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The effect of frontal features on chlorophyll concentration within the Kuroshio

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NONTECHNICAL SUMMARY

Physical features in the ocean created by winds and currents affect the productivity of the surrounding area. Frontal disturbances and upwelling eddies that draw nutrients up from deep water sustain higher levels of chlorophyll concentration, which can be used as a proxy to estimate the rate of carbon production. The Kuroshio is a northerly flowing western boundary current that flows off the coast of Japan. Chlorophyll and nitrate concentrations were measured down to 300 m from sample bottles at stations along a cruise track from 29° N, 145° E to 41° N, 150° E from 25 February to 17 March 2013. Continuous surface measurements of chlorophyll, nitrate, and sea surface temperature (SST) were observed, along with satellite images of SST and sea surface height (SSH). The data were studied in order to reveal a relationship between chlorophyll concentrations and SST. Surface chlorophyll concentrations reached 0.593 μg L^{-1} within a front, more than twice the average chlorophyll concentrations south of 34 °N. Chlorophyll concentrations were increased within this specific area due to the physical processes that increased stratification and raised nutrient rich waters from depth.

ABSTRACT

Frontal features enhance biological production within the Kuroshio. Reoccurring frontal disturbances can form throughout the year and influence the biogeochemical cycle within the region. In situ measurements of temperature, salinity, nitrate, and chlorophyll from CTD casts were analyzed over a cruise transect from 29° N, 145° E to 41° N, 150° E within the Kuroshio from 25 February 2013 to 17 March 2013. Continuous surface measurements of temperature, chlorophyll, and nitrate were also gathered. Satellite images of sea surface temperature (SST) and sea surface height (SSH) were paired with in situ data to study the effects that nutrient rich, frontal water masses might have on chlorophyll concentrations. The data revealed a frontal feature from 34.5-35.7 °N that expressed a sudden drop in SST, and surface chlorophyll values that reached 0.593 μg L^{-1}, more than twice the average chlorophyll concentrations south of 34 °N. These values were comparable to chlorophyll concentrations of 0.40 μg L^{-1} in a cyclonic eddy shed from the Kuroshio at the Luzon Straight bordering the South China Sea (Chen et al. 2007). Within this front, SST was correlated to sea surface salinity ($R^2 = 0.92006$), surface chlorophyll ($R^2 = 0.75113$), and surface nitrate ($R^2 = 0.72998$). As the Kuroshio shifts its position over time, these data will provide a baseline for the location of the Kuroshio, the north-south SST gradient, and chlorophyll and nutrient concentrations in the late winter of 2013.

INTRODUCTION

Previous studies have found that oceanic fronts form when northerly flowing warm-water currents encounter southerly flowing cold-water currents, such as the Kuroshio and the Oyashio in the North Pacific (Taylor and Ferrari 2011). Cold-core eddies may form in the Kuroshio when a "finger" of warm water meanders from the current stream and folds back to enclose an eddy of cold water. This has been reported in the Gulf Stream, another western boundary current (Yoder et al. 1981). Frontal disturbances in the Kuroshio form with wavelengths of 100, 200, and 400 km and with periods of 5-8, 10-12, and 17-19 days, respectively (Kimura and Sugimoto 1993). These eddies and fronts form regions of high nutrient and chlorophyll concentrations that support those species that can feed directly on phytoplankton, such as sardine and anchovy larvae near the Enshu-nada Sea (Yoder et al. 1981; Shingo et al. 1997; Kimura et al. 2007). Estimates of eddy-driven nutrient fluxes into the euphotic zone range from less than 10% to more than 50% of annual new production (Siegel et al. 1999; Oschlies 2002). Because frontal features and cold core eddies form intermittently throughout the year in the Kuroshio, their effects on biological productivity may drastically alter the nearby marine community and the biogeochemical cycle of the region (Chen et al. 2007).

Numerical simulations have shown that restratification at fronts inhibits vertical mixing, which triggers phytoplankton blooms (Taylor and Ferrari 2011). When the forcing of such fronts outweighs that of turbulent mixing, a stratified euphotic zone provides the necessary habitat for a bloom. Oceanic fronts that separate waters of different densities can generate intermittent blooms in subtropical oligotrophic waters by upwelling additional nutrients into the euphotic zone (Mahadevan and Archer 2000). In sub polar waters, fronts reduce the flux of phytoplankton out of the euphotic zone. Therefore, these features affect productivity in both the subtropics and the highly productive sub polar oceans.

This study investigated the effect that frontal features had on biological productivity within the Kuroshio off the coast of Japan. Productivity is a measure of the rate at which organic carbon is produced. Here, chlorophyll was used as a proxy for phytoplankton production rates to further understand the physical factors affecting phytoplankton.

It was hypothesized that chlorophyll concentrations within the euphotic layer of frontal features in the Kuroshio will be significantly greater than concentrations outside of these features, due to the processes that bring cold, nutrient rich waters to the surface, and stratify the upper water column. Phytoplankton form the base of the food web and are a necessary component of the carbon cycle, as they consume CO_2 for photosynthesis. The oceans have absorbed about 30% of anthropogenic CO_2 emissions, decreasing the amount of CO_2 in the atmosphere and mitigating global warming (Sabine et al. 2004). Because the Kuroshio region is one of the most prominent basins of CO_2 uptake throughout the world's oceans, fronts have lasting impacts on the amount of carbon stored in sub polar waters and the global carbon cycle (Taylor and Ferrari 2011). By studying biophysical relationships, we hope to better understand the connections between physical processes, chlorophyll, productivity, and the carbon cycle.

METHODS

Chlorophyll and nutrient concentrations, sea surface temperature (SST), and salinity were analyzed over a cruise transect from 29° N, 145° E to 41 N°, 150 E° within the Kuroshio from 25 February 2013 to 17 March 2013 aboard the R/V *Melville*. A conductivity-temperature-depth profiler (CTD) was deployed at each of the 23 stations along a transect across the main axis of the Kuroshio Extension (Figure 1). In situ measurements of temperature, salinity, nitrate, and chlorophyll were collected from 8 Niskin bottles attached to a Rosette, which were tripped at depths from 0 to 300 m. Continuous measurements of temperature, salinity, and chlorophyll were also gathered from sensors on the CTD. Continuous surface measurements of SST and sea surface salinity (SSS), chlorophyll and nitrate were also gathered from a thermosalinograph (TSG), fluorometer and a Satlantic SUNA sensor, respectively, about once every minute. Discrete samples of surface chlorophyll and nitrate were collected every 6 hours from a continuous underway flow system, and were used to calibrate continuous measurements. The original satellite images of SST and surface color provided by the Ocean-Color Data Processing System (ODPS) were severely limited in detail due to cloud cover. Additional satellite images of sea surface height (SSH) and SST were gathered from AVISO and NASAPO.DAAC, respectively. Correlations of surface chlorophyll, surface nitrate, and SSS to SST within a frontal feature were determined.

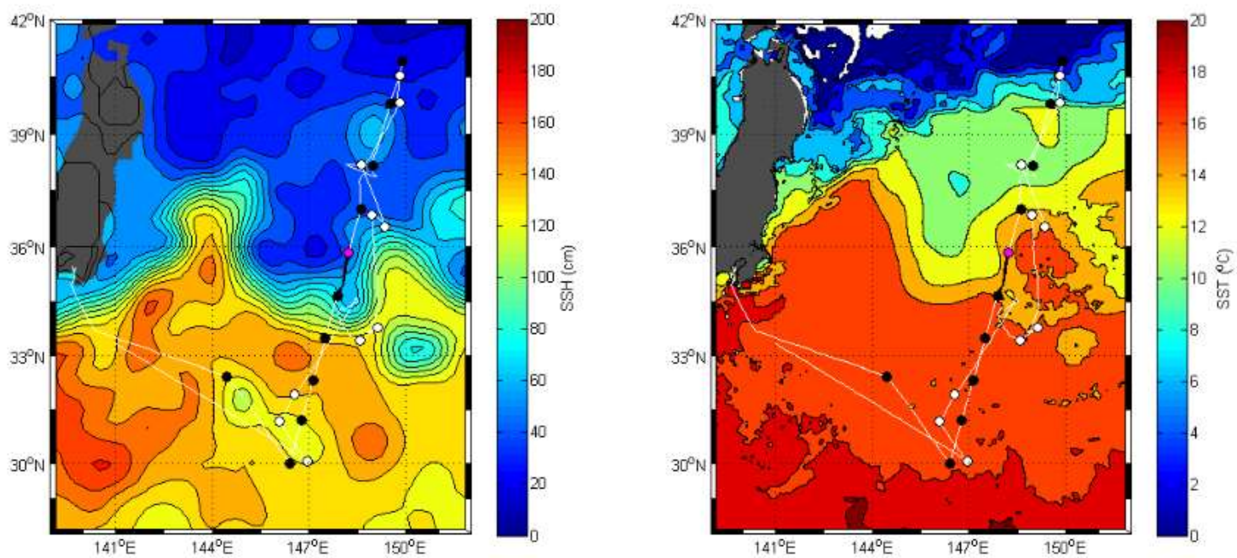


Fig. 1. Weekly averaged satellite images of SSH (left) and SST (right) gathered from AVISO and NASAPO.DAAC, respectively. Black and white dots denote CTD stations on the northern and southern transects, respectively. The black line represents the location of Feature 1. The purple dot denotes station 8.2.

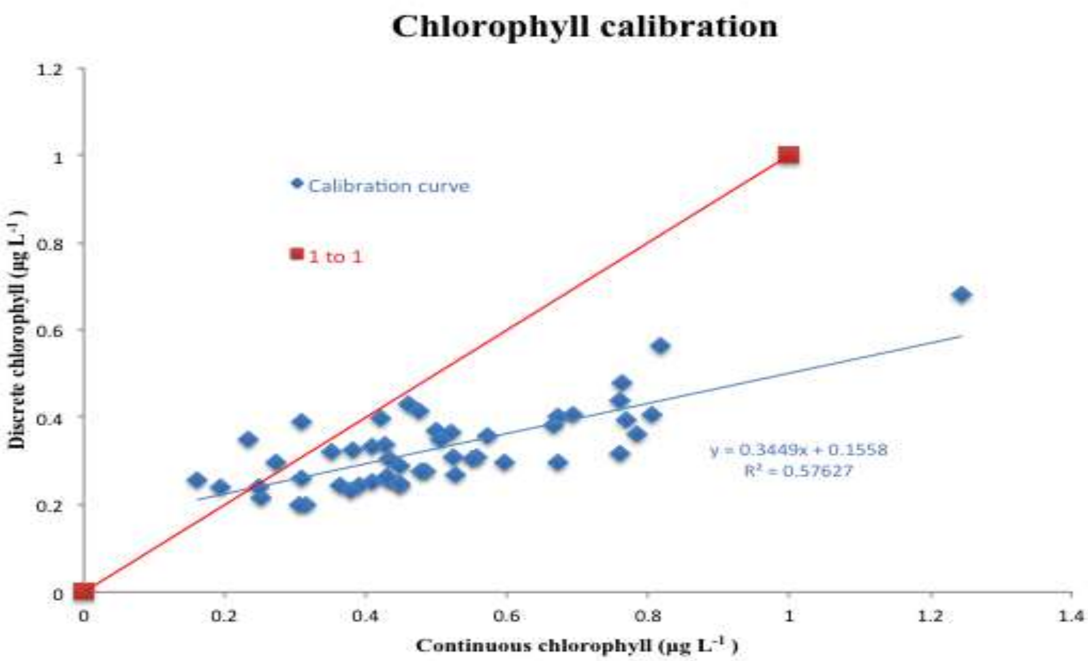
Discrete chlorophyll samples were filtered and submerged in 90% acetone before being sonicated and centrifuged (Lorenzen 1966). Samples were then analyzed using a Turner TD700 fluorometer. The Ocean Data Facility at Scripps Institute of Oceanography analyzed discrete nitrate samples gathered from CTD casts and the continuous flow system.

Discrete measurements of chlorophyll and nitrate were used to calibrate continuous measurements. A best-fit linear calibration curve of $y = 0.3449x + 0.1558$ was applied to continuous surface chlorophyll measurements, with a root mean square error (RMSE) of 0.2227. A best-fit linear calibration curve of $y = 1.2641x - 1.9991$ was applied to continuous surface nitrate measurements, with a RMSE of 0.9568 (Figure 2). For both calibration curves, y-values represent discrete measurements and x-values represent continuous measurements. Because only a qualitative analysis of chlorophyll throughout depth was given, chlorophyll values from the CTD sensor were not calibrated against discrete samples from the Niskin bottles.

RESULTS

The satellite image of SSH plots a very definitive location of the Kuroshio Extension (Figure 1). Low surface chlorophyll and nitrate values south of 34 °N define the southern region of the cruise transect (Figure 3). The subtropical waters of the Kuroshio are warmer and more saline in the upper 300 m (Figure 4). The southern region has a much deeper mixed layer (greater than 300 m), less stratified waters, and higher SSH than in the north (Figure 5). Low chlorophyll concentrations in the south are due to the depth of the mixed layer and nutricline, which are both well below the euphotic zone.

In the northern, sub polar waters of the Oyashio (north of 37 °N), surface chlorophyll and



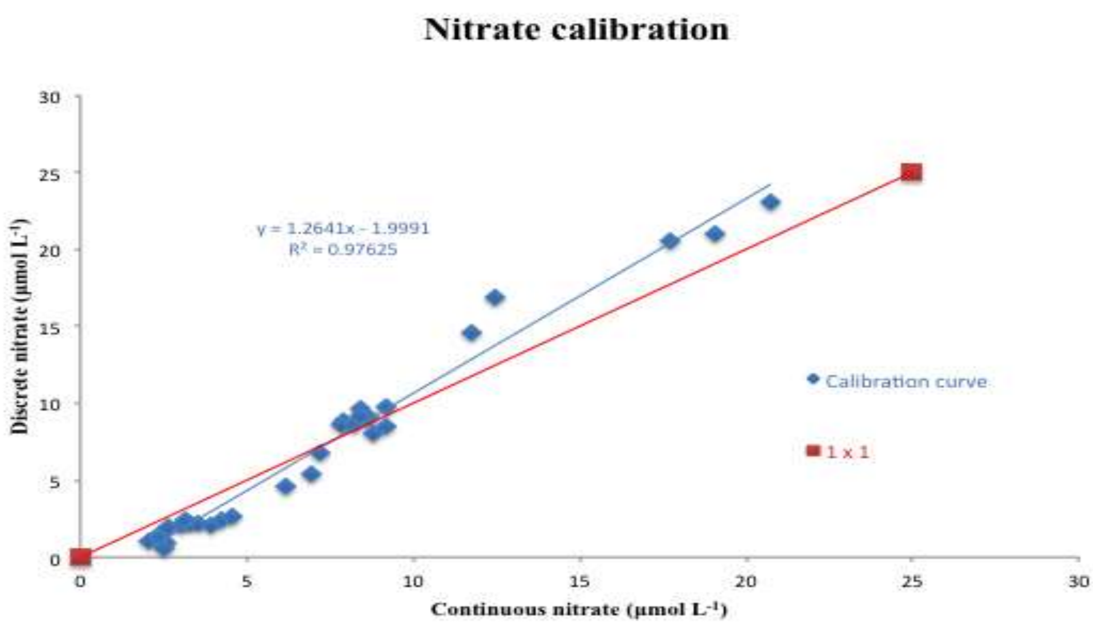


Fig. 2. Calibration curves for continuous measurements of chlorophyll (top) and nitrate (bottom).

nitrate values are noticeably higher than the waters of the Kuroshio (Figure 3). The mixed layer depth (defined as the 10 °C isotherm) and nutricline are present within the upper 200 m of the water column (Figure 5), and colder, less saline surface waters dominate the sub polar north Pacific (Figure 4).

The meander of the Kuroshio Extension is outlined by the SSH contours that fluctuate from 33 – 39 °N (Figure 4). The area of the Kuroshio current axis crossed by the ship is characterized by strong stratification and a steep gradient in SSH from 34 – 36 °N, where continuous measurements of both surface nitrate and chlorophyll increased more than twofold as SST and SSS sharply decreased (Figure 4). As the ship crossed over the current axis, the thermocline and the nutricline shoaled, and the SSH rapidly decreased (Figure 5).

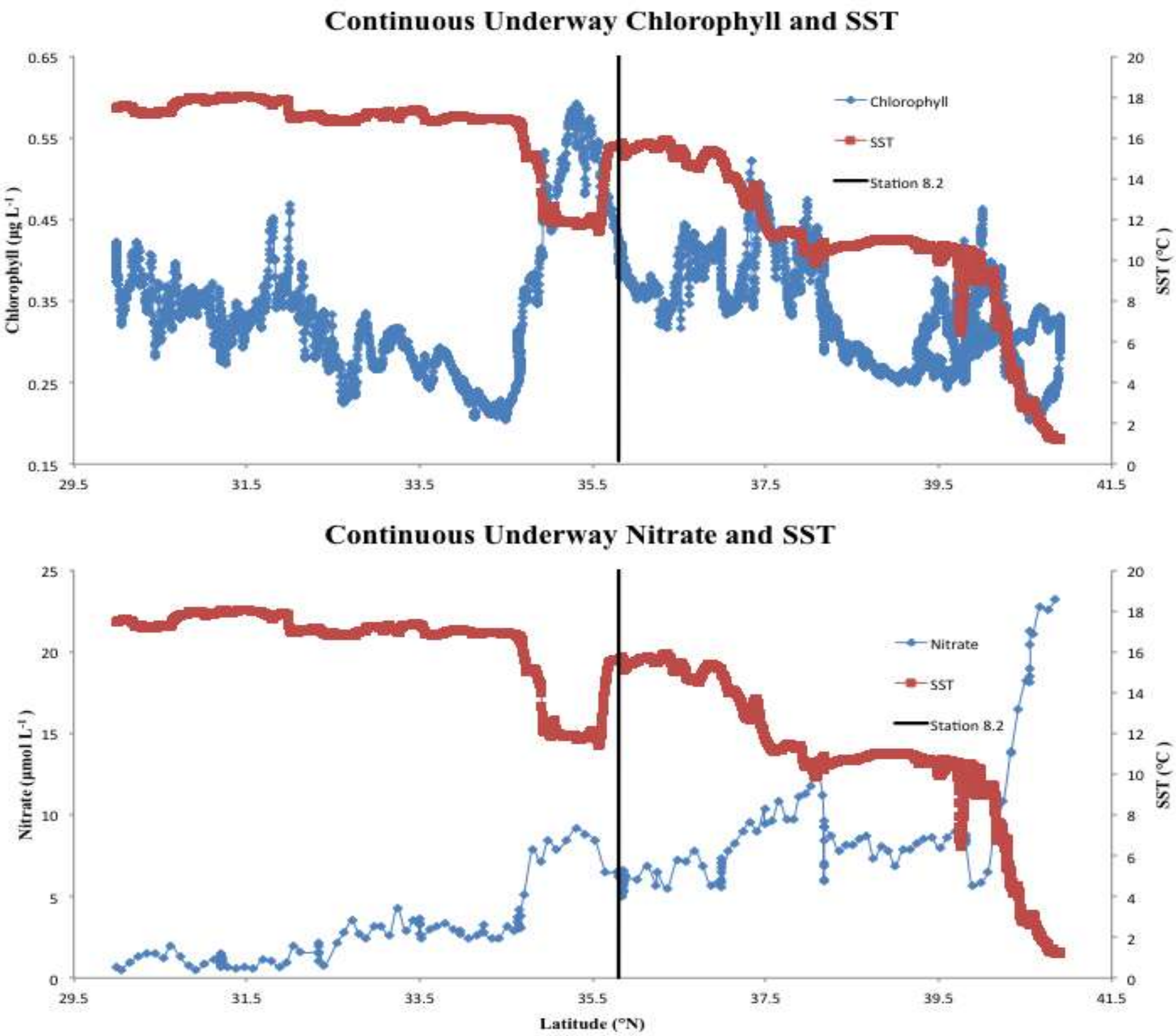


Fig. 3. Continuous surface chlorophyll and SST (top) and continuous surface nitrate and SST (bottom) plotted against latitude on the northern transect of the cruise. The nearest CTD cast at station 8.2 is plotted for reference. Notice the feature from 34.5 to 35.7 °N, where a sharp increase in chlorophyll and nitrate occurs simultaneously with a sudden decrease in SST.

Compared to the mean continuous surface chlorophyll concentration of 0.266 μg L^{-1} south of 34 °N, values reached 0.593 μg L^{-1} within an area of lower SST from 34.5-35.7 °N, from here out referred to as ‘Feature 1’. Surface nitrate values reached 9.16 μmol L^{-1} within this feature, before dropping down to roughly 6 μmol L^{-1} outside of this feature (Figure 3). The chlorophyll section revealed a low chlorophyll plume of water being forced to the surface near station 8.2 – the most productive waters at this location were within the top 50 m of the water column (Figure 5).

A deep chlorophyll maximum (DCM) existed around 275 m at station 8.2. Because this plume of chlorophyll is well below the euphotic zone, it must have been forced to depth from vertical shear between the two water masses. The Fa:Fo ratio of this plume was similar to that of other surface values. Therefore, it was determined that the chlorophyll had not yet begun to degrade, and that the deep chlorophyll plume had recently been forced below the surface.

Within this front, SST was correlated to sea surface salinity (R^2 = 0.92006), surface chlorophyll (R^2 = 0.75113), and surface nitrate (R^2 = 0.72998) (Figure 6). In general, surface chlorophyll and surface nitrate values were inversely correlated to SST, while SSS was positively correlated to SST.

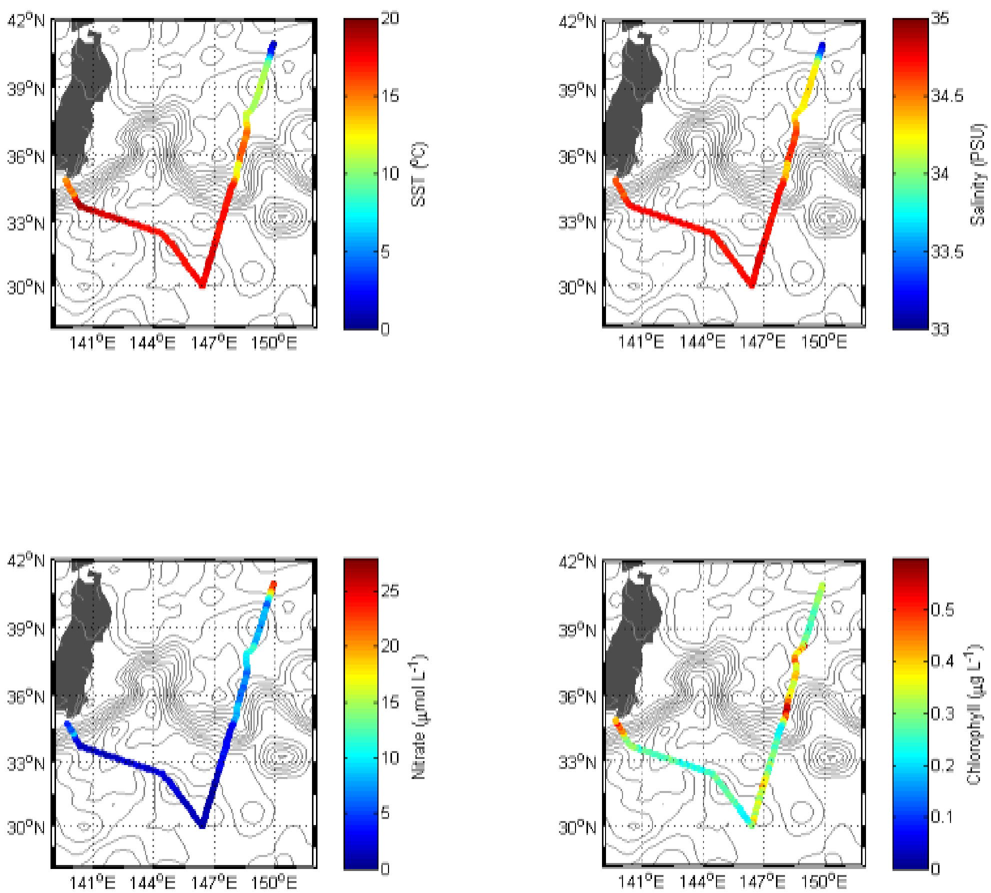


Fig. 4. SST (top left), SSS (top right), nitrate (bottom left), and chlorophyll (bottom right) plotted on the cruise transect over contours of SSH. Note the sudden increase in nitrate and chlorophyll and decrease in SST and SSS when crossing Feature 1, from 34.5-35.7 °N.

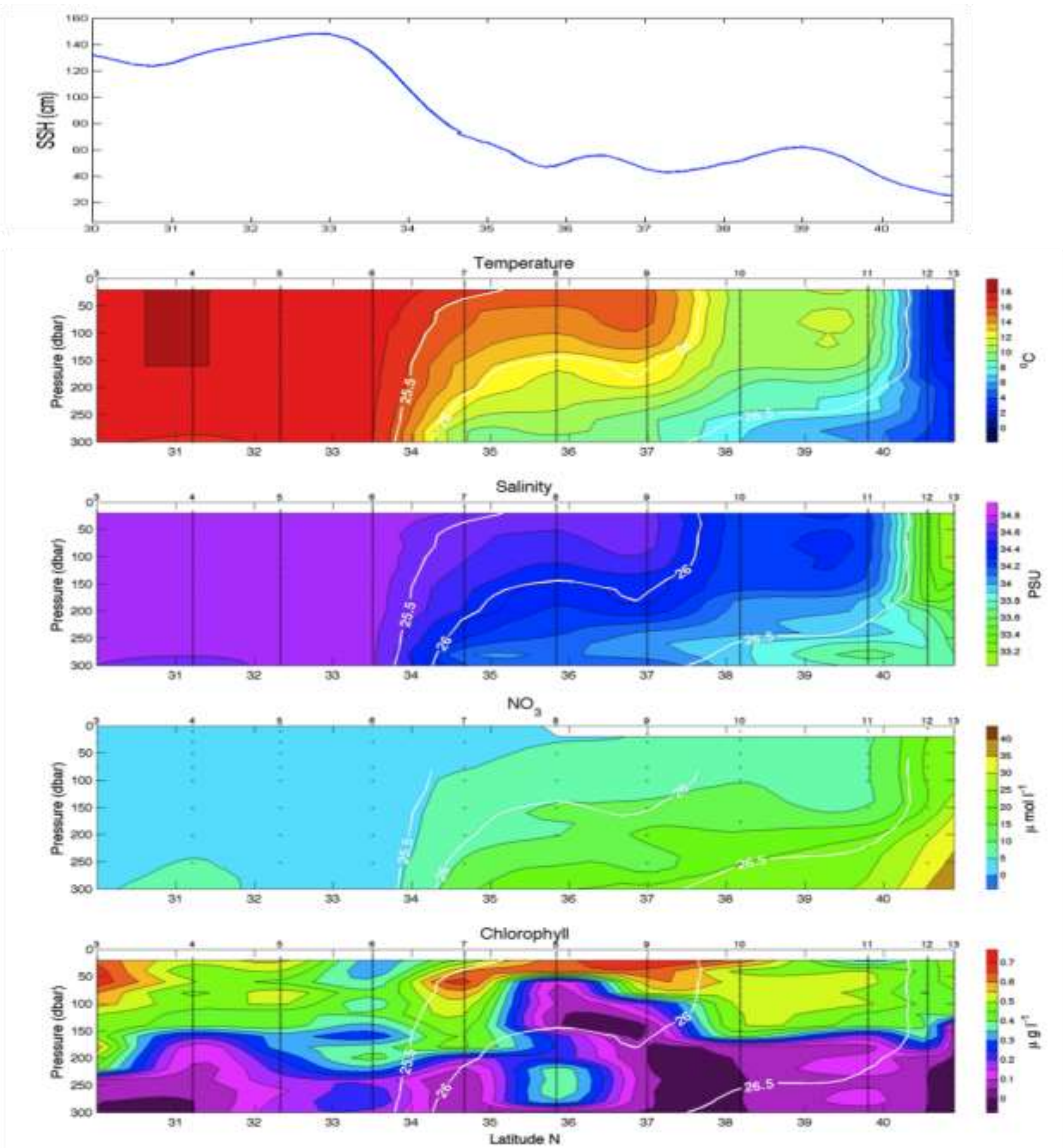


Fig. 5. SSH in cm (top) and sections of temperature, salinity, nitrate, and chlorophyll (bottom) across the northern transect. The black dots denote station samples. The white numbers and lines denote density (+1000 kg m^{-3}). Notice that chlorophyll values from the CTD sensor were not calibrated against discrete samples from the Niskin bottles.

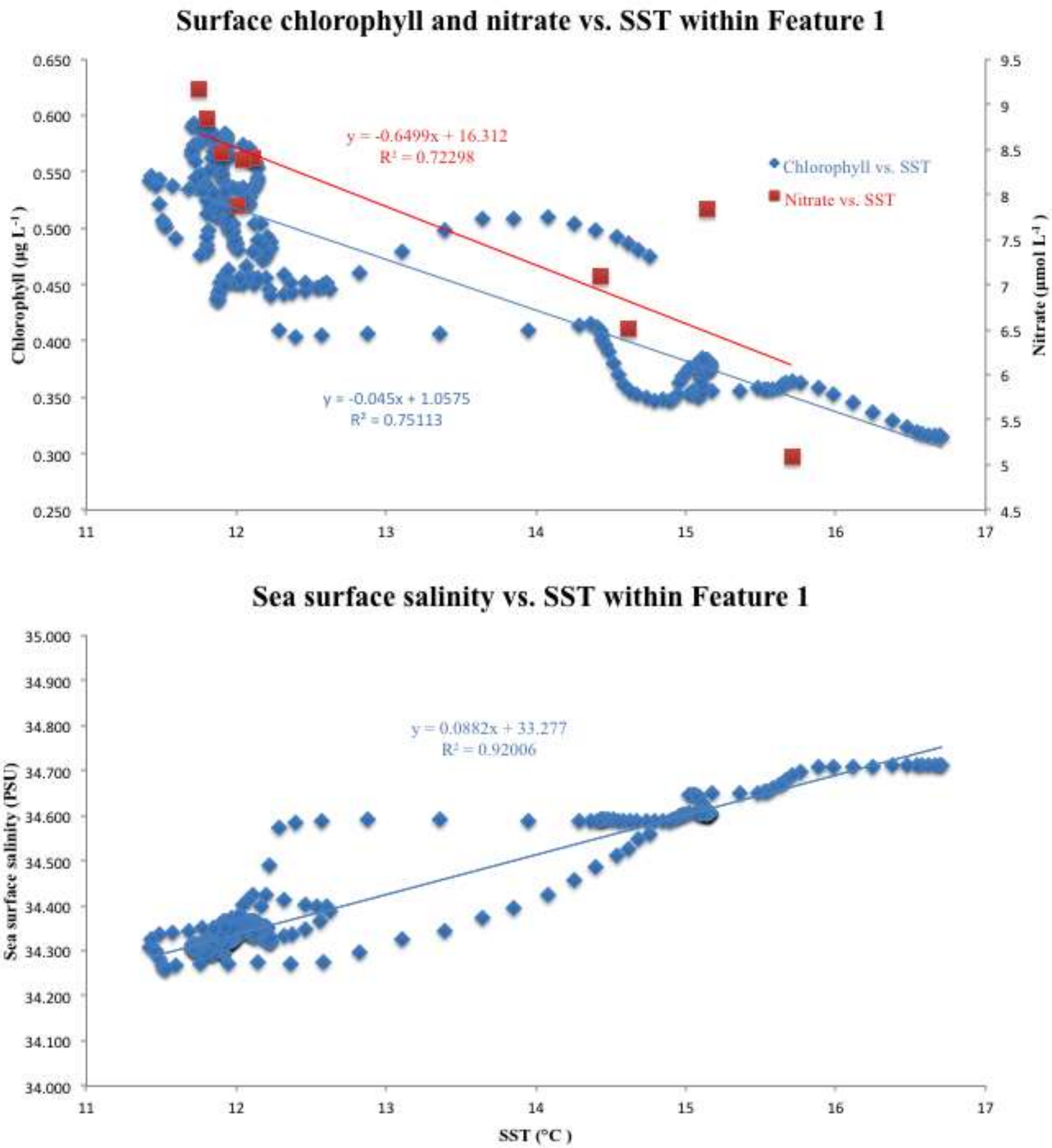


Fig. 6. Surface chlorophyll and nitrate (top) and SSS (bottom) plotted against SST within Feature 1.

DISCUSSION

A steep SST and SSH gradient indicated the presence of some type of front at Feature 1. The meander in the Kuroshio near station 8.2 may have been in the early stages of forming a spin off eddy (Figure 1) (Yoder et al. 1981). If this was the case, a divergence may have formed at the surface when the current curved back north, in a cyclonic direction. This divergence of surface waters would have drawn up colder, nutrient rich water from depth (Sasai et al. 2006). The lower SSH at station 8.2 is indicative of a divergent water mass. However, the possibility of this eddy was later dismissed after having analyzed more recent satellite images of SSH (AVISO).

More likely, as the warm, subtropical waters of the Kuroshio collided with the cold, sub polar waters of the Oyashio, a front formed. This front was characterized by strong stratification and steep SSH and SST gradients. The forcing of the stratification dominated that of vertical mixing, thus suspending phytoplankton in the front (Taylor and Ferrari 2011). Vertical shear between water masses of different densities caused upwelling, which delivered nutrient rich waters to the euphotic zone, allowing for a bloom to occur (Mahadevan and Archer 2000). Within and across this front, chlorophyll concentrations were enhanced both at the surface and throughout the euphotic zone due to upwelled nutrients from deeper water (Kimura et al. 1997) and a more stratified upper water column. A maximum surface chlorophyll concentration of 0.593 μg L^{-1} within Feature 1 was comparable to chlorophyll concentrations of 0.40 μg L^{-1} in a cyclonic eddy shed from the Kuroshio at the Luzon Straight bordering the South China Sea (Chen et al. 2007).

Chlorophyll measurements throughout the upper 300 m of the water column revealed a plume of water from 50-200 m containing a chlorophyll minimum near station 8.2. It appeared as if a plume of low chlorophyll water was forced towards the surface as it moved south, while a more productive water mass was forced to depth as it moved north due to vertical shear between differing water densities at the front (Figure 5).

A deep chlorophyll maximum existed at 275 m near station 8.2 (Figure 5). Pommier et al. (2009) found evidence of a deep chlorophyll maximum (DCM) that was maintained for a few weeks after the spring bloom, at the bottom of the euphotic zone. However, the depth of this chlorophyll maximum was too far below the euphotic zone to have received any light. Because the cells at 275 m were still fluorescing, it is likely that the water mass containing the chlorophyll was forced to depth from vertical mixing near Feature 1. The F_o :F_a ratio from the chlorophyll sample at 275 m was similar to other values, suggesting that this chlorophyll patch had not yet begun to degrade. Therefore it was concluded that the chlorophyll had only been below the euphotic zone for a limited amount of time, possibly a few weeks.

Limitations of methods and data

A cyclonic eddy was present near 33°N 151°E, but was not in our path (Figure 1). If future studies were to research changes in water properties across an eddy, it would be helpful to compare that data to the data presented here.

CONCLUSIONS

Continuous surface chlorophyll concentrations, nutrient concentrations, and SST were combined with CTD data and satellite images to determine the effect of physical processes on biological productivity within the Kuroshio region. From 34.5 – 35.7 °N an evident frontal feature of some sort was crossed. Surface chlorophyll and nitrate concentrations spiked as SST dropped quickly. The feature was due to the formation of a front that had formed where the Kuroshio met the Oyashio. The density differences between water masses were responsible for creating a stratified water column. This stratification suspended phytoplankton in the euphotic zone, while drawing cooler, nutrient rich waters to the surface from depth. The suspension of phytoplankton and additional nutrients were cause for elevated chlorophyll concentrations within the front.

If this research were to be conducted again, continuous measurements of surface chlorophyll, nitrate, and SST should be monitored in real time to determine when the ship was crossing a front. This information could then be paired with satellite images of SST and SSH. With this information, CTD casts could be deployed near the center of such physical features. The depth profiles from these CTD measurements could then be used to further analyze how physical processes affect the concentration and distribution of chlorophyll and nutrients.

This research will aid in future studies aiming to understand the relationship between physical features and productivity within the Kuroshio extension. As the Kuroshio shifts its position over time, these data will provide a baseline for the location of the Kuroshio, the north-south SST gradient, and chlorophyll and nutrient concentrations in the late winter of 2013.

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