behind variability in SeaWiFS chlorophyll *a* concentrations over 1998-2006 in the North Atlantic inter-gyre region (defined here as 40-60 °N, 20-40 °W; black box, Figure 3a and 3b), I use a regional biogeochemical model of the North Atlantic basin to examine the influences of light and nutrient limitation on chlorophyll in the inter-gyre region. I determine that driving mechanisms for chlorophyll change are nutrient supply into this region by the large-scale circulation through the nutrient stream and eddy mixing. My goal for this thesis is to better understand the relationship of physical variability to these observed trends.

2. METHODS

A model was used to assess the influence of light and nutrients on the chlorophyll concentrations in the North Atlantic gyre region.

2.1. Physical-Biogeochemical-Ecosystem Model

The Massachusetts Institute of Technology general circulation model configured for the North Atlantic Ocean (MITgcm.NA) [Marshall *et al.*, 1997a; Marshall *et al.*, 1997b] simulation from Ullman *et al.* [2009] was used to overcome the current nutrient observation deficits. The model domain extends from 20 °S to 81.5 °N, with a horizontal resolution of 0.5° x 0.5° and a vertical resolution of 23 levels that have a thickness of 10 m at the surface and gradually becomes coarser to 500 m thickness intervals for depth levels deeper than 2200 m.

NCEP/NCAR Reanalysis I daily wind, heat, freshwater, and radiation fields from 1980-2006 are used to force the general circulation of the model [Kalnay *et al.*, 1996]. To characterize sub-grid-scale processes, the Gent-McWilliams [Gent and McWilliams, 1990] eddy parameterization and the KPP boundary layer mixing schemes [Large *et al.*, 1994] are used. The phosphorus-based ecosystem is parameterized following Dutkiewicz *et al.* [2005], using one zooplankton class and two phytoplankton (diatoms and “small” phytoplankton) classes. Additionally, the biogeochemical model explicitly cycles alkalinity, carbon, iron, phosphorus, and silica after Dutkiewicz *et al.* [2005] and Bennington *et al.* [2009]. Nitrate concentrations were analyzed instead of phosphorus because nitrate is generally the limiting

nutrient in global oceans, and for comparability to other studies. Nitrate is estimated from phosphorus model output via a standard Redfield ratio (N:P = 16:1).

Model validation analyses against World Ocean Atlas, Bermuda Area Time Series, SeaWiFS, etc. were performed by Bennington *et al.* [2009] and Ullman *et al.* [2009]. The Ullman *et al.* [2009] model run spans 1992-2006. The years used for this analysis were 1998-2006 to overlap with SeaWiFS chlorophyll *a* data, which covers September 1997 to December 2010.

2.2. Model Analysis

Averaged monthly values of the MITgcm.NA photosynthetically active radiation (PAR), chlorophyll concentrations, velocities, and nitrate concentrations were compared over the inter-gyre region (40-60 °N, 20-40 °W) to determine the cause behind the pattern in chlorophyll concentrations. All analyzed time series were smoothed over 12 months to filter any high frequency variability out unless otherwise stated. To explore nitrate transport mechanisms into the inter-gyre region, a nitrate budget was created. The nitrate budget examined various modes of nitrate supply and removal from 40-60 °N, 20-40 °W, and accounted for increasing annual average maximum mixed layer depths at 5° latitude intervals northward (from south to north: 320.2, 380.2, 424.2, and 687.0 m). The average maximum mixed layer depth (depth at which $\Delta\sigma_\theta = 0.125 \text{ kg m}^{-3}$) is used because when the mixed layer is at its deepest (generally winter), water within the mixed layer will move to the permanent thermocline, explaining why the permanent thermocline possesses the properties of the winter mixed layer [Stommel, 1979; Williams *et al.*, 1995]. This phenomenon is known

colloquially as “Stommel’s Mixed Layer Demon” [Stommel, 1979; Williams *et al.*, 1995]. The factors in the nitrate budget include biological uptake and remineralization within the region, in addition to horizontal and vertical advection, particulate organic nitrate (PON) sinking, and horizontal (calculated residually—see Results, section 3.3) and vertical mixing at each of the faces of the box (excluding the surface and any faces irrelevant to a specific term; Figure 4). Nitrate advection was estimated using monthly nutrient and velocity fields, and vertical mixing was calculated from monthly nitrate and the KPP vertical tracer coefficient.

In order to understand the drivers behind nitrate transport changes, gyre structure variability was examined via a Gyre Index, which is the first principle component of the surface ocean velocities over an entire basin [Häkkinen and Rhines, 2004]. This was compared to the wind stress at 45 °N, the zonal velocity of the Gulf Stream between 45 and 50 °N and integrated down to 380.2 m (the average maximum mixed layer depth between 45 and 50 °N), the nitrate transport between 45 and 50 °N and integrated down to 380.2 m, and surface chlorophyll concentrations at 40-60 °N, 20-40 °W. Nitrate transport was used for correlations as opposed to the nitrate advection used for the nitrate budget in order to understand the influence of nitrate movement by the velocity without the influence of the nitrate gradient.

3. RESULTS

Chlorophyll comparisons between the SeaWiFS data (Figure 3a and 3c) MITgcm.NA model output (Figure 3b and 3d) reveal that while the model underestimates mean chlorophyll *a* concentrations and the absolute magnitude of trends over the time period (1998-2006) within the inter-gyre region (black box; Figure 3), it still accurately portrays similar chlorophyll concentration patterns. In this section, we analyze the model to understand the drivers for these trends.

3.1. Light versus Nutrients

In order to determine the drivers behind chlorophyll variability in the North Atlantic inter-gyre region, two time series of the monthly Michaelis-Menton parameterizations for light (PAR) and nitrate concentrations (Eqn. 1) for both phytoplankton classes represented in the model for the inter-gyre region (defined in this study as 40-60 °N, 20-40 °W) are presented (Figure 5). In winter, phytoplankton growth for both phytoplankton groups is limited by PAR (Figure 5); however, on interannual time scales, smoothed nitrate and chlorophyll concentrations have a significant, positive relationship ($r = 0.77$, $p < 0.05$), with nitrate concentrations leading chlorophyll concentrations by 1-2 months (Figure 6). Despite increasing shortwave radiation by 1.5% in the 40-60 °N, 20-40 °W region, PAR and chlorophyll concentrations have a significantly negative relationship ($r = -0.94$, no lag, $p < 0.05$, Figure 6). The negative relationship found between PAR and chlorophyll concentrations is consistent with phytoplankton self-shading that is parameterized in the model; i.e., with less phytoplankton in the water, more light can penetrate. Thus, we find that

PAR reacts to changes in chlorophyll concentrations (and by proxy, phytoplankton) instead of PAR driving the chlorophyll concentrations. As a result of these relationships, it is evident that nitrate, not light, is the driving force behind modeled chlorophyll concentrations in this region on interannual timescales.

3.2. Physical Changes

In order to understand how nutrients are moved into an inter-gyre region, the physics of the circulation must be understood. Figure 7a reveals the first EOF of the magnitude of surface velocities (m s^{-1}), explaining 14.7% of the variance. The EOF indicates more variance at the gyre boundaries, consistent with the wind-driven geostrophic circulation. The first principle component (PC1) for this EOF indicates the temporal pattern of the pattern's variability. Following Häkkinen and Rhines [2004], I use PC1 as a "Gyre Index" (Figure 7b; brown) to indicate the relative strength of the circulation in both the subtropical and subpolar gyres. The Gyre Index illustrates that there has been a decrease in surface speeds over the period 1998-2006. A strong, significant, positive correlation ($r = 0.92$, $p < 0.05$; Table 1) exists between the x -component of the wind stress at 45°N (τ_{45}) and the Gyre Index, which is consistent with the wind-driven gyre mechanism. Despite the first and second EOF of surface currents not separating well from each other (variances of 14.7% and 12.9%, respectively), the Gyre Index correlates highly with the wind stress, and is independently calculated from the wind stress; thus, the first EOF is likely reasonable for the Gyre Index. The Gyre Index and the wind stress both decline in strength over time (Figure 7b), which is clear evidence of

a wind-driven gyre spin-down of both the subtropical and subpolar gyres over the 1998-2006 period.

3.3. Nutrient Budget

I now consider the budget for nitrate in the inter-gyre region (40-60 °N, 20-40 °W; Figure 4).

Figure 8 quantifies nitrate fluxes into and out of the inter-gyre region for the 1998-2006 average, 1998-2000 average, and the 2004-2006 average. Horizontal and vertical mixing terms (orange) and net horizontal advection (dark blue) transport nitrate into the box (as shown in Figure 4), while net vertical advection (light blue) and the storage term (red) remove nitrate from the area. Through the sinking of particulate organic nitrate (PON) and biological uptake, net biological processes (green) also remove nitrate from the box; remineralization of PON to nitrate that occurs within the box is included as a compensating mechanism. The storage term, which is calculated as the change in nitrate concentrations in the box from January of one year from the nitrate concentrations from January of the previous year ($d[\text{NO}_3]/dt$), describes the overall change in nitrate in the budget; all terms must add up to the storage term in order to balance the budget. This negative mean storage term indicates a long-term loss of nitrate over the period 1998-2006.

Though the horizontal and vertical advection terms differ in sign, they are on the same order of magnitude (Figure 8). All of the supply and loss terms weaken over time, except for the storage term, which increases. An increase in the strength of the storage term indicates less nitrate in the box than in previous years. Reduction in the biological term is

consistent with the decrease in chlorophyll concentrations, as a decrease in nitrate uptake would coincide with fewer phytoplankton to take up the nitrate and remove it from the box.

The mixing term is dominated by horizontal mixing (orange with hatching, Figure 8), with vertical mixing being a much smaller component (orange with no hatching, Figure 8). In the MITgcm.NA, along-isopycnal mixing is parameterized by the Gent-McWilliams scheme [Gent and McWilliams, 1990; hereafter referred to as “GM”]. Unfortunately, the GM eddy fluxes were not saved output for these runs; thus, horizontal mixing in this budget was calculated as the residual from other terms in the nutrient budget for this region and cannot be separated by box face. As a result, this term also contains the uncertainty in the other terms in the budget as well as horizontal mixing terms. In this model, constant GM parameters were used, and thus the GM fluxes should be proportional to the slope of the isopycnals [Danabasoglu and Marshall, 2007]. Weakening isopycnal mixing due to a decrease of the isopycnal slopes is consistent with the relaxation of the wind stress and reduced Ekman divergence and upwelling. Future analysis will lead to better understanding and partitioning of the changes in horizontal mixing.

The western face of the box at 40°W contributes to 53.8% of the net horizontal advection term (yellow hatching, Figure 8), which is the same box face that the North Atlantic nutrient stream intersects. Figure 9 shows the mean nitrate advection over 40 °W, with positive shading indicating advection into the box. Between 45-50 °N, a jet of positive nitrate advection is the model nutrient stream. This feature sits just above the average maximum mixed layer depth (red line) and between the 1027.0 and 1027.4 kg m⁻³ isopycnals. This supports the existence of a nutrient stream, and appears in the MITgcm inter-gyre region

in approximately the same location as that found through hydrographic observations in Pelegrí and Csanady [1991].

Comparing a meridional cross-section of nitrate transport from the MITgcm.NA from within the inter-gyre box at 35 °W (Figure 10a) to a cross-section of hydrographic observations at 35 °W in Pelegrí *et al.*, [1996] (Figure 10b), indicates that the model adequately simulates the nutrient stream. The stream in the model is more diffuse than in the observations, which is consistent with the model having a discrete 0.5 degree grid. Furthermore, the core of the nutrient stream is lower in the depth column in the observations (approximately 450 m; Figure 10b) than the model (approximately 350 m; Figure 10a). However, the coarse resolution of the depth layers in the model may explain the discrepancy. However, the 1027.2 kg m⁻³ isopycnal intersects the core of both the model and observations.

Over the period 1998-2000 to 2004-2006 at 45-50 °N, and for the surface to 380.2 m (the average maximum mixed layer depth between 45-50 °N), the nutrient stream weakens from by 13.2%. Thus, it is likely that the nutrient stream reduction dominates the decrease in the horizontal advection into the inter-gyre region seen in Figure 8.

3.4. Correlation analysis

To better understand the mechanistic links between wind-driven gyre spin-down and inter-gyre chlorophyll concentrations, a correlation analysis was performed. Correlations were calculated between the wind stress at 45 °N, Gyre Index, zonal velocity of the Gulf Stream between 45-50 °N and integrated down to 380.2 m, nitrate transport between 45-50

°N and integrated down to 380.2 m, and surface chlorophyll concentrations in the region of interest (Table 1).

I find that the zonal velocity of the Gulf Stream decreases following the Gyre Index with a 12 month lag ($r = 0.68, p < 0.05$, Table 1). With zero lag, zonal velocity changes are positively correlated with a changes in nitrate transport, i.e. they both decrease over this period ($r = 0.87, p < 0.05$, Table 1). The decrease in nitrate transport then leads to decreasing chlorophyll concentrations over the inter-gyre region 2-3 months later ($r = 0.69, p < 0.05$). Consistently, the chlorophyll response to the change in the wind stress takes 15 months. Table 1 shows the correlations, which are all significant at the $p < 0.05$ level.

4. DISCUSSION

In the MITgcm.NA, nitrate concentrations are the leading contributor to interannual chlorophyll concentration changes in the North Atlantic inter-gyre region. Despite being a region of transition from nutrient-limitation to light-limitation, the relationship between light and chlorophyll in this region strongly suggests self-shading of the phytoplankton rather than growth-inhibition by light interannually. While nutrients dominate chlorophyll concentration changes on interannual timescales (Figure 6), PAR does drive growth on seasonal timescales, as seen in Figure 5. In winter months (typically December through March), light limits the growth for both phytoplankton groups until summer, where enough sunlight penetrates the surface ocean to encourage phytoplankton growth. As a result, biological uptake of nitrate causes nitrate concentrations to become sparse, causing nitrate to become the limiting factor during summer. Figure 5 reveals that Sverdrup's "critical depth" hypothesis [Sverdrup 1953] does apply to this model on seasonal timescales, which is consistent with recent observational studies [Lozier *et al.*, 2011, Dave and Lozier, 2010].

SSTs over the entire North Atlantic basin do not increase in all areas. In fact, the SSTs in the western portion of the inter-gyre region decrease with the eastern SSTs increase. According to the Sverdrup hypothesis and the theories regarding stratification impacts on phytoplankton growth (Figure 1), chlorophyll concentrations should decrease with surface warming in the subtropics and increase in the subpolar region. Despite the inter-gyre region being an area of transition and uneven warming, the chlorophyll decreases uniformly over the inter-gyre region for the period of 1998-2006 (Figures 3c and 3d). A nitrate budget (Figure 8) reveals that the horizontal and vertical advection components are on the same order of

magnitude on average from 1998-2006, which supports the work by Dave and Lozier [2010], Lozier *et al.* [2011], and Williams *et al.* [2006] in that the vertical transport of nutrients is not the sole important contributor to surface nutrient concentrations. In this region, it is the horizontal movement of nutrients that drives chlorophyll change.

In a climatological analysis, Williams *et al.* [2006] found that 40% of the nutrients that travel via the nutrient stream make it into the euphotic zone. In the MITgcm.NA, the nutrient stream contributes to 54% of the nitrate advection into the inter-gyre region (Figure 9). While Williams *et al.* [2006] examined the movement from the permanent thermocline into the well-lit euphotic zone of the subpolar gyre rather than into this specific box in the inter-gyre region that is defined down to the average maximum mixed layer depth, the percentages are still relatively consistent with one another and suggest that the nutrient stream plays an important role in nutrient movement.

Furthermore, it appears that horizontal mixing is the dominant driver behind interannual nitrate changes in the inter-gyre region. This study finds a net supply of nutrients into the North Atlantic inter-gyre region through parameterized isopycnal mixing in a 0.5 degree, non-mesoscale eddy resolving model. With resolved mesoscale eddies, McGillicuddy *et al.* [2003], found a net removal of nutrients by horizontal and vertical eddy-induced mixing in the inter-gyre region. The vertical advection term in the McGillicuddy *et al.* [2003] study reveals a positive net vertical nitrate advection, while this study reveals a negative vertical advection. However, the McGillicuddy *et al.* [2003] study examined eddy fluxes over 1993-1997, and the time period for this study was over 1998-2006. Additionally, the mixed layers in the model of McGillicuddy *et al.* [2003] are deeper in the inter-gyre region

than the MITgcm.NA. Furthermore, smoothing has been applied, whereas this study did not use any filters for the nitrate budget. In contrast, Oschiles [2002] used an eddy permitting ecosystem-circulation model to examine the climatological nitrate input into the euphotic zone, and found a net horizontal movement and vertical mixing of nitrate into the inter-gyre region, and a net removal of nitrate by vertical advection. The results of Oschiles [2002] are more consistent with the results presented in the current study; but there is no consideration of temporal trends. While the MITgcm.NA does capture observed chlorophyll trends quite well (Figure 3), which provides critical validation for the mechanistic drivers of the observed changes (Figure 8), it would still be of great value to further explore the physical drivers of observed chlorophyll trends in an eddy resolving model for this same time period.

Lovenduski *et al.* [2013] found that by updating the GM parameters to vary with time, eddy-induced advection and diapycnal mixing of dissolved organic carbon was able to be captured more accurately in the Southern Ocean than with constant GM eddy mixing parameters. In order to better understand exactly what is causing along-isopycnal nitrate movement in this model, the next step in this study is to use an updated version of this numerical model from which GM terms have been output so that the spatial pattern of change in along-isopycnal nitrate mixing can be elucidated.

The wind stress at 45 °N and Gyre Index change simultaneously according to the correlation analysis, which is consistent with the wind-driven gyre mechanism as surface waters are forced directly by the surface winds. The 12 month lag between the wind stress at 45 °N and the zonal velocities of the Gulf Stream at 45-50 °N suggests a long adjustment process and is consistent with Sirven [2005]. Sirven [2005] used a geostrophic 1.5-layer

model of the ocean to understand the lag times of the mid-latitude ocean western boundary currents to wind stress variations, and found a response time lag between zero and four years due to a combination of surface Ekman response (shorter timescales) and Rossby wave propagation (longer timescales). Sirven [2005] also found this to be consistent with a range of other studies. The 3 month lag between nutrient stream nitrate transport and chlorophyll concentrations in the inter-gyre region suggests a delayed biological response to nitrate consumption, consistent with seasonal lag following maximum wind speeds that cause enhanced biological drawdown in winter.

A wind-driven spin-down of the North Atlantic gyres has been studied previously [Häkkinen and Rhines, 2004; Hátún *et al.*, 2005; Lozier *et al.*, 2008]. Häkkinen and Rhines [2004] found a spin-down of the North Atlantic gyre through satellite altimetry data over 1992-2002. Hátún *et al.* [2005] found a declining Gyre Index over 1995-2005, which is consistent with the findings in this study. The duration of the Gyre Index decline may indicate that a wind-driven spin-down may be due to an atmospheric trend that exists on longer timescales than the North Atlantic Oscillation or Atlantic Meridional Oscillation.

5. CONCLUSIONS

In order to understand the decrease in surface chlorophyll concentrations seen in the satellite record from 1998-2006 in the North Atlantic inter-gyre region, a regional configuration of the MIT general circulation model was employed to understand the influence of light and nutrients on chlorophyll concentrations. Sverdrup's critical depth hypothesis is supported on seasonal timescales, but interannually, horizontal advection and mixing of nutrients drives change in chlorophyll concentrations in the model. These modeled chlorophyll changes have the same relative magnitude and spatial pattern as observed from SeaWiFS ocean color. In the model, horizontal advection of nutrients is on the same order of magnitude as vertical nutrient advection, which supports findings from studies such as Dave and Lozier [2010], Lozier *et al.* [2011], and Williams *et al.* [2006]. However, horizontal mixing dominates over all other transport processes, which means that not only does the horizontal movement of nutrients, in addition to the vertical, need to be taken into account in further studies, but the isopycnal mixing of nutrients is also important. Studies of models with explicit resolution of mesoscale eddies would be valuable to better understand nutrient movement.

Over the period 1998-2006, all nutrient transfer processes decrease in strength. In the MITgcm.NA, these changes are due to a wind-driven spin-down of the North Atlantic gyres, which led to decreased horizontal nitrate transport into the inter-gyre region and a decline in the slopes of isopycnals. Both changes led to fewer nutrients available for phytoplankton growth, and caused a decrease in chlorophyll concentrations.

Next steps for this work include utilizing an idealized sector model [Lovenduski and Ito, 2008] with Dr. Nicole Lovenduski at the University of Colorado Boulder in order to isolate the impacts of wind stress change on nutrient transport mechanisms. An updated model simulation of the MITgcm.NA will be used to elucidate nitrate transport beyond 2006 in addition to outputting Gent-McWilliams horizontal mixing terms for further analysis. This newer model output explicitly calculates nutrient fluxes at all time steps, which will eliminate the need to residually estimate the horizontal mixing fluxes and reduce uncertainty that stems from neglecting nonlinearities in monthly advection calculations. In future studies, analysis performed in this study could be extended to include the impact of gyre spin-down on air-sea carbon fluxes and anthropogenic carbon uptake by the ocean.

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TABLES AND FIGURES

Table 1. Correlations for the wind stress in the x-direction at 45 °N (τ_x), the Gyre Index (the first principle component of surface currents from 20-70 °N, 0-80 °W), the velocity of the Gulf Stream between 45-50 °N, nitrate transport ($u^*[\text{NO}_3]$) by the Gulf Stream between 45-50 °N and down to 380.2 m, and surface chlorophyll concentrations in the 40-60 °N, 20-40 °W region. All correlations are significant at the 95% confidence level. Italicized correlations indicate a 12 month lag, bold correlations indicate a 3 month lag, and underlined correlations indicate a 15 month lag.

	τ_x	Gyre Index	Gulf Stream u Velocity	$u^*[\text{NO}_3]$	Chlorophyll Concentrations
τ_x	1.00	--	--	--	--
Gyre Index	0.92	1.00	--	--	--
Gulf Stream u Velocity	<i>0.45</i>	<i>0.68</i>	1.00	--	--
$u^*[\text{NO}_3]$	<i>0.64</i>	<i>0.78</i>	0.87	1.00	--
Chlorophyll Concentrations	<u>0.63</u>	<u>0.69</u>	0.51	0.69	1.00

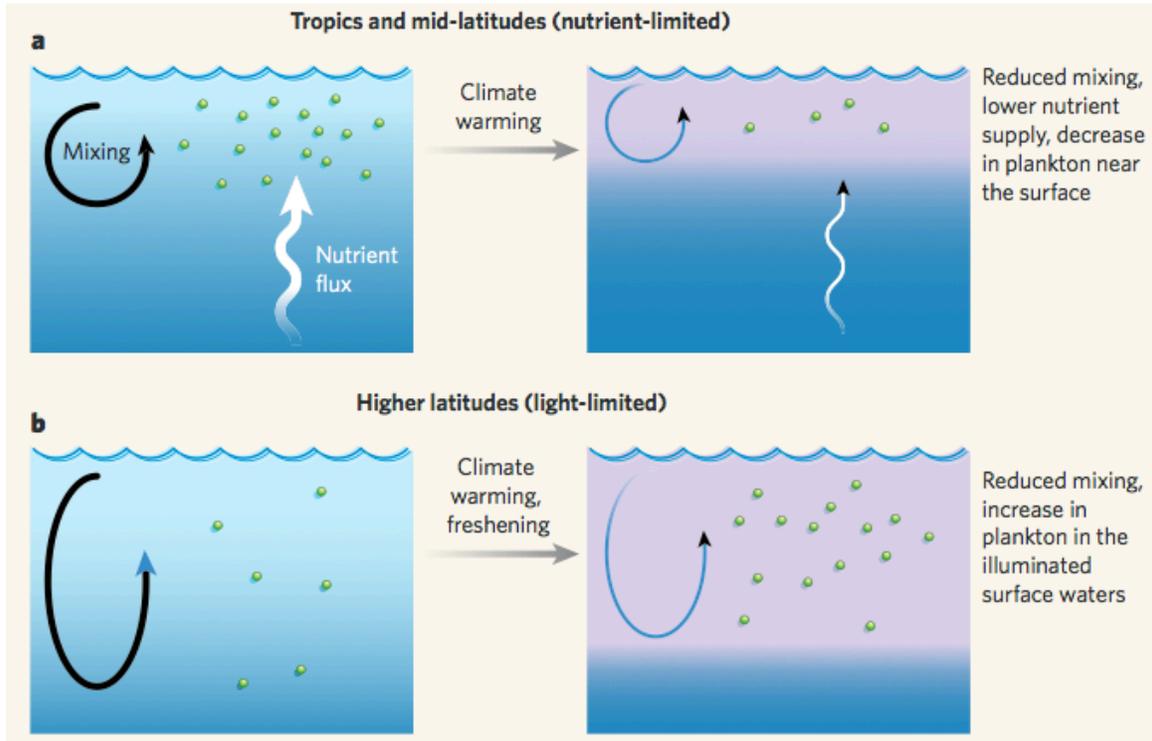


Figure 1. Schematic illustrating the impacts of reduced mixing due to increased stratification from increased surface heating on phytoplankton populations in the nutrient-limited tropics (a) and light-limited polar regions (b). From Doney [2006].

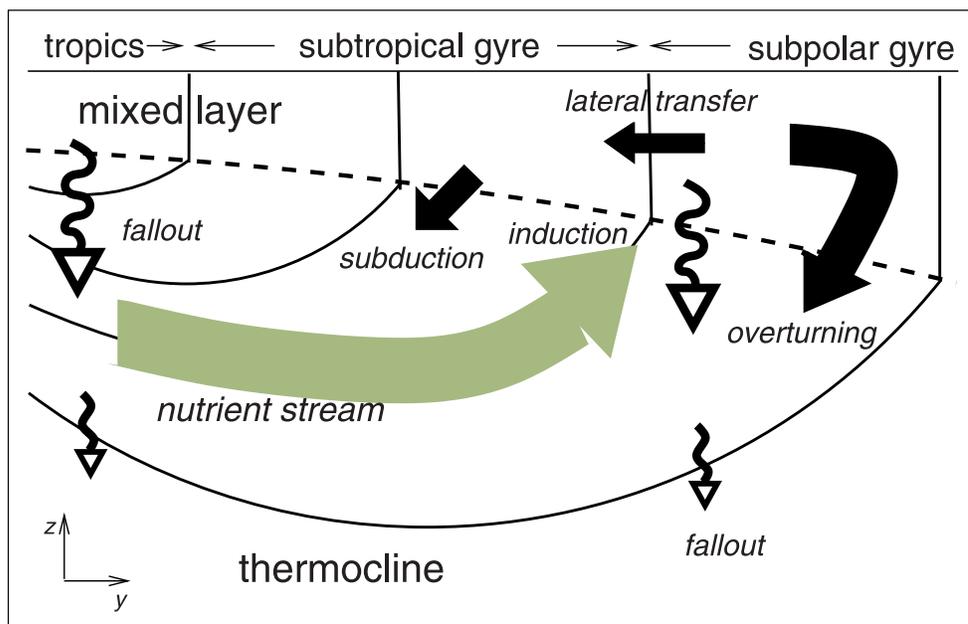


Figure 2. An illustration of the multiple processes that contribute to nutrient transport in the ocean. These processes include lateral transfer within the mixed layer (mixed layer depth denoted by dotted line), induction and subduction along isopycnals (isopycnals denoted by solid lines) from the mixed layer to the permanent thermocline, and nutrient streams (green arrow), which transport nutrients from the tropics to the subpolar gyre. From Williams *et al.* [2006].

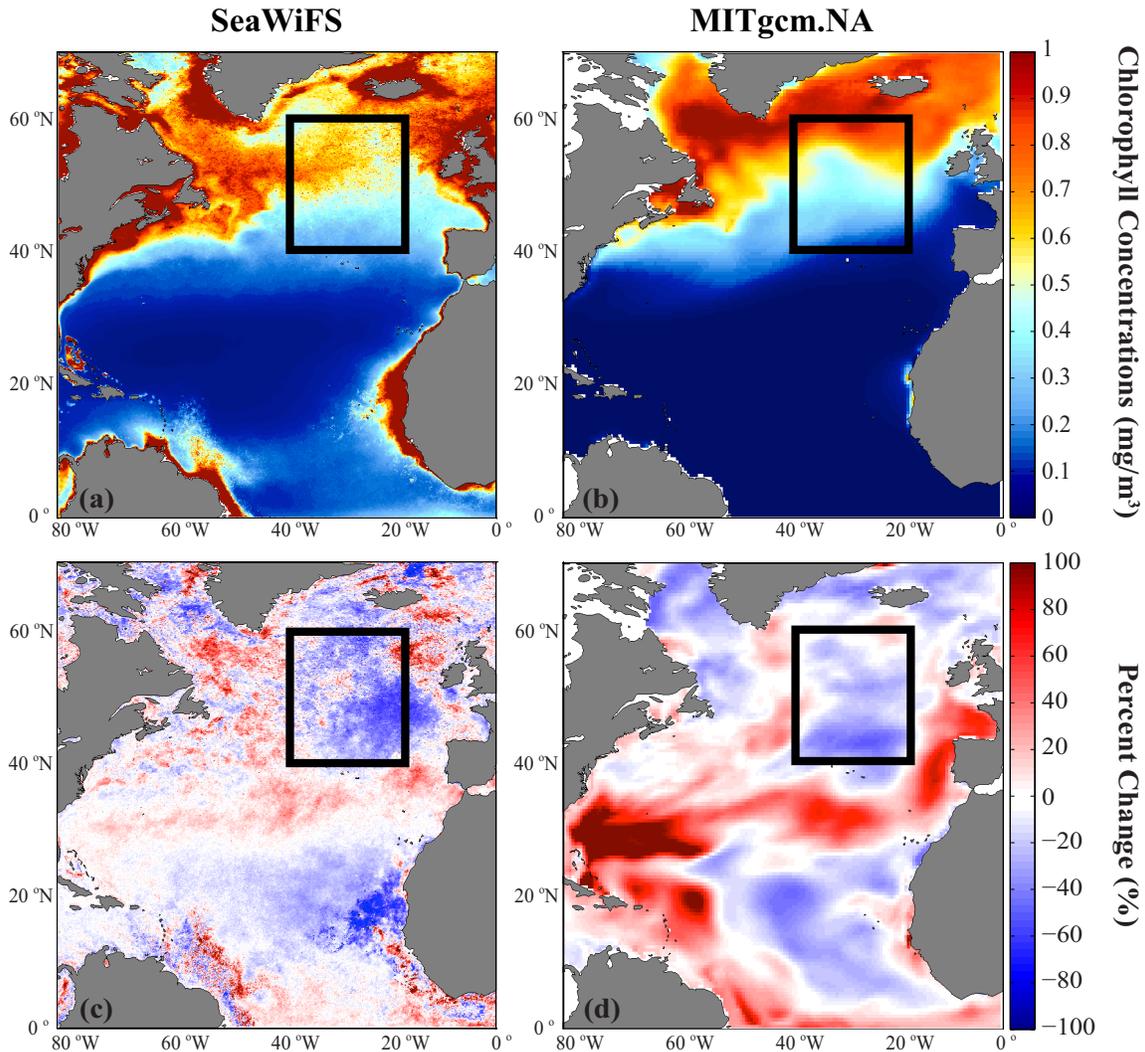


Figure 3. SeaWiFS (a and c) and MITgcm.NA (b and d) mean chlorophyll concentrations (mg/m^3) over 1998-2006 (a and b) and the percent change in chlorophyll concentrations from the 1998-2000 average to the 2004-2006 average (c and d).

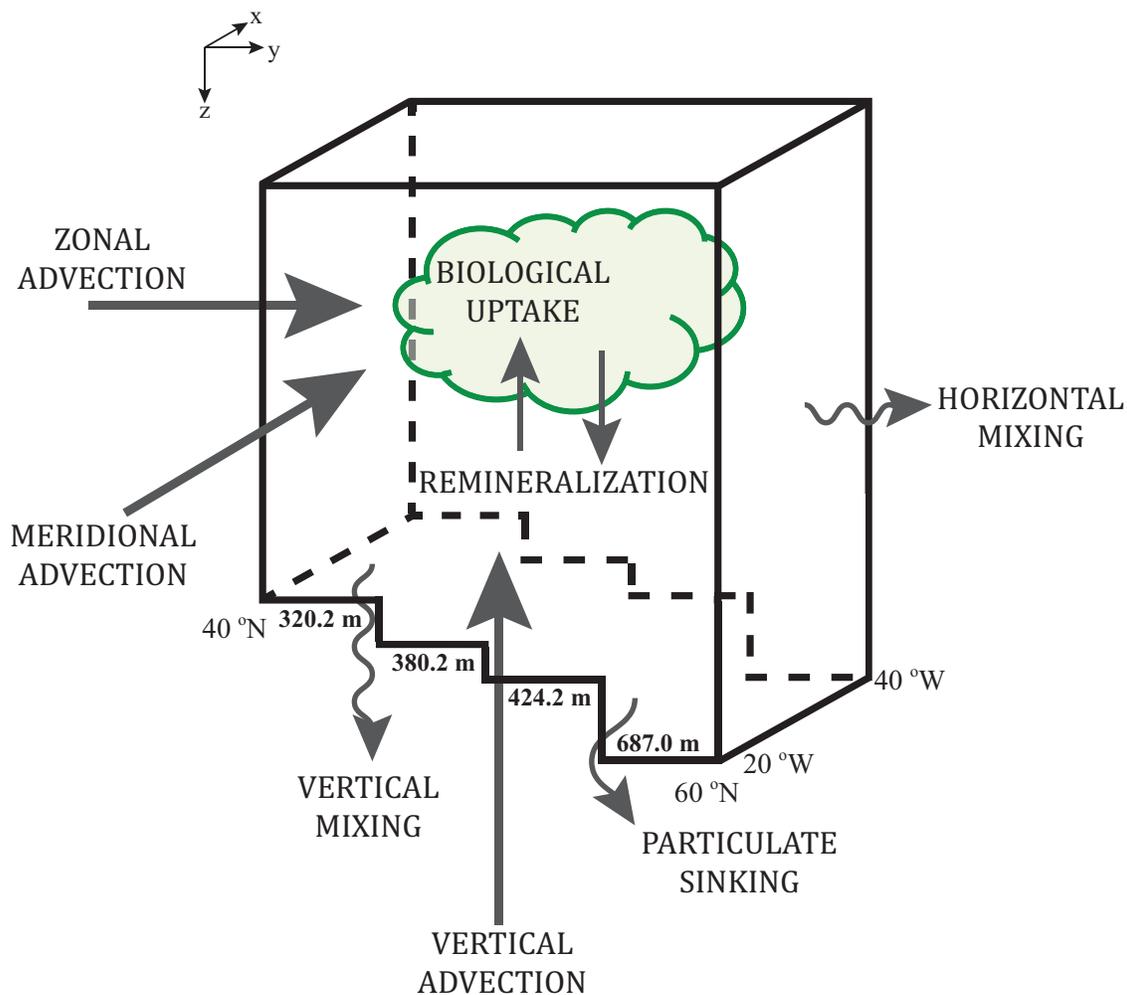


Figure 4. Schematic of the components of the nutrient budget from 40-60 °N, 20-40 °W. For the base of the box, the average maximum mixed layer depths calculated at five degree latitude intervals were used, with exact depths being (from south to north) 320.2, 380.2, 424.2, and 687.0 m.

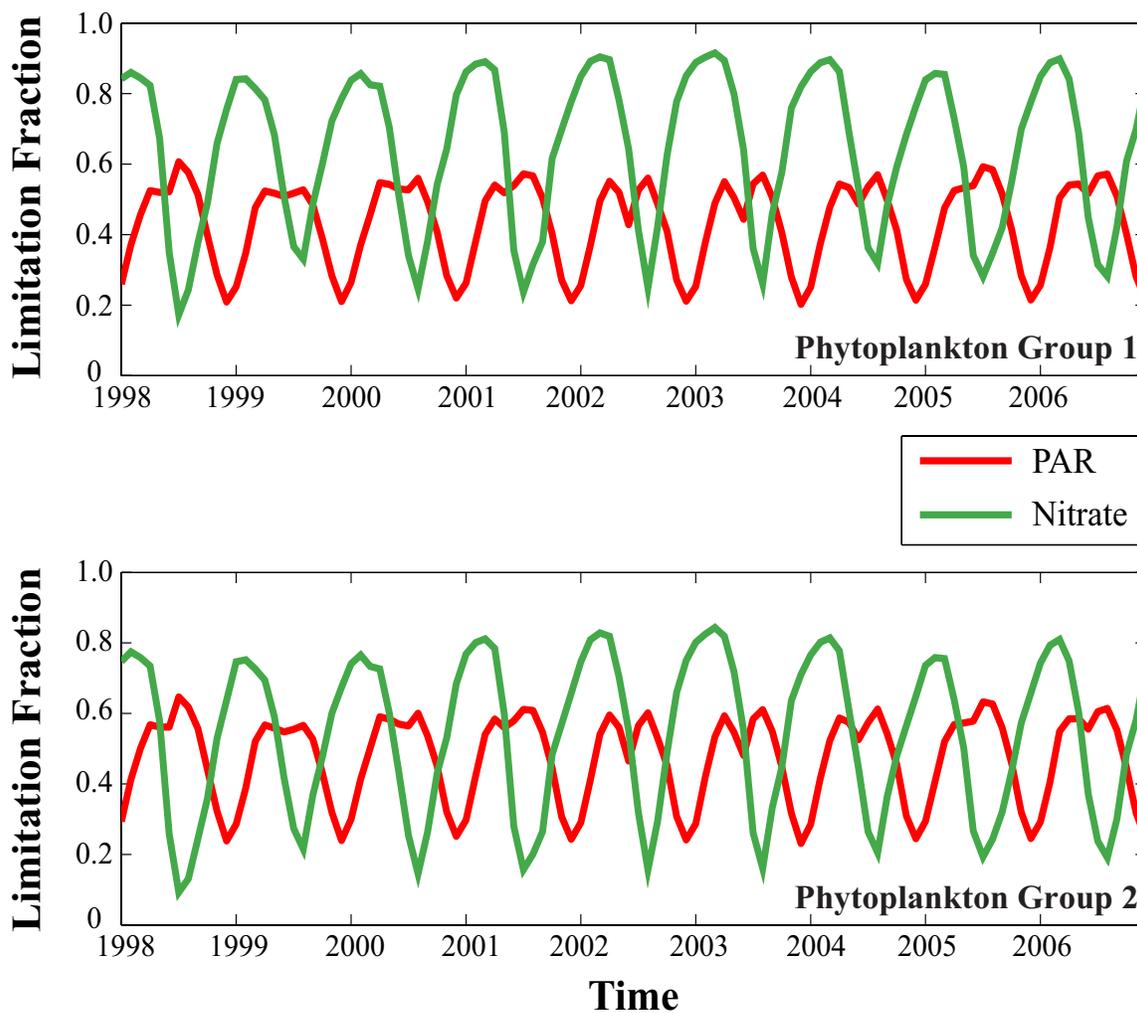


Figure 5. Monthly half-saturation fractions for PAR (red) and nitrate (green) for phytoplankton group one (top) and two (bottom) growth for 1998-2006 over 40-60 °N, 20-40 °W and the top 100 m. The fraction with the lowest value indicates the factor that is limiting phytoplankton growth (Eq. 1).

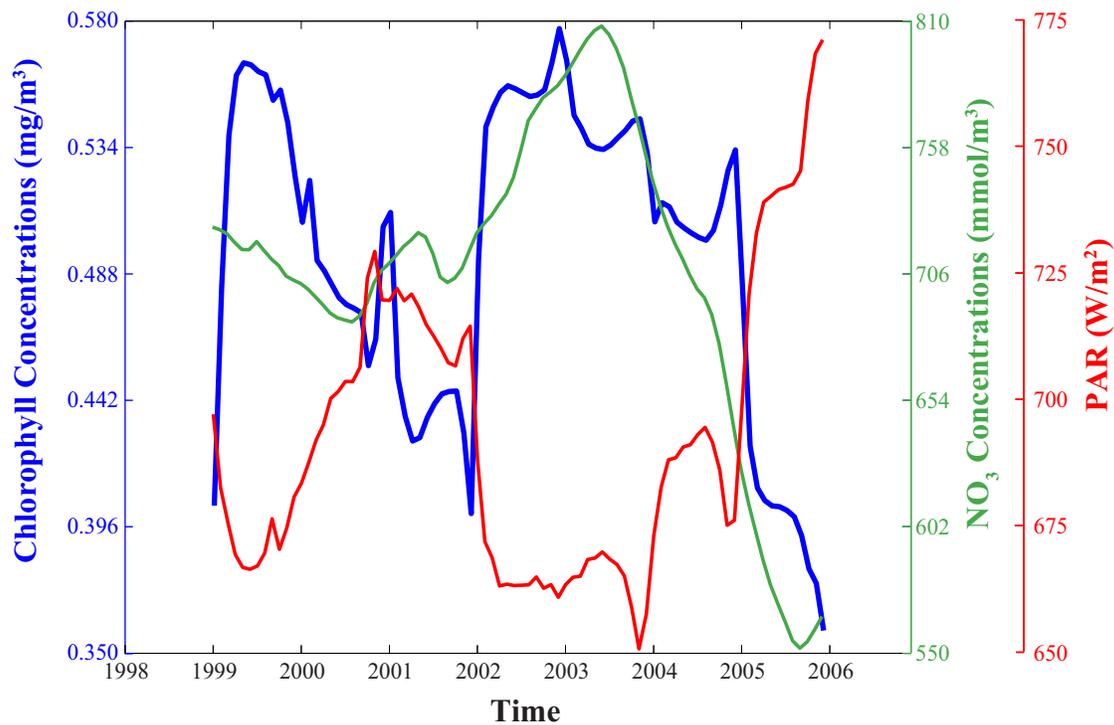


Figure 6. Twelve-month smoothed time series of surface chlorophyll concentrations (mg m^{-3} ; blue), nitrate concentrations (mmol m^{-3} ; green), and PAR (W m^{-2} ; red) over 1998-2006 from MITgcm.NA output over the region of interest, $40\text{-}60^\circ\text{N}$, $20\text{-}40^\circ\text{W}$, and over the top 100 m for nitrate and PAR. Nitrate concentrations have a significantly positive correlation with chlorophyll concentrations ($r = 0.77$, $p < 0.05$) and PAR has a significantly negative correlation with chlorophyll concentrations ($r = -0.94$, $p < 0.05$).

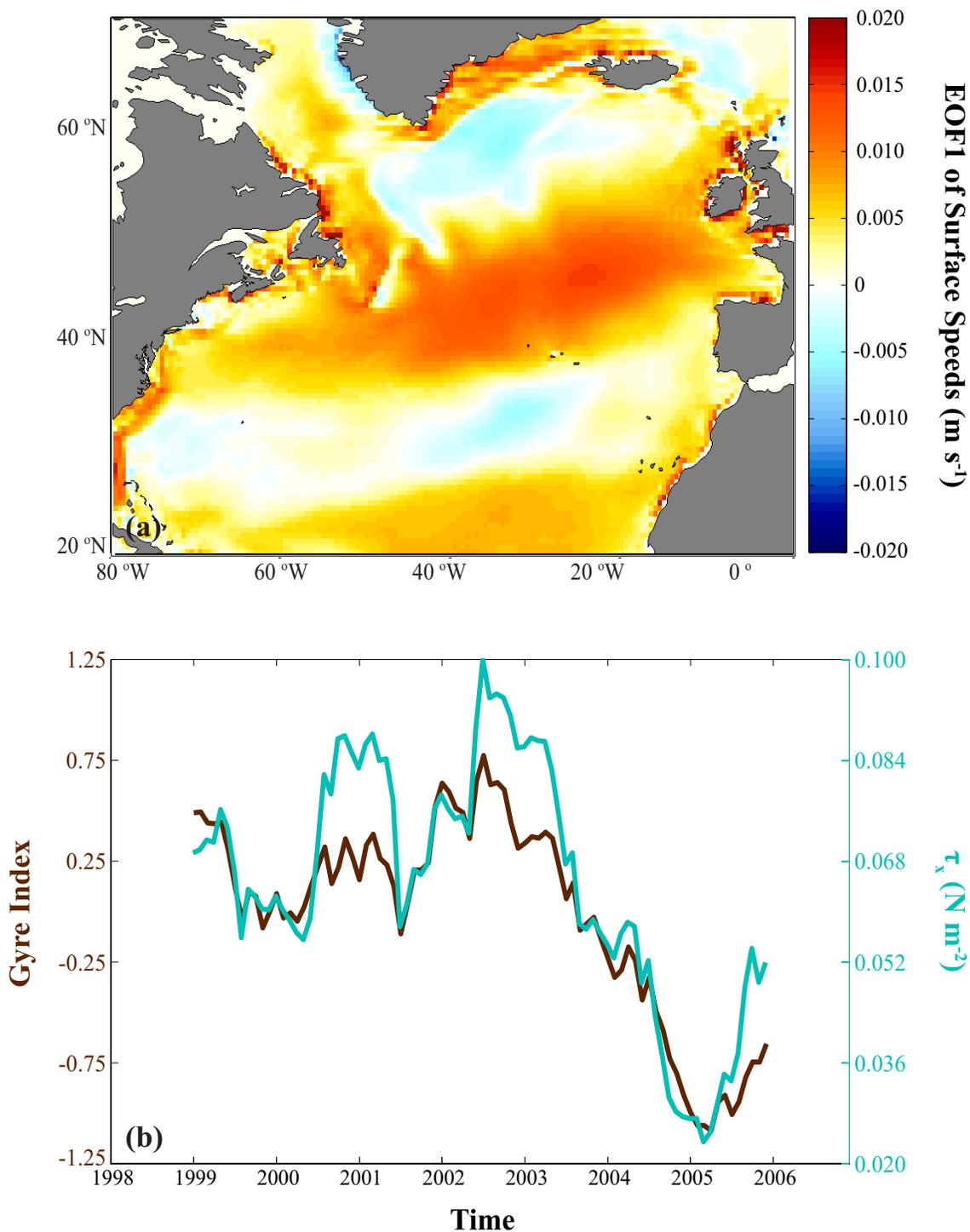


Figure 7. Top (a): First EOF of surface speeds (m s^{-1}) with 14.7% of the variance. Bottom (b): Twelve-month smoothed time series of the Gyre Index (first principle component of surface speeds over 20-70 °N, 0-80 °W) (unitless; brown) and the wind stress at 45 °N (N m^{-2} ; teal) over 1998-2006 from MITgcm.NA output ($r = 0.92$, $p < 0.05$).

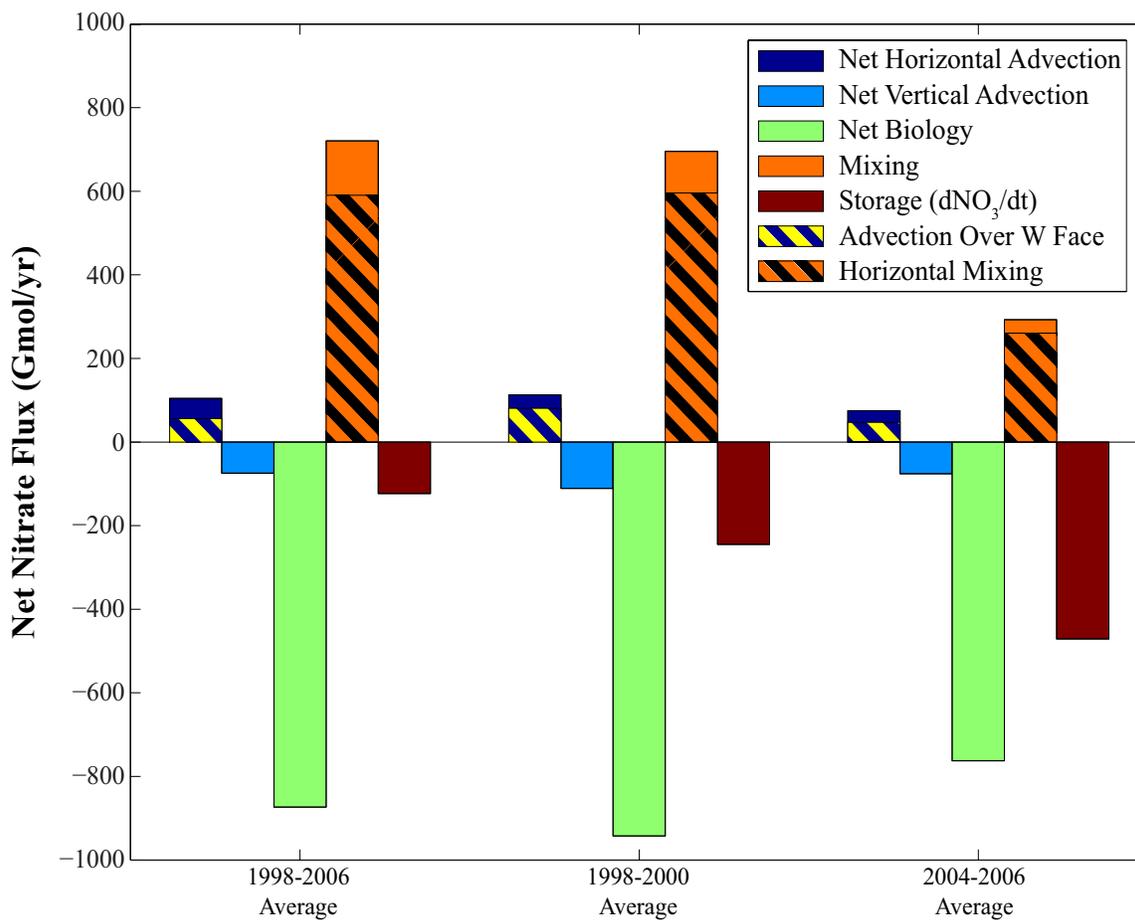


Figure 8. Bar plot showing the net nitrate transport (Gmol yr^{-1}) into and out of the $40\text{-}60^\circ\text{N}$, $20\text{-}40^\circ\text{W}$ box shown in Figure 4 for the 1998-2006 average (left cluster), 1998-2000 average (middle cluster), and 2004-2006 average (right cluster).

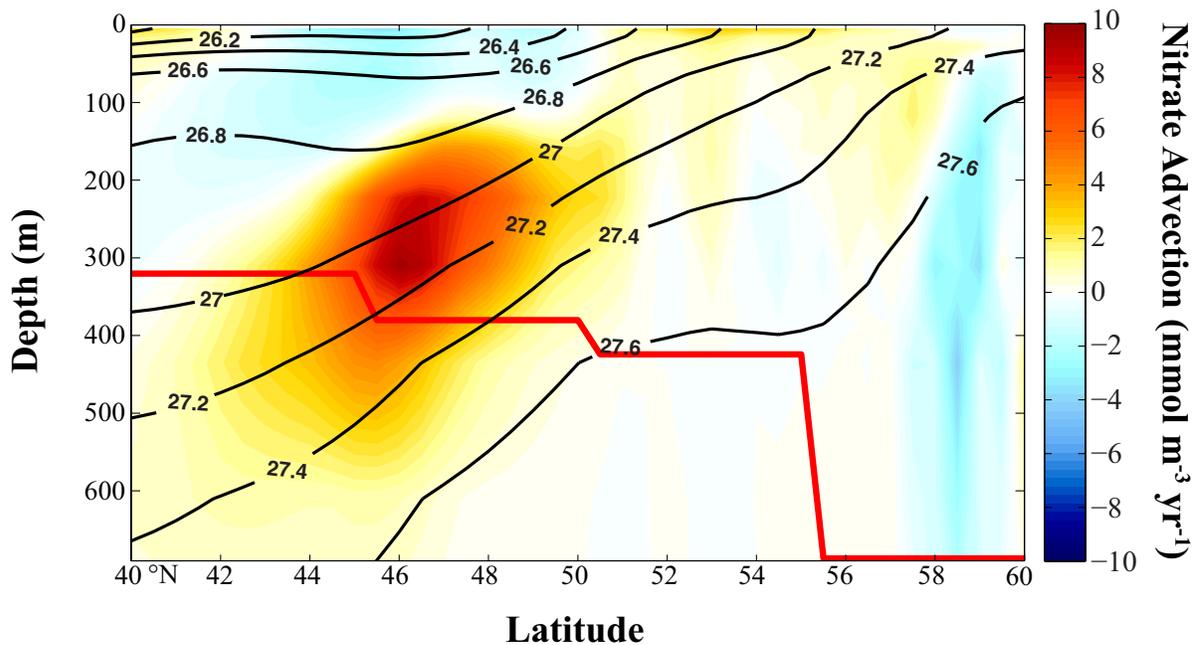


Figure 9. 1998-2006 average nitrate advection ($\text{mmol m}^{-3} \text{ yr}^{-1}$; shading) across 40°W from $40\text{--}60^\circ \text{N}$. Black lines reflect potential density σ (kg m^{-3}) and the red line indicates the base of the annual average maximum mixed layer (m; exact values shown in Figure 4). Positive shading indicates positive nitrate advection into the box.

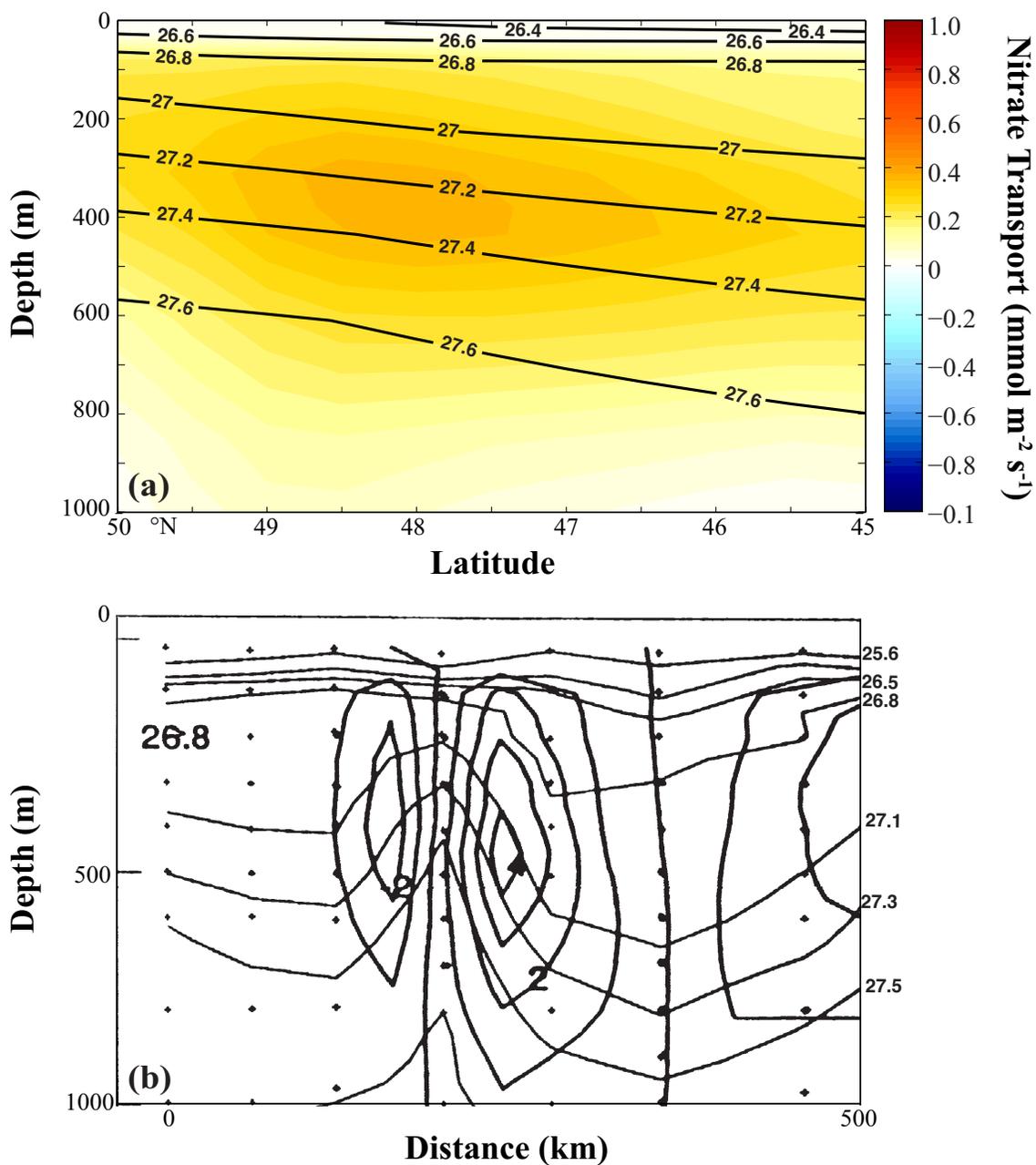


Figure 10. Top (a): 1998-2006 average August nitrate transport (mmol m⁻² s⁻¹; shading) across 40 °W from 45-50 °N. Black lines reflect potential density σ (kg m⁻³). Positive shading indicates positive nitrate transport into the box. Bottom: Nitrate transport (mmol m⁻² s⁻¹; circular contours) across a hydrographic section at 35 °W in August 1983. Thinner lines are σ (kg m⁻³). Adapted from Pelegrí *et al.*, [1996].