Remote Sensing of Suspended Particulate Matter and Algal Blooms in San Francisco Bay and Delta Using Landsat 8 OLI and Sentinel 2

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ABSTRACT

Landsat-8 Operational Land Imager has high spatial resolution (~30 m nominal), improved signal-to-noise and expanded band set which opens up new applications for coastal and in-land waters. We use a newly developed ocean color processor for Landsat-8 to examine changes in the Northern San Francisco Bay, in particular looking for possible changes due to the California drought and 2016 El Nino. Product maps using panchromatic enhancement (~15 m resolution) and scene based atmospheric correction allow a detailed synoptic look every 16 days. We have developed a similar product for Sentinel 2A data and when Sentinel 2B is on orbit in 2017 the coverage will be once every 5 days. Sentinel 2 data contains additional vegetation red edge bands we use to identify phytoplankton blooms. This work is part of a larger NASA funded project aimed at improving the modeling and predictive capabilities of the biogeochemical state for the San Francisco Bay. Here we highlight using Landsat 8 OLI and Sentinel 2 for remote sensing of San Francisco Bay and Delta.

1. INTRODUCTION

The San Francisco Bay and Delta Ecosystem (SFE), including the lower reaches of the Sacramento River and Delta, San Pablo Bay, and Central Bay, is the largest estuary and wetland habitat on the Pacific coast of the United States (Fig. 1). It is an ecologically important system that links freshwater and marine environments, provides drinking water to over 25 million urban users, and irrigation water for agriculture in the highly productive Central Valley (Service, 2007). Ecological pressures are expected to intensify in the future with continued population increase (ABAG, 2015) and changes in climate (Cloern et al., 2012). The San Francisco Estuary Delta is in the process of review for major water infrastructure projects, known collectively as the Water Fix and Eco Restore: an estimated $23 billion plan to be implemented over 5 years. The centerpiece of this effort is the diversion of water from the Sacramento River above Hood, CA approximately 30 km upstream from the SFE Delta, that will be routed under the Delta in 50 km long tunnels to the Central Valley (Federal) and State Water Project pumping stations in the south Delta at Tracy, CA. Unlike the previously proposed new water infrastructure in the Delta, the Water Fix companion program, Eco Restore, will recover 30,000 acres of wetlands -- within areas such as the Yolo Bypass, Suisun Marsh and the central Delta -- with the goal of sustaining delta water resources and ecosystem function and the protection of endangered species. The Water Fix will result in changing patterns in the amount of freshwater flow, water residence time, and the salinity field within the Delta. This has ramifications both for the SFE and the adjacent coastal ocean.

To create tools to address these issues we have been conducting a NASA Interdisciplinary Science SFE project to put in place remote sensing, in situ data collection and modeling framework for the scientific basis of an ecosystem approach to the stewardship of the SFE including freshwater and marine resources within the SFE and adjacent ocean ecosystems. Here we highlight one component of that effort; using Landsat 8 OLI and Sentinel 2 for remote sensing of Suisun Bay and the Delta.

2. BACKGROUND

The SFE project combines three components: (1) satellite observations, (MODIS, MERIS, HICO, Landsat-8 OLI and Sentinel 2); (2) field observations of nutrients, phytoplankton, suspended sediments, CDOM and optical properties; and (3) the CoSiNE ecological model integrated with the SCHISM hydrological model of SFE. We also conduct outreach and coordination with stakeholders and share our results with SFE agency leaders responsible for managing this complex system. While this work includes exchanges with the coastal ocean and inputs from the rivers and sewage plants, it does not specifically include the Delta, exchanges with the surrounding wetlands and benthos, or the dynamics of suspended matter from those sources. To gain a better insight into those processes we have begun a focused effort using Landsat and Sentinel 2 to image those areas and tune product algorithms for those regions.

At the start the SFE project we processed remote sensing data for a 10-year model validation study (2002-2012) using the MERIS Full Resolution (FR) data for the SFE and adjacent waters. MERIS FR data has 300 m spatial resolution and 18 spectral channels selected for ocean measurements making it the best long-term ocean color data set for the SFE and we have been using it to validate the SFE model results. We also processed and analyzed all available HICO 100 m hyperspectral data. Both of these were ideal for the bays and offshore waters, but did not have the spatial resolution necessary for the rivers and delta region. In the last year we initiated the collection and processing of data from Landsat 8 OLI which has 5 visible bands at 30 m resolution, and an improved SNR making it useful for the bay and delta regions (Fig. 1 and Table 1). More recently we have begun using Sentinel 2 with 20 m GSD and additional channels in the red which we use for identifying phytoplankton blooms (Table 1).

3. APPROACH

We acquired Landsat-8 OLI level 1b data (calibrated at sensor radiances) from the USGS Earth Resources Observation and Science (EROS) Data Center. We acquired Sentinel 2A data from the European Space Agency (ESA) Sentinel Online Data Hub. We then atmospherically correct these data using the algorithms described by Vanhellemont and Ruddick (2015). In particular atmospheric correction was done using an iterative SWIR method optimized for highly turbid waters (Vanhellemont & Ruddick 2015). Atmospheric correction is currently computed using the ACOLYTE processor (Vanhellemont and

Ruddick, 2016). For product maps we are using recently published methods for turbidity (Dogliotti et. al. 2015), and total suspended sediments (TSS; Nechad et. al. 2010; Nechad et. al. 2015). We optimize these products using regionally tuned algorithms -- regressions with SFE *in situ* data from our 2013-2016 SFE cruises. We are working to further extend algorithms using in situ data from the SFE cruises. Steve Ackleson collected extensive *in situ* data sets of inherent optical properties (IOP's) from San Pablo Bay, Suisun Bay and the Delta that provide detailed parameterizations of water constituent optical properties up into the rivers and delta (Ackleson et al., OO Poster). These data will be used to tune existing sediment and turbidity algorithms for SFE.

To identify large phytoplankton blooms with Sentinel 2 data we developed a version of the Gower, et al. (2005) MCI algorithm. The MCI (Maximum Chlorophyll Index) shows the amplitude of a peak near 705 nm in the radiance spectrum of light reflected from the earth's surface which is a strong indicator of chlorophyll concentration at the ocean surface. The MCI algorithm was developed for use with MERIS data; the MERIS MCI is computed as peak radiance at 709 nm above a linear baseline defined by radiances at 681 and 753 nm. For Sentinel 2 data (Table 1) we used peak radiance at 704 nm above a linear baseline defined by radiances at 665 and 740 nm. Values are computed from level 1b data (calibrated at sensor radiances) before atmospheric correction since the waters we are studying typically have high radiances in the red which are outside the range that can be handled by standard atmospheric correction algorithms.

4. RESULTS

Landsat 8 OLI data was processed for spring 2015 (extreme drought conditions) and spring 2016 (El Nino flood conditions). Atmospheric correction was done using an iterative SWIR method optimized for highly turbid waters (Vanhellemont & Ruddick 2014). The standard open ocean OC3 chlorophyll algorithm produces anomalously high values in these turbid waters (not shown). Turbidity maps (Dogliotti et al., 2015; blended 645-859) for 22 April and 8 May 2015 show an increase of turbidity in the lower Sacramento River and North San Pablo Bay (Figure 2). Turbidity in the river is similar for both images being highest in Suisun Bay. The higher turbidity in the NW part of San Pablo Bay in the May 8th image is most likely due to wind resuspension of sediments from these very shallow waters (<3 m).

In 2016 there was a moderate El Nino that ended the four year drought. The heaviest rainfall was in March 2016 (Figure 3) with flows approaching 30,000 cfs in early March. At the time of the March 23rd image the flows were around 3,000 cfs (ten times the 2015 flow rate) and similarly the turbidity was ten times higher. Note that the high turbidity is seen in the Sacramento River, all of Suisun Bay and much of San Pablo Bay. The higher river flow carries the turbid waters into San Pablo Bay.

Following the high flow conditions in March 2016, May 2016 was characterized by a major phytoplankton bloom in the convergence zone of the delta. A USGS cruise on May 6 (Fig. 4) and an SFE project cruise on May 19 both captured this bloom (Fig. 5). We processed the Sentinel 2 data from May 15 using the MCI algorithm and were able to capture the same bloom features. We note particularly that the Sentinel 2 data shows the bloom extending to the south into the San Joaquin River part of the convergence zone, an area not sampled by either research cruise. The SFE cruise included measurements of nitrate and ammonia uptake rates and as shown in fig. 5

the bloom happens in the river when conditions are right so that the phytoplankton is able to take up the large amount of nitrate available to them for growth. This bloom is generally similar to blooms observed in prior years (e.g. Wilkerson et al., 2006), but this is one of the largest and with the SFE cruise data and the additional view from the Sentinel 2 data we can document the full extent of the bloom.

5. DISCUSSION

We are currently making intensive use of both Landsat-8 (launched in 2013) and Sentinel-2A (launched in 2015) to map turbidity within SFE (e.g. Figure 2). Sentinel-2B will be brought on line after launch in 2017. The strength of this constellation of sensors is their high spatial resolution (Landsat-8, 30 m, 15 m panchormatically enhanced; Sentinel-2, 20 m), improved signal to noise compared to earlier land sensors, which is essential for retrieval of water leaving radiances, and additional bands, particularly in the near-IR, which is proving valuable for bloom detection and atmospheric correction. The current sensor constellation provides imagery the study domain every ~9 days, and we anticipate acquiring imagery every 5 days when Sentinel-2B data is available in 2017.

In high sediment waters like those found in SFE Traditional atmospheric correction and chlorophyll algorithms do not work because of high sediments. However the ACOLYTE processer developed by Vanhellemont and Ruddick seems to work quite well. Suspended sediment is the most important product and it is necessary to account for this before it is possible to calculate chlorophyll and CDOM.   The Dogliotti et al. (2015) turbidity algorithm and the Nechad et al. (2015) total suspended sediment algorithm both appear to work well for SFE waters. We are using our SFE project in situ data to validate the best model for this region. MCI type algorithms seem to work the best for chlorophyll in these turbid waters. Because of the turbid waters (typical Secchi depth <1 m) blooms are formed by species that stay at the surface, and therefore the MCI algorithm works particularly well.

6. CONCLUSIONS

While land sensors have traditionally had broad bands and low signal-to-noise ratio the current group of sensors (Landsat-8 OLI and Sentinel 2) have additional bands and greatly improved SNR that make them very useful for coastal waters and in particular rivers and river deltas. These algorithms have been demonstrated in European waters and we are using regionally tuned versions of their algorithms to track the sediment and phytoplankton dynamics of SFE. These products are inputs we are using to develop an improved model of the sediment and biological dynamics of the SFE.

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Figure 1. *Landsat-OLI image from 28 May 2014 of the San Francisco Bay area including the Sacramento-San Juaquin River Delta in the upper right.*

Table 1. *Comparison of Landsat-8 OLI and Sentinel 2 bands. The Sentinel 2 red bands (marked red in table) are used for the MCI index to identify phytoplankton blooms.*

Landsat OLI Bands	Wavelength (micrometers)	Resolution (meters)	Sentinel 2 Bands	Center Wavelength (micrometers)	Resolution (meters)
Band 1 - Coastal Aerosol	0.43 - 0.45	30	Band 1 - Coastal Aerosol	0.443	60
Band 2 - Blue	0.45 - 0.51	30	Band 2 - blue	0.490	10
Band 3 - Green	0.53 - 0.59	30	Band 3 - Green	0.560	10
Band 4 - Red	0.64 - 0.67	30	Band 4 - Red	0.665	10
			Band 5 - Vegetation red edge	0.705	20
			Band 6 – Vegetation red edge	0.740	20
			Band 7 - Vegetation red edge	0.783	20
Band 5 - Near Infrared (NIR)	0.85 - 0.88	30	Band 8 NIR	0.842	10
			Band 8A Vegetation red edge	0.865	20
			Band 9 – Water Vapor	0.945	60
Band 6 - SWIR 1	1.57 - 1.65	30	Band 11 - SWIR	1.610	20
Band 7 - SWIR 2	2.11 - 2.29	30	Band 12 - SWIR	2.190	20
Band 8 - Panchromatic	0.50 - 0.68	15			
Band 9 - Cirrus	1.36 - 1.38	30	Band 10 - Cirrus	1.375	60

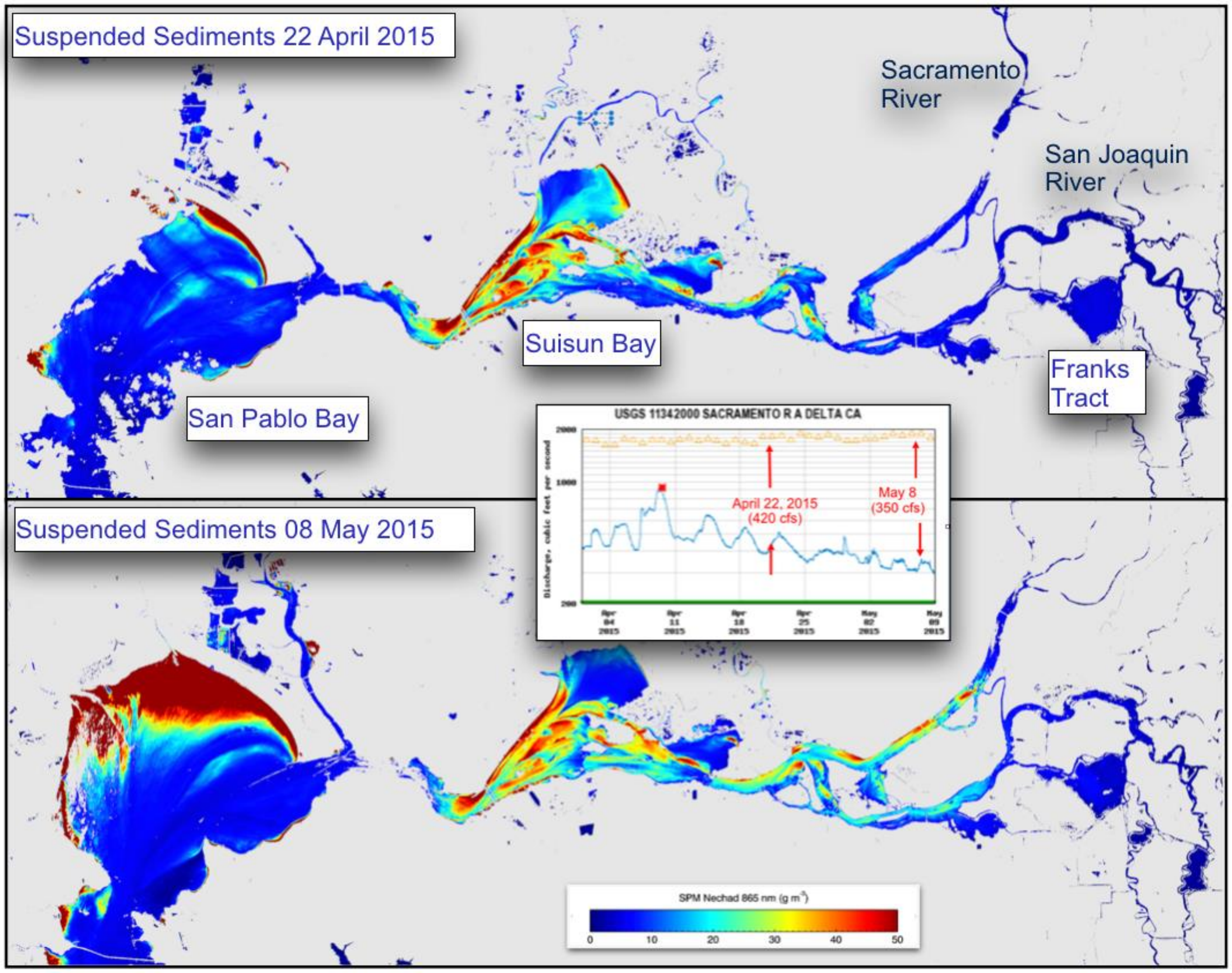

Figure 2. *Landsat-8 turbidity (suspended sediments) maps for the Northern Bays and Delta during the spring of 2015. Land and clouds are gray and clouds cover much of San Pablo Bay on the 22nd of April. As shown in the inset graph from the USGS gauging station for the Sacramento River, the historical norm for flow is ~2000 cfs. During the drought, a flow of ~400 cfs was typical. These low flows allowed intrusion of salt water into the Delta potentially destroying sensitive habit in regions such as the Franks Tract section toward the right. This risk was so severe that a temporary rock dam was put in place in 2015 to prevent salt water intrusion into Franks Track.*

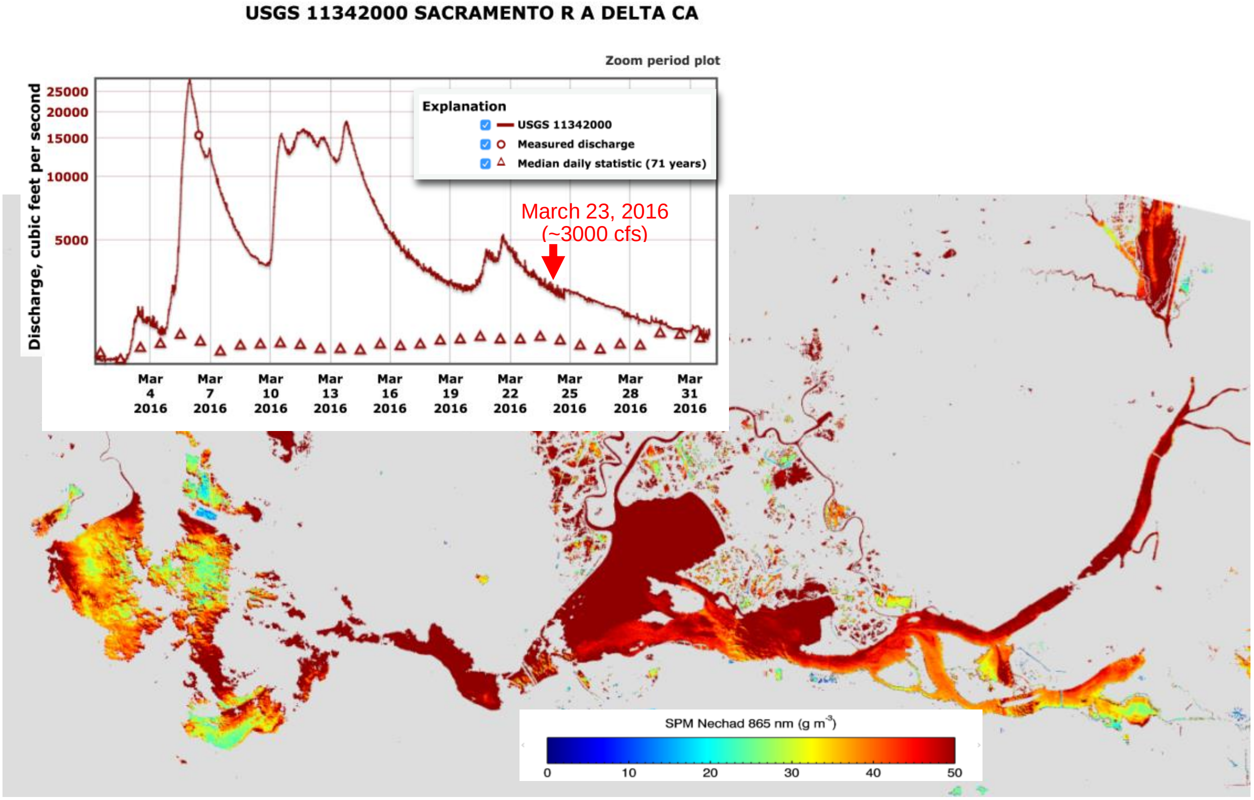

***Figure 3**. March 23, 2016 SPM map from Landsat data. Land and clouds are gray and clouds cover much of San Pablo Bay. March 2016 was during an El Nino and flow rates peaked near 30,000 cfs or 15 times the average flow. On March 23rd the flow rates and SPM were 10 times higher than the previous year (figure 2).*

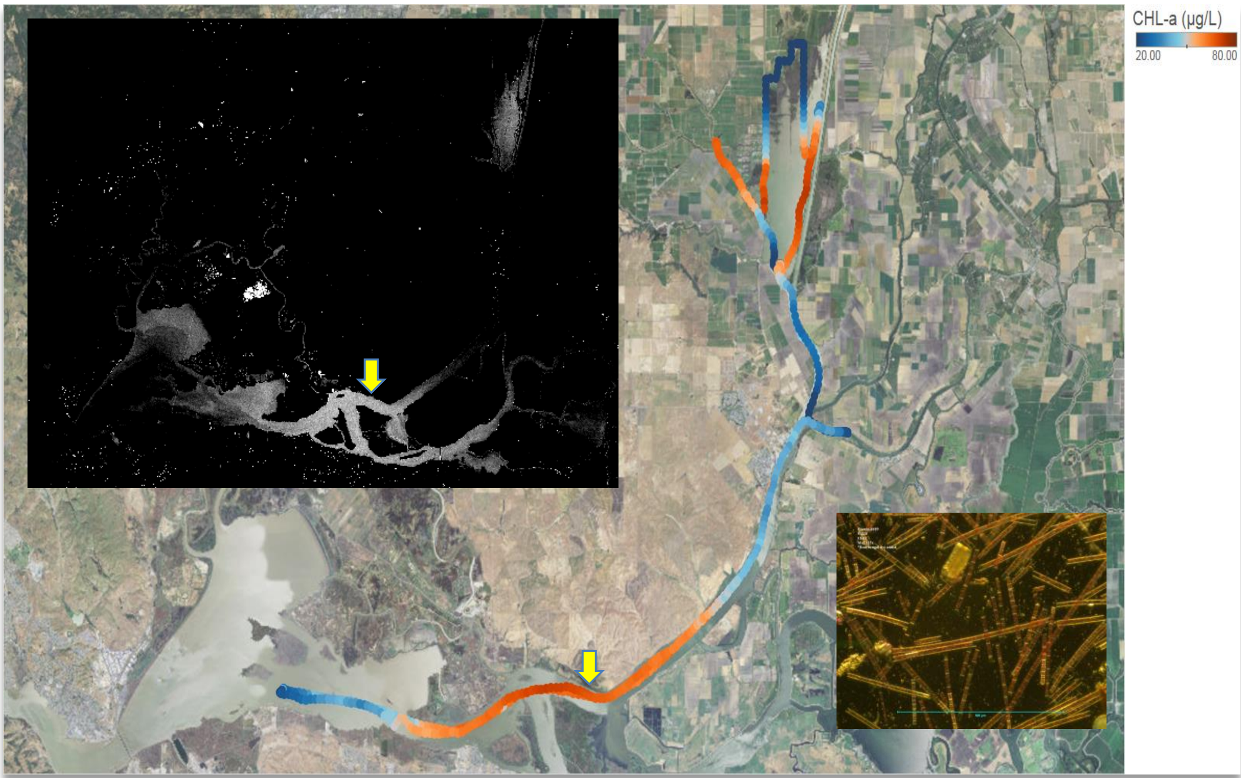

Figure 4. *Background is Landsat image overlain with USGS measured underway chlorophyll fluorescence from May 6, 2016. Upper left inset May 15, 2016 Sentinel 2 image of the phytoplankton bloom (Gower et al. 2005 MCI algorithm). Yellow arrows indicate the location of the peak bloom which is identical in both images. Lower Right inset photomicrograph of the bloom phytoplankton (primarily Melosira and Aulacoseira).*

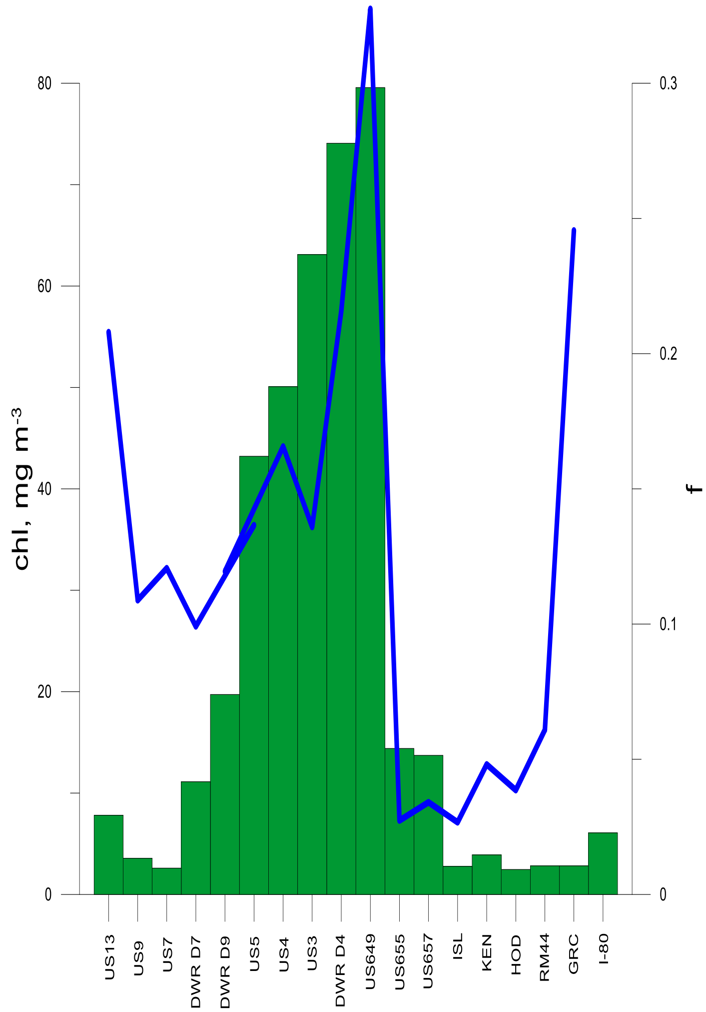

Figure 5. *May 19, 2016 SFE Cruise data for chlorophyll and f ratio (nitrate uptake rate/ (nitrate uptake rate + ammonium uptake rate) showing how the bloom forms when the phytoplankton are able to take up nitrate. The bloom peak location at station DWR D4 is near the yellow arrows indicating the bloom in figure 4.*