Ocean fronts trigger high latitude phytoplankton blooms

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[1] Density fronts are ubiquitous features of the upper ocean. Here, numerical simulations show that restratification at fronts inhibits vertical mixing, triggering phytoplankton blooms in low-light conditions. The stability of the water column at fronts is set by a competition between frontal instabilities, which restratify the upper ocean, and turbulent mixing, which acts to destroy this stratification. Recent studies have found that frontal instabilities can restratify the upper ocean, even in the presence of strong surface cooling and desta-bilizing winds. During winter at high latitudes, primary production by phytoplankton is generally limited by low ambient light levels and deep turbulent mixing. When the turbulent mixing, inhibited by frontal restratification, becomes smaller than a 'critical turbulence' threshold, a phytoplankton bloom can develop. The finding that fronts can trigger phytoplankton blooms by reducing mixing, provides an explanation for satel-lite observations of high chlorophyll concentrations at high latitude fronts. **Citation:** Taylor, J. R., and R. Ferrari (2011), Ocean fronts trigger high latitude phytoplankton blooms, *Geophys. Res. Lett.*, *38*, L23601, doi:10.1029/2011GL049312.

1. Introduction

[2] Free-floating photosynthetic micro-organisms, collec-tively known as phytoplankton, form the foundation of the marine food web. Phytoplankton are responsible for about half the global primary production (PP) [*Longhurst et al.*, 1995] and contribute to the ocean uptake of carbon dioxide [*Longhurst and Harrison*, 1989], which is especially large at high latitudes [*Laws et al.*, 2000; *Takahashi et al.*, 2009]. Oceanic PP does not occur uniformly, but is punctuated by patchy blooms lasting a few weeks [*Dutkiewicz et al.*, 2001]. This heterogeneity in space and time is poorly understood, and it contributes to the uncertainty in global estimates of PP and the ocean carbon uptake. Previous studies [*Lévy et al.*, 2001; *Mahadevan and Archer*, 2000; *Mahadevan and Tandon*, 2006] have found that ocean fronts, separating waters with different densities, can generate intermittent blooms in oligo-trophic subtropical waters by upwelling additional nutrients into the euphotic zone, defined here as the uppermost layer of the ocean with sufficient sunlight to support photosynthesis [*Thurman and Trujillo*, 1999]. Here, we show that fronts can also trigger phytoplankton blooms at high latitudes when growth is more limited by light exposure than nutrient avail-ability. Frontal instabilities lead to a restratification of the upper ocean and reduce the turbulent flux of phytoplankton cells out of the euphotic zone, thereby increasing the mean light exposure. As a result, fronts act as hotspots for biological activity not only in the subtropics, but also in the more highly productive subpolar oceans. This implies that fronts might be crucial players in the ocean ecosystem in subpolar regions where the ocean absorbs large quantities of carbon dioxide from the atmosphere, thereby impacting the global carbon cycle.

[3] An example of a highly productive frontal region cap-tured by the MODIS Aqua satellite is shown in Figure 1. Here, a front is formed when warm waters carried north by the Gulf Stream encounter much colder water brought south in the Labrador Current. The dashed white contour line shows the 1000 m isobath, delineating the southern tip of the Grand Banks, historically one of the most productive fish-eries in the world. The sea surface temperature (SST) indi-cates that the front is dynamically active, with evidence of eddies on scales ranging from 10–100 km. At this time of the year, in early spring, a massive greening event known as the *spring bloom* develops in the subpolar waters across the North Atlantic. The satellite-derived chlorophyll concentra-tion shown in Figure 1 is more than an order of magnitude larger at the front than in the surrounding water, particularly east of −49° longitude, where the front exhibits many fine-scale bends and wrinkles. Since the highest chlorophyll concentrations are localized at the front, they are likely gen-erated by a local process, rather than being advected from another location (the Gulf Stream flows to the east and then bends northward in the region shown in Figure 1).

[4] At high latitudes during winter, the ocean is strongly forced by the atmosphere, leading to a deep surface bound-ary layer (SBL), defined as the region of the upper ocean where turbulence is enhanced by surface forcing. Deep SBLs typically have high nutrient concentrations because they entrain deep nutrient-rich waters as they form. Despite having abundant nutrients, deep SBLs can inhibit phyto-plankton growth by mixing phytoplankton cells below the euphotic zone, away from abundant light. Light limitation is particularly strong during high latitude winters when SBLs are deep and incident light levels are low. The timing of the spring bloom has traditionally been associated with the shoaling of the SBL at the end of winter [*Gran and Braarud*, 1935; *Sverdrup*, 1953]. According to the critical depth hypothesis, the spring bloom begins when the SBL becomes shallower than a 'critical depth'. *Sverdrup* [1953] derived an expression for the critical depth, under the assumption that phytoplankton cells are well-mixed in the SBL. Recently, [*Taylor and Ferrari*, 2011] extending the work of *Huisman et al.* [1999], suggested that the onset of the spring bloom is more closely associated with a reduction in turbulent mixing caused by changes in the atmospheric forcing. While this hypothesis has skill in predicting the overall timing of the spring bloom, it does not explain the intensification of PP and high chlorophyll levels at fronts.

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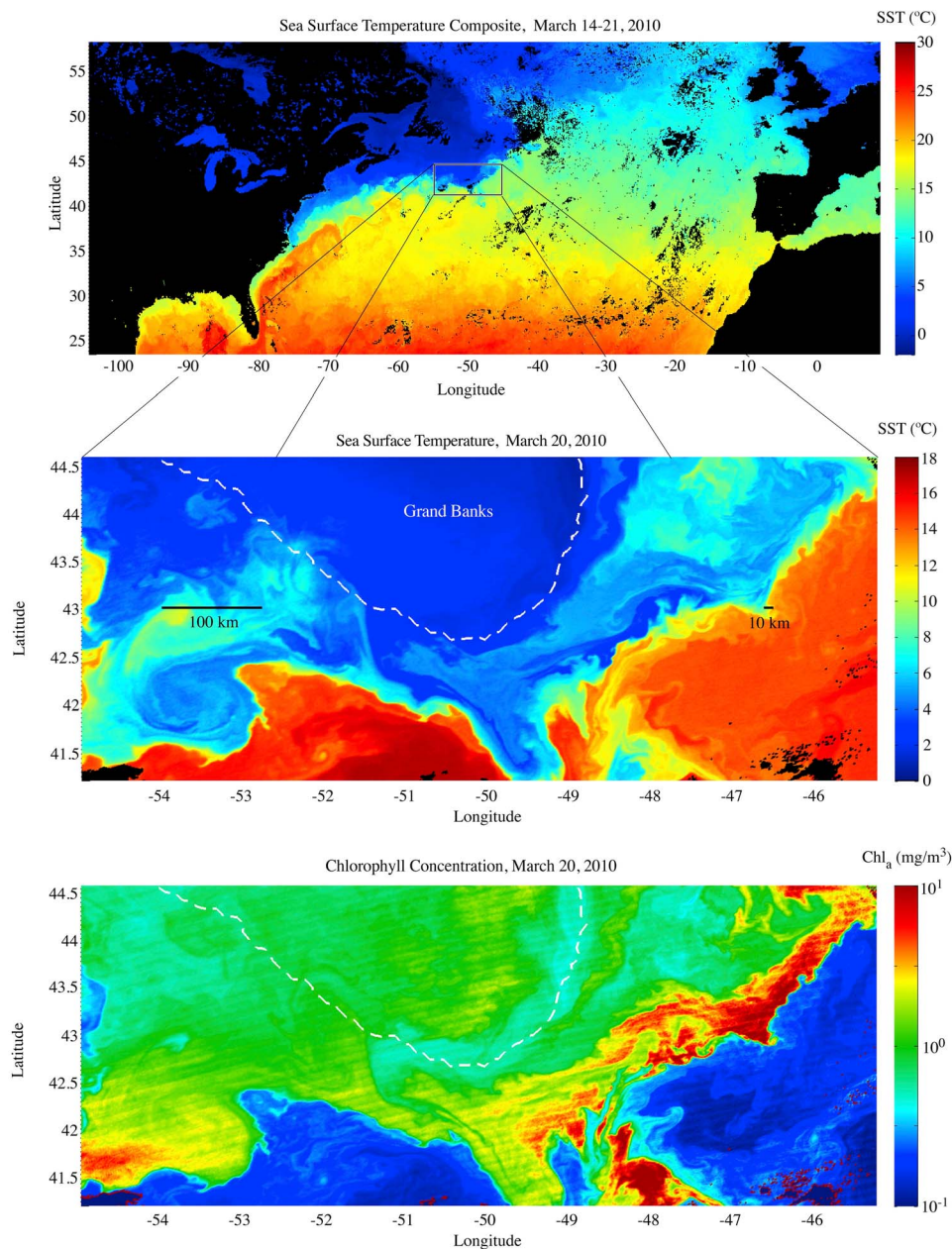
Figure 1. An example of a highly productive front captured by NASA's MODIS Aqua satellite. (top) A weekly composite of the sea-surface temperature (SST), and daily images of (middle) SST and (bottom) inferred Chlorophyll concentration in the highlighted region. The dashed white line shows the 1000 m isobath. The frontal zone is dynamically active on a range of scales from $O(10 - 100\ km)$. At the same time, the chlorophyll concentration is much higher at the front than in the surrounding water, indicating that this front is richly productive.

[5] We hypothesize that fronts are hotspots for the development of blooms through a suppression of vertical mixing by frontal dynamics. In a non-rotating fluid, the hydrostatic pressure gradient associated with horizontal changes in density would cause a front to quickly restratify, with water on the light side of the front flowing over the top of the dense water. In the ocean, the hydrostatic pressure gradient is often in geostrophic balance with the Coriolis acceleration associated with the Earth's rotation [e.g., *Tandon and Garrett*, 1995; *Rudnick and Luyten*, 1996]. However, this equilibrium is unstable, and in the absence of forcing, frontal instabilities cause the front to restratify, albeit at a slower rate than in the non-rotating case. This restratification, in turn, reduces the vertical mixing within the frontal zone. According to the critical turbulence hypothesis [*Huisman et al.*, 1999], weak vertical mixing reduces the flux of phytoplankton cells out of the euphotic zone. A bloom can then develop when the increase in biomass due to photosynthesis outpaces the loss of cells in the euphotic zone from downward mixing, sinking, grazing, and other losses.

[6] Here, we focus on two very common types of frontal instability, namely symmetric and baroclinic instability, and
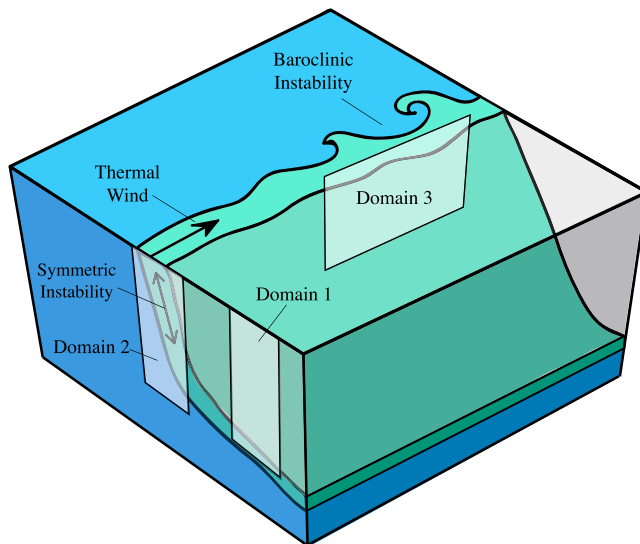
Figure 2. Schematic of a frontal zone separating water masses with two different densities. Initially, the along-front thermal wind balances the tilted density surface. In time, however, the front becomes unstable first to symmetric instability, and later to baroclinic instability, both resulting in an increase in the stratification. Three shaded regions indicate the domains used in the simulations shown in Figure 3. Domain 1 is assumed to be far enough away from the front that its effects are not felt, while Domains 2 and 3 are embedded within the frontal zone.

examine their impact on mixing in the SBL and phytoplankton growth. The characteristics of both instabilities have been described in previous studies, [e.g., *Stone*, 1966; *Boccaletti et al.*, 2007; *Taylor and Ferrari*, 2009]. Previous studies have also shown that these frontal instabilities are capable of restratifying the upper ocean, even in the presence of strong surface heat loss and winds [*Fox-Kemper et al.*, 2008; *Mahadevan et al.*, 2010; *Taylor and Ferrari*, 2010; *Thomas and Taylor*, 2010]. Here, we consider turbulence generated by convection forced by an ocean heat loss to the atmosphere. We will show that a front of moderate strength (~0.25°C/km), forced by surface cooling of −100 W/m², reduces the vertical mixing rate enough to trigger a phytoplankton bloom. In comparison, the largest SST gradients at the Gulf Stream front shown in Figure 1, are ~2°C/km. In the auxiliary material, we summarize previously-derived scalings for symmetric and baroclinic instability, and compare the frontal restratification to destabilizing atmospheric forcing for other physical parameters.[1]

[7] The reduction in vertical turbulent mixing at fronts does not contradict the well-established observation that fronts are regions of enhanced upwelling of nutrients towards the surface. We find that the rate of vertical mixing *in the SBL* is reduced compared to an unstratified boundary layer, following the development of stratification. Symmetric and baroclinic instability drive motions that are very effective at transporting fluid properties along density surfaces, or isopycnals. However, the relatively shallow isopycnal slope, following restratification, suppresses *vertical*

mixing. At the same time, circulations associated with the formation and instability of the front extend into the thermocline, and draw nutrient-rich fluid into the SBL [*Thomas et al.*, 2008]. The reduction of vertical mixing in the SBL at fronts increases light exposure and leads to blooms in light-limited regions, while the upwelling of nutrients into the SBL leads to blooms in nutrient-limited conditions.

2. Numerical Simulations

[8] Numerical simulations provide a means to test the hypothesis that reduced mixing at fronts can trigger phytoplankton blooms. The simulation domains shown in Figure 2 were chosen to examine the response of a phytoplankton population to distinct frontal dynamics. Domain 1 is assumed to be far enough away from the front so that its effects are not felt, while Domains 2 and 3 are embedded within the frontal zone. Each stimulation starts with a mixed layer of uniform density and depth $H = 150$ m, and a linearly stratified fluid below. The strength of the front, measured by the horizontal density gradient, is constant in each simulation. Turbulence is generated by cooling the surface with a constant heat flux of $Q_0 = -100$ W/m². The phytoplankton concentration is initially uniform in the mixed layer ($P = P_0$) with no phytoplankton below the mixed layer. Based on the phytoplankton growth and loss rates used in the simulations (see auxiliary material, equation (S9)), the critical depth, $H_C = 100$ m, is shallower than the mixed layer depth, and according to the critical depth hypothesis [*Sverdrup*, 1953], net losses should outpace phytoplankton growth.

[9] Initially, the front is in equilibrium, with the lateral pressure gradient due to changes in density balanced by the Coriolis acceleration associated with an along-front flow. This equilibrium is unstable, and the front proceeds to slump in a two-step process. In the first stage, the front becomes unstable to symmetric instability, which has recently been observed at the Kuroshio [*D'Asaro et al.*, 2011] and Gulf Stream fronts (L. Thomas et al., Symmetric instability in the Gulf Stream, submitted to *Deep Sea Research*, 2011). By definition, symmetric instability is independent of the along-front direction, and it is captured in the two-dimensional slice of Domain 2. Later, meanders and eddies develop along the front, and slumping accelerates as a result of baroclinic instability. Although the eddies that eventually develop are three-dimensional, the most unstable modes of the instability are independent of the cross-front direction [*Stone*, 1970]. Since Domain 3 is a two-dimensional slice in the along-front and vertical directions, our analysis strictly applies only to the early stages of baroclinic instability, before strong three-dimensionality develops. Using two-dimensional slices has the advantage that only one frontal instability can develop in each simulation and allows for a cleaner discussion of the dynamics. Coupling between the various instabilities and three-dimensional effects will be important to examine in a future study, but they are not likely to alter the basic conclusions discussed below.

[10] In Domain 1, far from the front, the phytoplankton concentration remains well-mixed in the SBL, and decreases in time, in agreement with the prediction from Sverdrup's critical depth theory. After 6 days, the phytoplankton concentration is about 17% lower than its initial value in Domain 1, as shown in Figure 3. In contrast, the phytoplankton response is fundamentally altered by the front. In Domains 2 and 3, the SBL

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL049312.
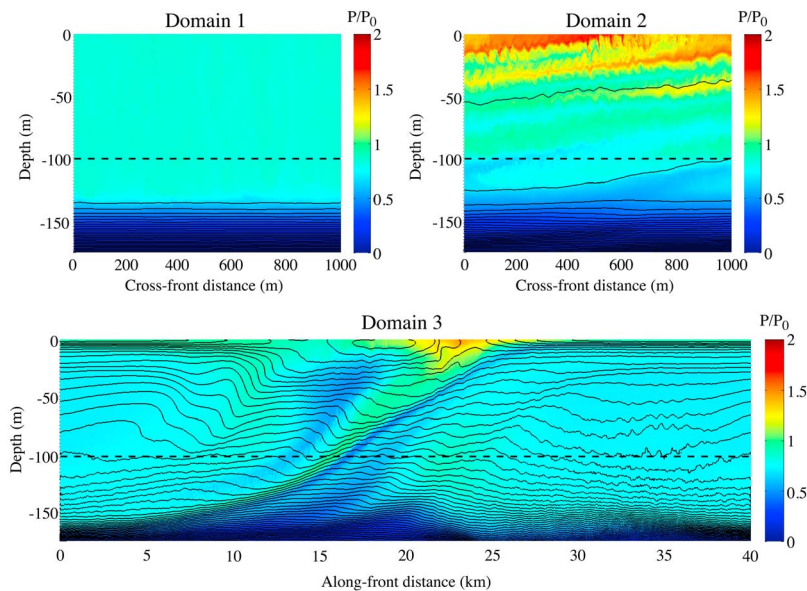
Figure 3. Numerical simulations in three two-dimensional slices though a frontal zone as illustrated in Figure 2. The phytoplankton concentration (color) and density contours (black) are shown after 6 days. In each simulation, the initial SBL depth ($H = 150$ m) was deeper than the critical depth ($H_c = 100$ m), indicated by the dashed black line. Isopycnals are plotted at an interval of 0.1 kg/m^3. The initial phytoplankton concentration was uniform in the SBL $P = P_0$, with $P = 0$ below the SBL. Unlike Domain 1 which is outside of the frontal region, a bloom develops in the frontal zones of Domains 2 and 3.

restratifies, and the phytoplankton grow near the surface where light is more abundant. Previous studies [*Huisman et al.*, 1999; Taylor and Ferrari, submitted manuscript, 2011] have shown that phytoplankton growth is possible when the turbulent diffusivity, a measure of turbulent mixing, drops below a critical value. Using the parameters from the simulations shown in Figure 3, the critical turbulent diffusivity is $\kappa_c \simeq 9 \times 10^{-3}$ m^2/s (see auxiliary material). Far from the front, in Domain 1, the turbulent diffusivity resulting from surface cooling is $\kappa_T \simeq 3 \times 10^{-1}$ m^2/s, much larger than the critical value. In comparison, the turbulent diffusivity is much smaller in the frontal zone, with $\kappa_T \simeq 8 \times 10^{-3}$ m^2/s in Domain 2 and $\kappa_T \simeq 1 \times 10^{-2}$ m^2/s in Domain 3. The formation of surface-intensified blooms in Domains 2 and 3 is consistent with the fact that κ_T is less than or close to the critical turbulence level.

[11] The reduction in the rate of vertical mixing at fronts can be viewed as a consequence of the vertical stratification that develops in the SBL as the inclined isopycnals at the front slump in response to frontal instabilities. In Domain 1, convective plumes transport phytoplankton from the surface to the base of the SBL, mixing rapidly in the vertical direction. In Domains 2 and 3, the turbulent velocities are comparable or larger than those in Domain 1, but the dominant motion is now oriented along the isopycnals. Mixing of phytoplankton slows down because it takes much longer to transport biota away from the surface along very slanted trajectories - the aspect ratio of the isopycnals is very small. The restratification process is noticeably different in Domains 2 and 3. Symmetric instability quickly restratifies the boundary layer in Domain 2, but the level of stratification remains relatively weak. In this case, the stratification develops over the first 12 hours until the isopycnal slope is about 1/30, at which point restratification ceases. In Domain 3 the SBL remains unstratified for about 2 days, until baroclinic instability develops. After this stage,

the SBL quickly restratifies, and by day 6 the isopycnal slope is much shallower than in Domain 2, about 1/250. Notice that the turbulent diffusivity is slightly smaller in Domain 2 than Domain 3, and therefore is not purely a function of the level of restratification, but depends on details of the frontal dynamics. The scalings discussed in section 2 of the auxiliary material predict when frontal instabilities will be able to restratify the SBL, but do not directly predict the level of vertical mixing. Parameterizing the vertical mixing at fronts will be an important step towards improving biogeochemical models, but this is beyond the scope of the present study.

3. Discussion

[12] Permanent fronts like the Gulf Stream, shown in Figure 1, are confined to a few regions like the western boundaries of midlatitude oceans and the Southern Ocean. While we expect these exceptionally large fronts to support phytoplankton blooms, the dynamical processes described here should apply much more generally. A network of fine 'sub-mesoscale' fronts on scales of 1–10 km are found in many regions of the ocean [*Lévy et al.*, 2001; *Capet et al.*, 2008; *Klein and Lapeyre*, 2009]. While the density difference across sub-mesoscale fronts is much smaller than large fronts like the Gulf Stream, the more dynamically relevant quantity, the horizontal density *gradient*, can still be large since the density change occurs over a short distance. The strength of submesoscale fronts is commonly comparable to, or even larger than, the value considered here [*Capet et al.*, 2008].

[13] Reduced vertical mixing and enhanced mean light exposure at fronts provides a means for phytoplankton populations to survive high-latitude winters in sufficient numbers to re-emerge in the spring. Several previous studies have proposed mechanisms for the persistence of a small phytoplankton

population in winter [*Huisman et al.*, 2002; *Backhaus et al.*, 2003; *Ward and Waniek*, 2007], but none considered the role of spatial heterogeneity. Fronts could maintain the wintertime phytoplankton population by locally enhancing mean light exposure and supporting intermittent mid-ocean blooms. It has been speculated that fronts play a similar role in oligotrophic subtropical waters by drawing more nutrients into the euphotic zone, triggering patchy blooms [*Lévy et al.*, 2001; *McGillicuddy et al.*, 2007; *Mahadevan et al.*, 2008]. In both cases fronts act like oases, allowing the phytoplankton population a temporary respite in an otherwise forbidding environment.

[14] The mechanism described here is particularly relevant to high latitudes where light exposure is often a more limiting factor than nutrient availability. Since subpolar regions are generally more productive than the subtropics [*Lévy*, 2005], this mechanism could have a strong impact on the global PP. Reduced mixing at fronts also allows blooms to develop earlier in the season when the SBL is deeper than the critical depth, as seen in Figure 3. Previous work has found that early blooms in deep SBLs are capable of generating significantly more biomass than shallow blooms [*Stramska et al.*, 1995]. Through this mechanism, blooms at high latitude fronts could increase the ocean uptake of carbon dioxide and play an important role the global carbon cycle.

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