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PHYSICAL FACTORS INFLUENCING PHYTOPLANKTON ABUNDANCE IN SOUTHERN MONTEREY BAY

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ABSTRACT

As the base of almost all marine food webs, phytoplankton play a dominant role in determining the productivity of marine ecosystems. Recent studies have highlighted the dynamic variability of phytoplankton abundance in nearshore ecosystems over synoptic time scales. Therefore, a greater understanding of the physical mechanisms that contribute to this variability is required to assess impacts of current as well as future weather patterns on these ecosystems. In this study, chlorophyll fluorescence data from a nearshore location in southern Monterey Bay was used to identify the timing and duration of increases in phytoplankton concentrations. Regional physical parameters, including wind stress, wave height and water temperature were analyzed to determine what, if any, physical processes are associated with observed blooms. A significant negative correlation between water temperature and chlorophyll (high chlorophyll associated with cold water) was found for the two summer seasons studied (2012, 2013). The timing of high chlorophyll events coincided with relaxations of upwelling favorable wind conditions. Analysis of surface current data suggests that the incoming cold water masses are the result of poleward currents from the south of Monterey Bay. A conceptual model is proposed in which phytoplankton are advected into southern Monterey Bay during wind relaxation events preceded by upwelling events of great enough duration to establish well defined circulation patterns. The reversal of circulation patterns transports cold, phytoplankton-rich water into the bay from south of the Monterey Peninsula. This study demonstrates that wind relaxation events can be an important driver of localized high phytoplankton biomass events on the inner shelf by advecting recently upwelled water into coastal embayments that are relatively sheltered from strong upwelling favorable winds.

Keywords:

Chlorophyll; upwelling; surface circulation; HF radar; advection; upwelling reversal

1. INTRODUCTION

Coastal upwelling ecosystems represent the most biologically productive systems in the world's oceans. The high rates of primary productivity in these regions support rich coastal marine ecosystems and productive commercial fisheries (Pauly & Christensen 1995). Persistent equatorward winds drive upwelling of nutrient rich water to the euphotic zone which supports high phytoplankton abundance. Variation in the strength of these physical processes has been shown to dramatically affect primary production rates, with cascading effects on higher trophic levels (Barth et al. 2007; Krenz et al. 2011; Menge et al. 2009). Characterizations of these upwelling systems are often made on large spatial and temporal scales and discussed in terms of seasonal or monthly averages (e.g. Pennington & Chavez 2000; Thomas et al. 2001). The inability of satellite ocean color monitoring to resolve chlorophyll values at a resolution less than 1 km with a reliable temporal resolution of approximately 8 days, as well as being susceptible to interference from cloud cover and coastal fog, means these data cannot adequately capture the impact of nearshore dynamics on chlorophyll abundance and distribution. This study seeks to identify advective mechanisms that may play a determinant role in phytoplankton abundance over the inner shelf of southern Monterey Bay (Figure 1), located in the central California Current System.

Previous studies on upwelling and associated ecological responses in Monterey Bay and other locations have shown regional or continent scale analyses that average over seasonal time scales can obscure finer-scale variability. Pennington & Chavez (2000) constructed average year profiles of salinity, temperature, nitrate, and chlorophyll from a 7.5-year time series of measurements taken by the M1 mooring in the outer region of Monterey Bay (Figure 1) and used these measurements to characterize seasonal variability. These climatological averages illustrate a familiar pattern of upwelling and, after some time lag, primary productivity. Beginning in February, this upwelling process increases in strength until it reaches a maximum value in June and declines in the July-August period, with primary productivity peaking in June and July (Pennington & Chavez 2000). However, when the individual years of this time series were analyzed, they revealed the gradual trends observed in the climatology masked short term variation. Both upwelling and chlorophyll abundance showed strong episodic behavior on a time scales of days to weeks throughout the years examined (1989-1996). More recent work examining physical mechanisms governing phytoplankton blooms have highlighted the variability at relatively small temporal and spatial scales. McPhee-Shaw et al. (2011) observed short episodic blooms of phytoplankton even during steady upwelling conditions along the exposed rocky coast of California. At three different sites along the coast of Chile, Wieters et al. (2003) found that the highest degree of variance in chlorophyll occurred on a synoptic time scale (1–10 days) with wide variation across a relatively small spatial scale (≤ 20 km). These studies illustrate that a focus on seasonal patterns is insufficient to explain nearshore chlorophyll dynamics at a synoptic scale.

Two different physical mechanisms have been suggested as potential drivers of episodic bloom events in the two studies mentioned. Wieters (2003) found that a majority of the observed blooms occurred during periods of wind reversals from upwelling favorable to downwelling favorable conditions and consequent upwelling relaxation. Landward advection of water due to upwelling relaxation was proposed as the mechanism transporting offshore concentrations of phytoplankton to the nearshore. McPhee-Shaw et. al. (2011) found that during constant upwelling conditions along the rocky, exposed coast of central California, blooms predominantly occurred following periods of high wave energy and suggested wave driven mass transport as a mechanism causing the accumulation of buoyant phytoplankton in the nearshore waters. These two studies found specific seasons during which the physical mechanisms described were significant determinants of phytoplankton blooms. Along the California coast, McPhee-Shaw et al. (2011) found the correlation between phytoplankton abundance and wave events to be particularly strong during and after the spring onset of the upwelling season,. i.e. when phytoplankton were presumed available to be transported into shallow waters. Wieters et al. (2003) found that upwelling relaxation correlated most strongly during the spring and summer periods. Additional work has shown that different physical mechanisms can favor different taxonomic compositions of phytoplankton assemblages (Paquin May, 2012). While both wave fields and the atmospheric pressure gradients that drive wind patterns are regional in scale, the effects and biological response of nearshore ecosystems can be dominated by local conditions (Narváez et al. 2004; Wieters et al. 2003).

The focus of this study is the relationship between phytoplankton abundance and physical forcing over the inner shelf of southern Monterey Bay. The Monterey Bay region is characterized by persistent upwelling-favorable winds during the spring and summer. These winds cause upwelling along the exposed coastline and result in plumes of cold, nutrient-rich water coming to the surface to the north off Point Año Nuevo and to the south off Point Sur (Breaker & Broenkow 1994). Advection of water from Point Año Nuevo has been considered the main source of upwelled surface water into the Monterey Bay (Rosenfeld et al. 1994). Historically, three oceanographic periods have been defined for the Monterey Bay. These are the spring-summer upwelling season, late summer-fall oceanic season, and winter Davidson current season (Pennington & Chavez 2000; Skogsberg 1936; Skogsberg & Phelps 1946).

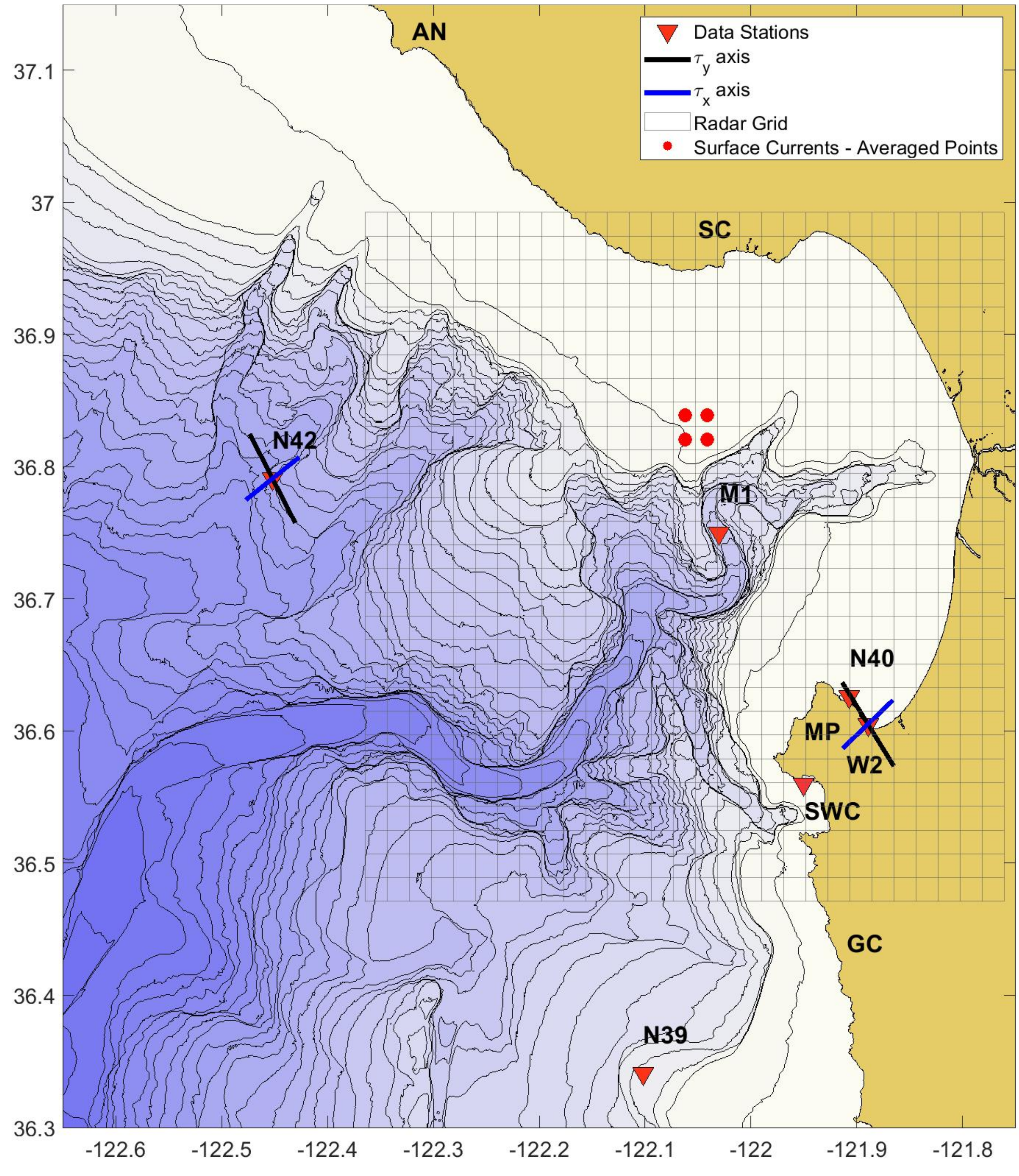

Figure 1. Study site, Monterey Bay with bathymetry. Data stations (red triangle marks) include NDBC buoys 46042 (N42), 46240 (N40) 46239 (N39) and MBARI M1, Stillwater Cove (SWC), and Municipal Wharf 2 (W2). Black and blue lines indicate the orientation of primary and secondary wind stress vectors respectively. Geographic reference locations are Point Año Nuevo (AN), Santa Cruz (SC), Monterey Peninsula (MP), and Granite Canyon (GC). Grid overlay displays extent of HF Radar coverage and red dots indicate the points used to calculate an average surface current flow. Contours indicate depth in increments of 100m.

With respect to surface current measurements on synoptic scales, it has been hypothesized that upwelled surface water entering Monterey Bay typically flows toward the southeast from Año Nuevo toward the middle of the bay, with the main water mass inside the bay flowing southward and exiting the bay past the outer coast of the Monterey peninsula (Graham & Largier 1997). Graham & Largier (1997) also indicate that slower ancillary flows occur closer to shore, which proceeds southward along the coast from the head of the canyon. This reduced flow closer to shore is thought to increase the residence time of water in the southeastern portion of the bay and helps account for increased surface temperatures regularly observed there (Graham & Largier 1997). This mechanism is fundamentally different from the buoyant surface plume in the north of the bay described by Graham and Largier (1997), to which the upwelling shadow is attributed. General surface circulation patterns in Monterey Bay have been characterized by a cyclonic flow within the bay and an anticyclonic flow outside the mouth of the bay (Paduan & Rosenfeld 1996). Additionally, cold upwelled water has been observed entering the Monterey Bay from the south, propagating northward around the Monterey Peninsula (Broenkow & Smethie 1978).

At nearshore locations in Monterey Bay, physical and biological processes can vary at small spatial scales. Woodson et al. (2009) demonstrated how local forcing mechanisms can interact with regional oceanographic conditions to produce drastic differences across the front of a buoyant plume. While more work has focused on the northern region of Monterey Bay (Graham & Largier 1997; Ryan et al. 2010; Woodson et al. 2009), similar connections between regional circulation and smaller-scale nearshore variability have been observed in southern Monterey Bay (Breaker & Broenkow 1994; Drake et al. 2005; Walter et al. 2014). Compared with other inner shelf locations in the region, southern Monterey Bay is characterized by long lags between wind forcing and sea surface temperature and a weak relationship between wind forcing and cross-shelf exchange (Drake et al. 2005; Woodson 2009). The majority of studies examining the synoptic scale variation of phytoplankton abundance and any potential relationships to physical advective mechanisms have focused on locations offshore of the cyclonic flow within the Monterey Bay (Olivieri & Chavez 2000; Pennington & Chavez 2000; Pilskaln et al. 1996; Service et al. 1998; Urmy & Horne 2016) or the northeastern section of the Monterey Bay (Ryan et al. 2010; Sevadjian et al. 2014).

Recent research indicates that synoptic scale variability in wind conditions influences water exchange across the mouth of Monterey Bay. Utilizing a conditional averaging approach to analyze surface currents during upwelling-favorable wind conditions, Paduan et al. (2016) demonstrated that water typically flows southward across the mouth of the bay without entering the bay under fully developed upwelling conditions. This is a result of previously documented anticyclonic flow outside the Monterey Bay and cyclonic flow inside the bay (Paduan & Rosenfeld 1996; Paduan & Cook 1997). The two contrasting current systems set up a transport barrier across the mouth of the bay and reduce exchange between the open ocean and inner bay waters. While the regional and local flows had been previously described, the approach in Paduan et al. (2016) of averaging surface currents only when certain wind conditions were met, rather than combining all surface currents for a season, resulted in a novel description of upwelling circulation in this region. Additionally, the description of surface circulation that resulted from periodic weakening or reversal of upwelling favorable conditions suggested an alternate circulation pattern driving water exchange between the open ocean and Monterey Bay. However, the relationship between synoptic variability in surface currents and nearshore phytoplankton abundance in southern Monterey Bay has not previously been explored.

This study addresses 1) the relationship between physical mechanisms and phytoplankton bloom events in southern Monterey Bay, and 2) seasonality in the relationships between physical mechanisms and phytoplankton abundance. Data from a suite of instruments deployed at a site in southern Monterey Bay are analyzed to identify specific chlorophyll events and characterize their magnitude and duration. The results of this study indicate that the supply of phytoplankton to the nearshore environment in southern Monterey Bay is episodic. During the summer months, when upwelling conditions were present, these episodic increases in phytoplankton are often preceded by weakening or reversal of upwelling favorable winds, and the interruption of surface current circulation patterns associated with upwelling. Wave driven mass transport is ruled out as a primary driver of observed chlorophyll variability at this location, which is relatively sheltered from wave energy. These results provide insight into both the mechanics governing phytoplankton delivery to the nearshore ecosystem of southern Monterey Bay, and the potential impact of wind relaxation events on nearshore ecosystems in upwelling regions generally.

2. METHODS

2.1 Monterey Wharf site, southern Monterey Bay

Monitoring of oceanographic conditions at the Monterey Wharf 2 in southern Monterey Bay is conducted through the Central and Northern California Ocean Observing System (CeNCOOS) and the

Moss Landing Marine Labs (MLML) Environmental Biotechnology Lab, at the site of the Monterey Abalone Company. This station is deployed at approximately 1.5 meters below mean low low water (MLLW). Chlorophyll fluorescence, salinity, turbidity, temperature, pH, and dissolved oxygen were measured every 5 minutes at the Monterey Municipal Wharf 2 (W2, Figure 1) from June 25, 2012 through October 11, 2013 by a YSI 6600 V2-4 Sonde with a chlorophyll fluorometer, phycoerythrin fluorometer, turbidity sensor, fast response pH electrode (glass bulb), conductivity-temperature sensor and an optical dissolved oxygen sensor. All optical sensors were equipped with mechanical wipers and cleaned every 15 minutes. All sensors were wrapped in copper tape to minimize fouling and the sensor head was encased in a brass/copper guard as additional fouling protection. The device was physically inspected on a monthly basis. Calibrations to establish zero points for chlorophyll, turbidity, and phycoerythrin were performed using filtered seawater on quarterly basis during equipment servicing. The site where this device is located is a partially sheltered location on the coast of the Monterey peninsula in the southern Monterey Bay at the Monterey Abalone Company site (W2, Figure 1). The servicing schedule for this station resulted in fragmented data. Only temperature could successfully be reconstructed into a contiguous time series. Chlorophyll data was confined to fragments, none of which extended beyond 4 months in length. National Data Buoy Center (NDBC) hosts and displays this data under the station ID MYXC1.

2.2 Meteorological Observations and Ocean Temperature

Hourly averages of the standard meteorological data were obtained from National Data Buoy Center (NDBC) buoy 46042 (N42, Figure 1). Wind stress was derived from hourly averaged wind speed measurements using the formulation of Large and Pond (1981). The vectors are decomposed into alongshore and cross-shore components using principal axis analysis (Emery & Thomson 2001). Negative alongshore wind stress is upwelling favorable for this region.

Additional data on sea surface temperature on the inner shelf were collected from the NDBC buoys 46240 (N40, Figure1), commonly referred to as the Cabrillo Point buoy. In order to construct a longer time series of water temperature at Wharf 2, a linear regression ($R^2 = 0.937$) between the temperature measured at Cabrillo Point and Wharf 2 was calculated to generate a more complete time series. In order to further analyze the movement of water masses around the Monterey Peninsula and throughout the region, temperature records for the time period covered by the Wharf 2 shore station were collected from NDBC buoys 46239 (N39, Figure 1) and 46092 (M1, Figure 1) and from long term thermistor deployments in Stillwater Cove (SWC) at depths of 0, 5, 10, and 15 meters that are maintained by the MLML Ichthyology Lab (Scott Hamilton, Principal Investigator). While still relatively sheltered, SWC is characterized by low mean temperatures and strong correlations between temperature and regional wind stress at all depths compared to other nearshore locations in Monterey Bay, indicating that is more exposed to upwelling-favorable winds (Drake et al. 2005). This relatively exposed site therefore provides a contrast to the Monterey Wharf site within Monterey Bay. Thermistor deployments and recovery were governed by availability of vessels and manpower as well as cooperation by weather conditions and, as such, were not consistent, either in temporal coverage or coverage across all depths, throughout the study period. For this study the measurements from the 10m depth provided the greatest continuous coverage during time periods of interest. All analyses involving SWC will use the 10m depth measurements. For NDBC buoys, 46042 and 46092 temperatures were measured at 0.6m depth below the water line while 46239 and 46240 were measured at 0.46m.

As this study focuses on synoptic scale events, where applicable, time series data was low pass filtered using the PL64 filter (Rosenfeld 1983) with a 33 hour half amplitude period to remove high frequency diurnal and tidal variability. Where time series lengths were 3 months or greater, additional harmonic analyses were performed to remove seasonal trends by fitting the data with annual and semiannual tidal constituents. Where the PL64 filter was not well suited for the data available, due to small gaps that were nonetheless too large to interpolate over, additional harmonic analyses were performed to extract variance associated with the diurnal tidal constituents responsible for the greatest variance (M2, K1, S1) following Woodson et al. (2009).

Due to the high degree of autocorrelation in oceanographic time series data, when performing any statistical tests an effective degrees of freedom calculation was performed. Decorrelation times were calculated by taking the first zero crossing in the autocorrelation spectrum of each variable. Effective degrees of freedom were calculated dividing the length of the time series by the decorrelation time and subtracting the appropriate value (e.g. N-1). Where cross correlations were performed, the longer of the two decorrelation times were used to generate the most conservative estimate of effective degrees of freedom, following Drake et al. (2005). These effective degrees of freedom were used whenever assessing the significance of correlation coefficients.

Satellite measurements of sea surface temperature (SST) were obtained from the NASA Group for High Resolution Sea Surface Temperature (GHRSST) project using a Level 4 processed AVHRR and AMSR-E microwave data product with a longitude/latitude resolution of 1 km.

2.3 Chlorophyll

As no segments of chlorophyll data from the W2 site are greater than 4 months in duration, seasonal variation in chlorophyll was accounted for by removing linear trends from the data set. All observations were low pass filtered using the PL64 filter to remove high frequency variability. The non-normal distribution of chlorophyll data was accounted for in correlation analyses by taking the natural log of the detrended fluorescence measurements.

2.4 Surface Currents

High frequency (HF) radar derived surface current data were obtained from the Central and Northern California Ocean Observing System (CeNCOOS), hosted by Scripps Institute of Oceanography, using latitude boundaries of approximately 36.5 to 37 degrees north, longitude boundaries of -121.7 to -122.35 degrees, and 2 km resolution. While HF radar coverage was not consistent across all grid points during the months of this study (June 2012 to October 2013), the available data was used to determine general trends and large-scale patterns in surface current circulation in Monterey Bay. Surface currents were examined in combination with temperature time series to determine the advective effects of surface currents on distinct water masses. The time series of surface current data was analyzed to determine those grid points with greatest coverage, as determined by the number of valid measurements, during the two summer periods of greatest interest. Tidal velocities were filtered out from surface current data using the t_tide MATLAB function for those previously listed tidal constituents (Pawlowicz et al. 2002).

After being identified, those grid points with the greatest data coverage were averaged to further provide a general understanding of surface current patterns experienced in the Monterey Bay. Four grid points in central Monterey Bay had the lowest number of missing values (red dots, Figure 1). These points were averaged between respective locations to provide a mean vector of surface current flow for Monterey Bay. Time series of alongshore and cross-shore components of surface currents were compared with water temperature measured at Wharf 2 and Stillwater Cove to examine any relationship between large scale circulation patterns and synoptic scale changes in the nearshore environment. The four points chosen for time series comparisons provide an index of variability for the surface currents outside the mouth of the bay. Additionally, daily averaged surface currents across the entire domain are used to examine evolving surface current patterns during a transition between oceanographic conditions in the south Monterey Bay.

3. RESULTS

3.1 Oceanographic conditions

3.1.1 Wind

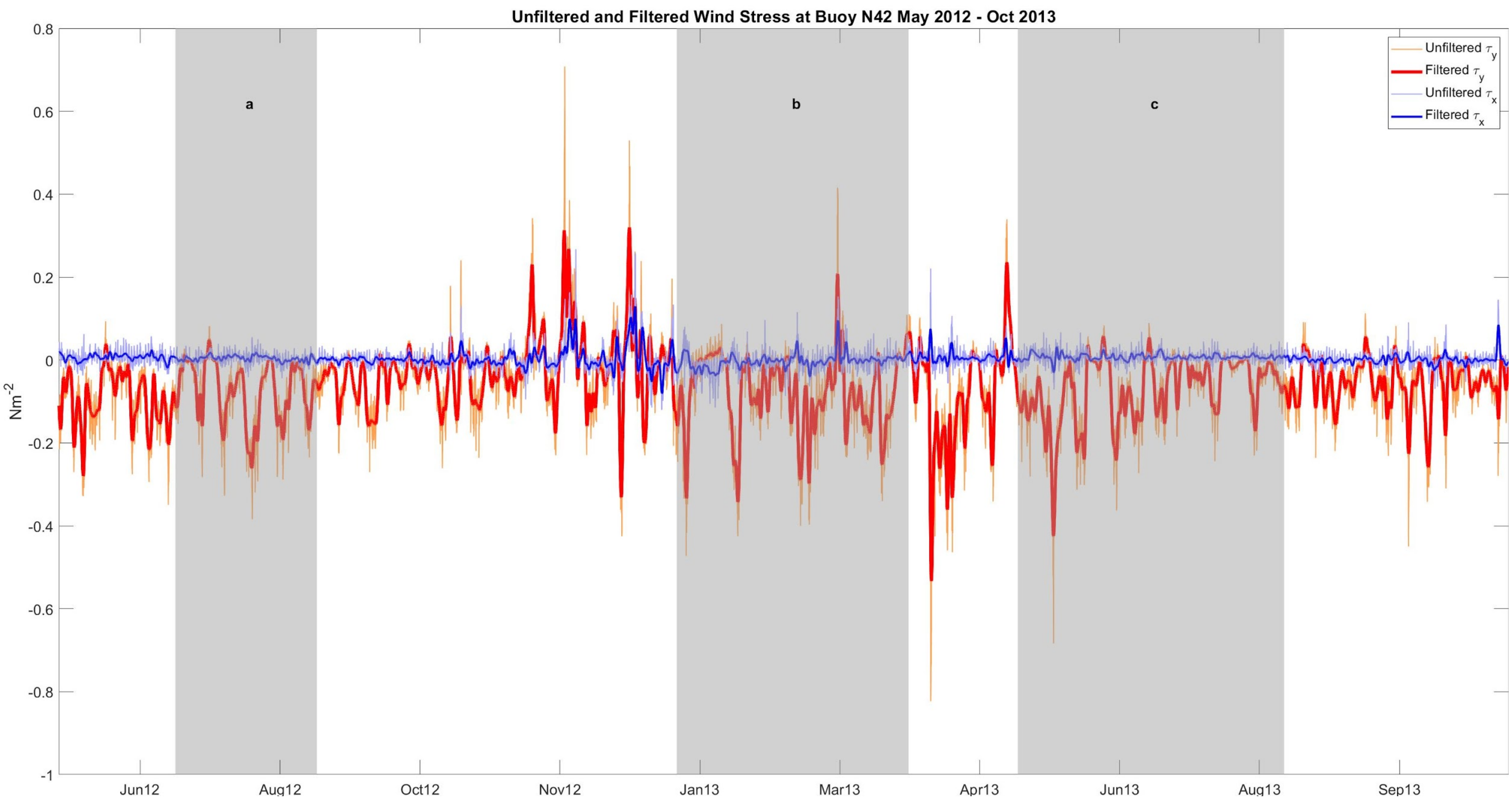

Figure 2. Unfiltered (thin lines) and low pass filtered (thick lines) wind stress measured at NDBC 46042 from May 2012 to October 2013 using rotated coordinate system shown in Figure 1. The shaded sections indicate the two summers (a,c) and one winter (b) when Wharf 2 temperature is compared with chlorophyll (Table 1).

Wind stress during the study period was primarily upwelling favorable, with primarily northwesterly winds occurring in the summer periods of each year studied (Figure 3). Upwelling favorable winds (300º to 350º) occurred, with some reversals, throughout most of the study period. This aligns closely with the angle of the coastline. Both summers studied experienced upwelling reversals. Following Huyer (1983), the intermittency of wind stress can be quantified using the ratio of the inverse mean value (positive indicating upwelling favorable conditions) to the standard deviation ($-\mu\tau_y/\sigma\tau_y$) for each month, Figure 3). The year 2012 was characterized by little to no upwelling conditions in early spring (low values) and then a rapid increase to persistent upwelling (high values) by May. This persistent upwelling condition was maintained through September, after which conditions rapidly returned to a state of non-upwelling. In contrast, the year 2013 was characterized almost entirely by an intermittent upwelling condition. These results, when compared to the long-term average, show that neither year was typical, although the pattern exhibited in 2012 was more consistent with the historical average.

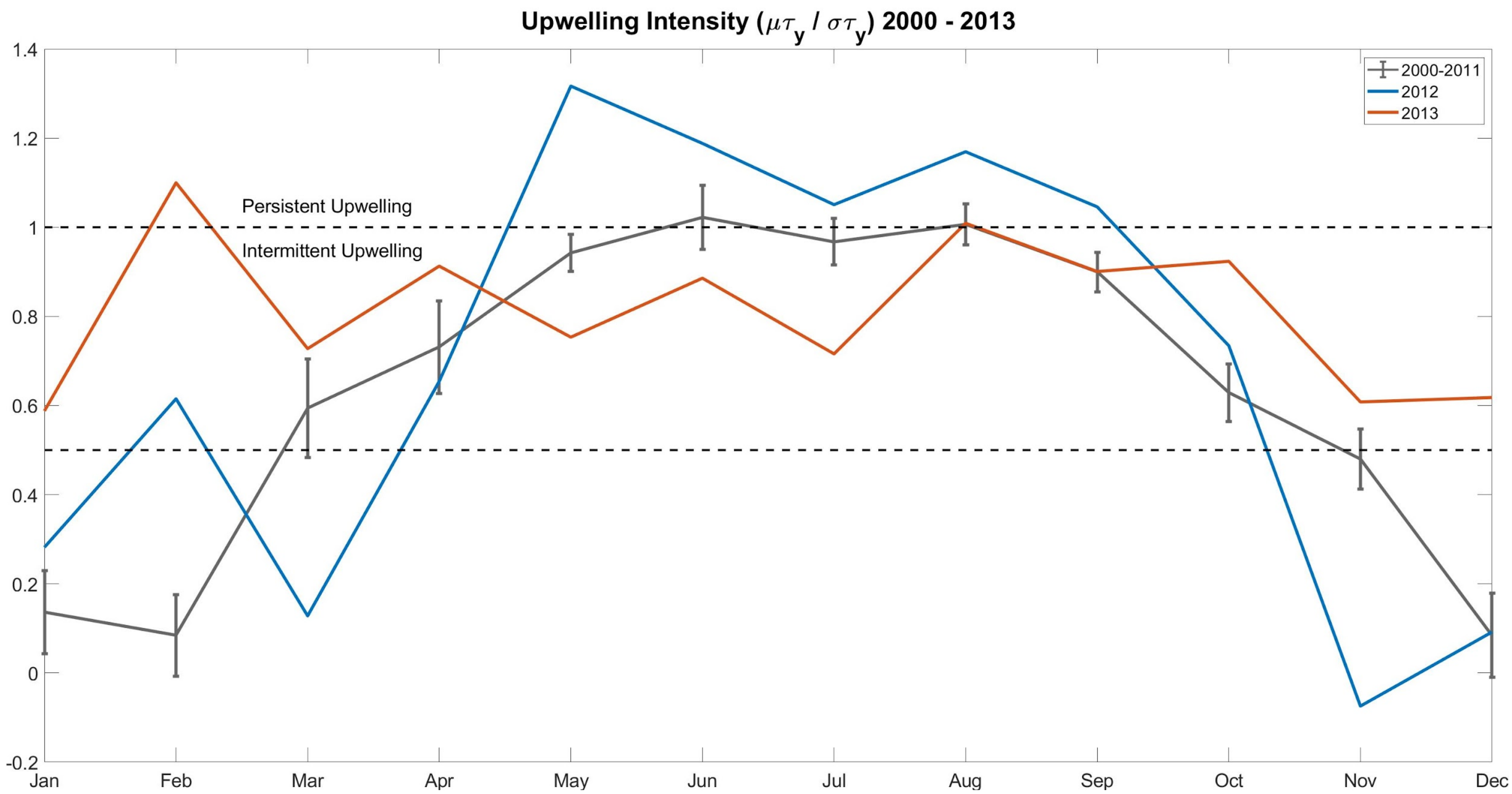

Figure 3. Monthly calculations of upwelling intensity index (-μτy/στy). Dashed lines at 0.5 and 1.0 indicate thresholds for intermittent and persistent upwelling respectively. Error bars represent the standard error of average upwelling intensity for 2000 – 2011.

3.1.2 Ocean Temperature

Water temperature at Wharf 2 displayed strong synoptic variation as well as seasonal trends. Comparisons were made between regional oceanic conditions as measured at N42, somewhat exposed coastal conditions as measured at Stillwater Cove, and the protected coastal conditions found at Wharf 2 (Figure 4). While the amplitude of the overall seasonal trend is reduced at Stillwater Cove, the trend exhibited across all stations is consistent. As will be shown in Section 3.3, despite relative proximity, the water temperature at Stillwater Cove and Wharf 2 exhibit very little correlation at the synoptic scale.

The cooler temperatures seen at Stillwater Cove are consistent with past examinations of the inner shelf of Monterey Bay (Drake et al. 2005).

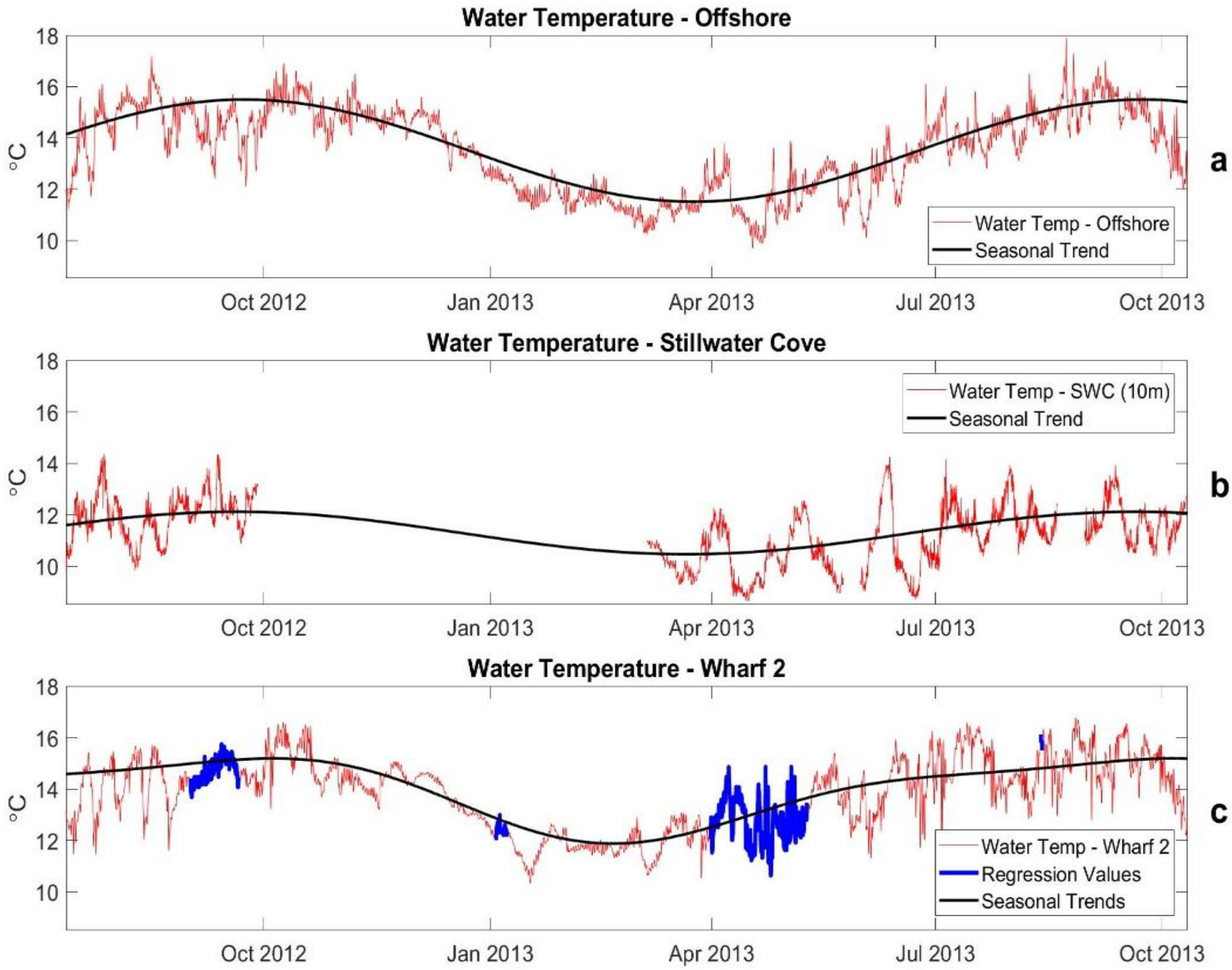

Figure 4. Water temperature with seasonal trends for a) Offshore (NDBC 46042), b) Stillwater Cove thermistor deployment, and c) Wharf 2 shore station.

3.1.3 Chlorophyll-a

Chlorophyll concentrations were highly variable between June 2012 and October 2013 (Figure 5). The one prolonged period of low fluorescence, from November 2012 to mid-February 2013, was punctuated with short term increases in chlorophyll concentrations. The prolonged high chlorophyll concentration that occurred in the fall of 2013 is considered atypical for the region (Palacios et al. 2016). It did correlate with higher abundances of planktivorous fish species, sea lions, sea birds, and humpback whales which were observed in Monterey Bay later in the year than is common (Palacios et al. 2016). Despite the gap in data from 04-Sep-2012 to 20-Sep-2012, it is unlikely that phytoplankton blooms of similar amplitude and duration occurred in the fall of 2012. A Welch t-test using effective degrees of freedom determined 2013 was a significantly more biologically active year than 2012. However, the focus of this study is identifying the physical factors that drive the typical variability of chlorophyll in Monterey Bay rather than the anomalous conditions during fall 2013. During all seasons captured in the time series, short term variation (1-6 days) was evident in the chlorophyll values.

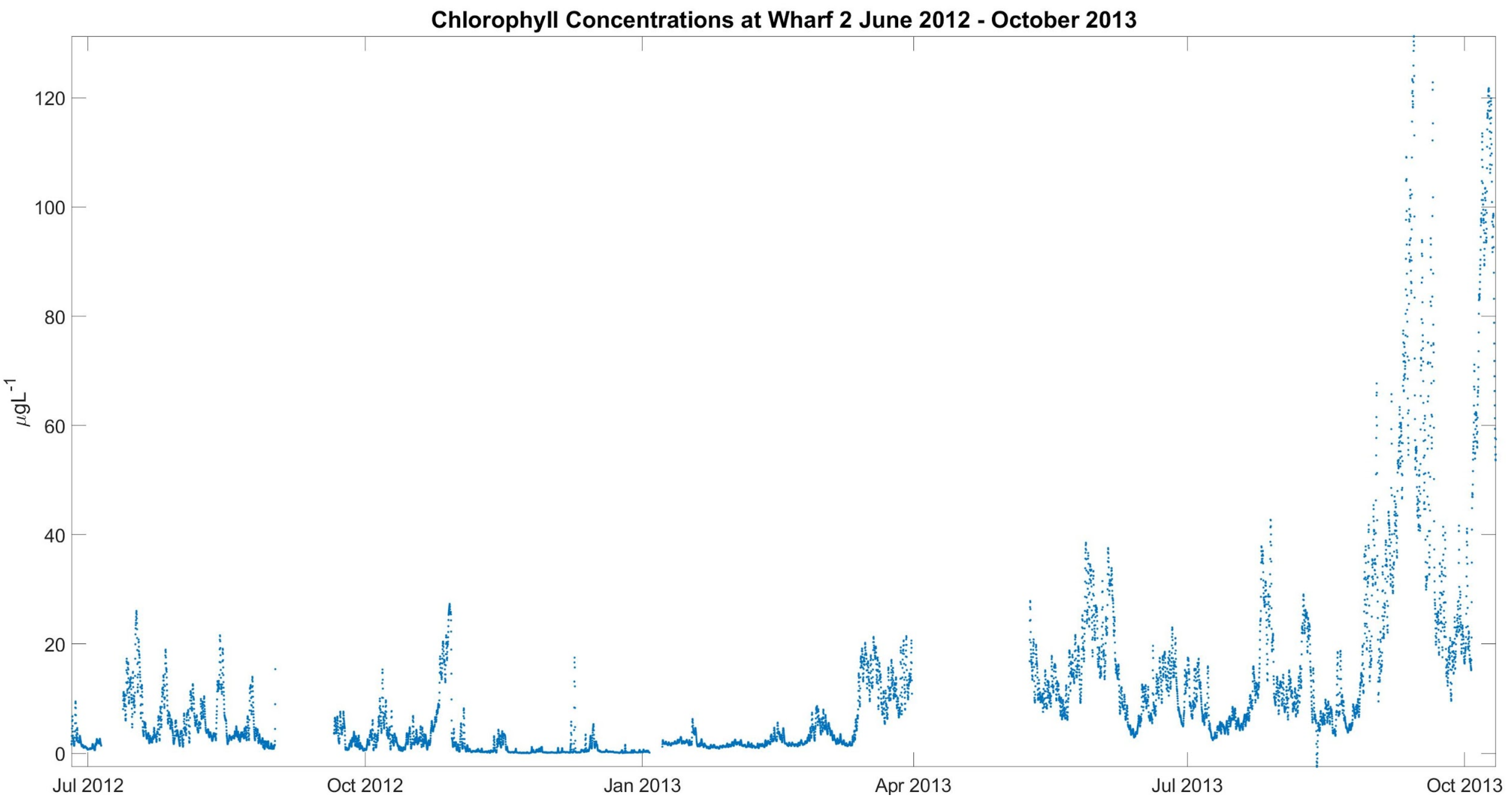

Figure 5. Hourly averaged chlorophyll values for June 2012 through October 2013 at Monterey Municipal Wharf 2.

3.2 Relationships between chlorophyll and physical variables

3.2.1 Correlation Analyses & Regression

Correlation analyses revealed that, of the various physical parameters measured, water temperature as measured at Wharf 2 was most consistently correlated with the log-transformed chlorophyll concentrations (Table 1) and had the greatest explanatory power. After correlation analyses revealed the closest correlation to exist between nearshore temperature and chlorophyll, linear regressions were calculated between log transformed chlorophyll measurements and water temperature (33 hour cutoff) where the correlation was significant (Figure 6). Initial regressions were calculated with low pass filtered data as well as unfiltered data but R^2 values were unaffected. These results demonstrate that, during the two summers studied, high chlorophyll at Wharf 2 was correlated with colder water temperature at the same location. This relationship is reversed during the one winter time segment observed during this study. Due to only a single winter being present in the study period, this work focused on characterizations of the two summer seasons studied.

Predictor	Time Period	R	Lag (hrs)	Effective DF	P
W2 Temperature	Jul 2012 – Sep 2012	-0.656	-13	26	$1.5e^{-4}$
W2 Temperature	Sep 2012 – Jan 2013	-0.239	163	23	0.25
W2 Temperature	Jan 2013 – Mar 2013	0.545	-46	21	$7.2e^{-3}$
W2 Temperature	May 2013 – Aug 2013	-0.699	3	18	$6.1e^{-4}$
W2 Temperature	Aug 2013 – Oct 2013	0.333	136	14	0.21
N42 Temperature	Jul 2012 – Sep 2012	0.448	19	21	0.03
N42 Temperature	Sep 2012 – Jan 2013	-0.135	157	24	0.51
N42 Temperature	Jan 2013 – Mar 2013	0.474	-102	24	0.14
N42 Temperature	May 2013 – Aug 2013	-0.366	-124	27	0.05
N42 Temperature	Aug 2013 – Oct 2013	0.448	130	14	0.08
M1 Temperature	Jul 2012 – Sep 2012	-0.366	70	24	0.06
M1 Temperature	Sep 2012 – Jan 2013	-0.285	148	30	0.11
M1 Temperature	Jan 2013 – Mar 2013	-0.635	61	13	0.01
M1 Temperature	May 2013 – Aug 2013	-0.625	61	22	$1.1e^{-3}$
M1 Temperature	Aug 2013 – Oct 2013	0.369	85	10	0.23
N42 Alongshore Wind Stress	Jul 2012 – Sep 2012	-0.475	-131	24	0.01
N42 Alongshore Wind Stress	Sep 2012 – Jan 2013	-0.146	-26	45	0.40
N42 Alongshore Wind Stress	Jan 2013 – Mar 2013	-0.333	-93	26	0.08
N42 Alongshore Wind Stress	May 2013 – Aug 2013	-0.411	-147	27	0.03
N42 Alongshore Wind Stress	Aug 2013 – Oct 2013	0.415	17	14	0.11
N42 Cross shore Wind Stress	Jul 2012 – Sep 2012	0.360	-69	26	0.06
N42 Cross shore Wind Stress	Sep 2012 – Jan 2013	0.123	-165	45	0.41
N42 Cross shore Wind Stress	Jan 2013 – Mar 2013	-0.431	-90	26	0.02
N42 Cross shore Wind Stress	May 2013 – Aug 2013	0.147	95	27	0.45
N42 Cross shore Wind Stress	Aug 2013 – Oct 2013	-0.308	-18	14	0.25
N42 Wave Height	Jul 2012 – Sep 2012	0.482	57	32	0.00
N42 Wave Height	Sep 2012 – Jan 2013	-0.248	-88	37	0.13
N42 Wave Height	Jan 2013 – Mar 2013	-0.269	-168	27	0.16
N42 Wave Height	May 2013 – Aug 2013	0.220	19	38	0.17
N42 Wave Height	Aug 2013 – Oct 2013	-0.269	-93	36	010
Cross shore Surface Currents	Jul 2012 – Sep 2012	-0.379	-69	13	0.06
Cross shore Surface Currents	Sep 2012 – Jan 2013	-0.243	-165	43	0.11
Cross shore Surface Currents	Jan 2013 – Mar 2013	---	---	---	---
Cross shore Surface Currents	May 2013 – Aug 2013	-0.454	95	27	0.01
Cross shore Surface Currents	Aug 2013 – Oct 2013	0.462	-18	14	0.07

Table 1. Results of correlation analysis between physical variables and log-transformed Wharf 2 Chlorophyll concentration. Shaded rows indicate where correlations were significant ($p < 0.05$). Negative lag indicates changes in predictor parameter leads changes in chlorophyll. Only predictors that were significantly correlated with chlorophyll during at least one time period studied are shown in this table. This excluded alongshore surface currents and N39 temperature.

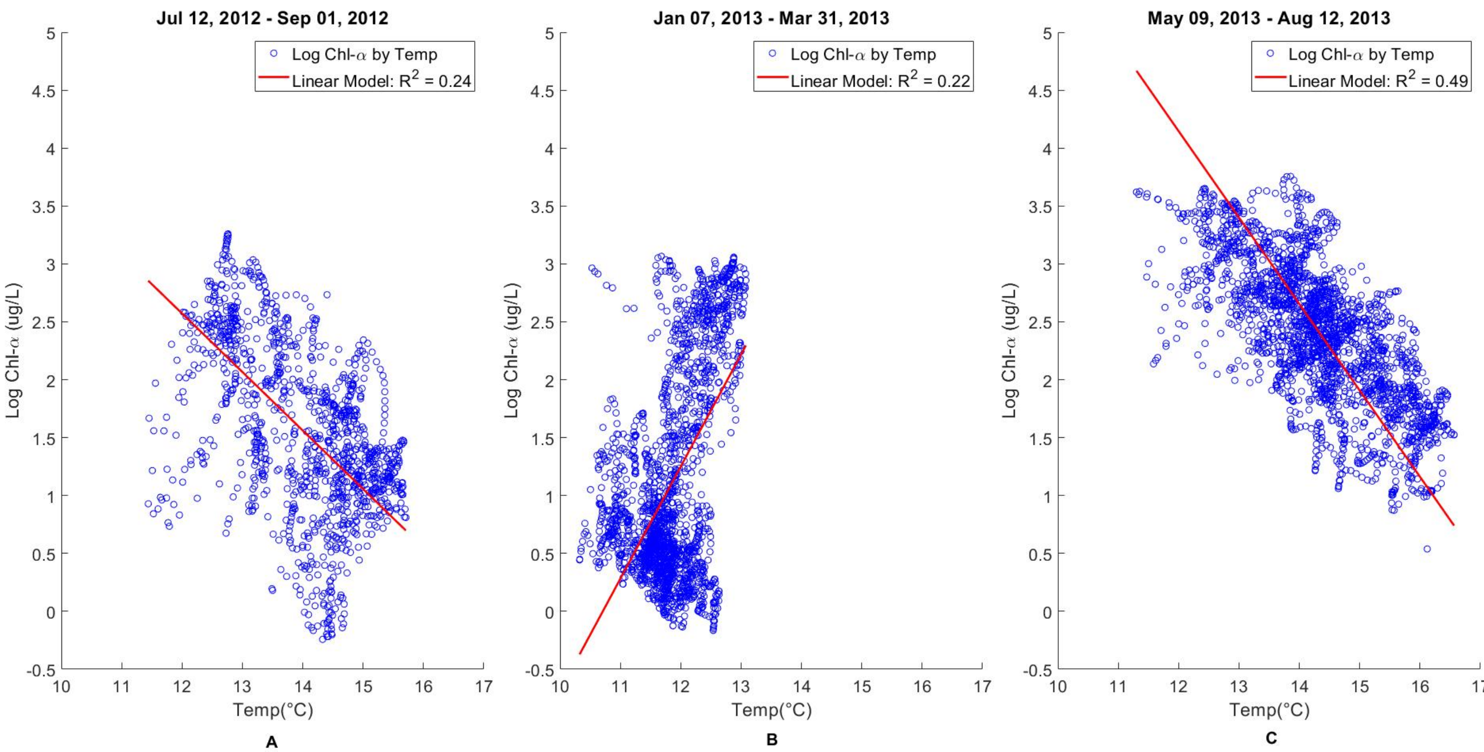

Figure 6. Low pass filtered (33 hour cutoff) temperature and low pass filtered/log transformed chlorophyll at Wharf 2 with linear regression for Summer 2012 (a), Winter-Spring 2013 (b) and Summer 2013 (c).

3.2.2 Regional patterns of variability and forcing

In order to better understand the advective mechanisms that influence water temperature at Wharf 2, time series of surface currents, wave height, and wind stress were examined along with the temperature and chlorophyll time series. To contrast a relatively exposed coastal environment as well as conditions at the mouth of the bay with the more sheltered Wharf 2 study site, water temperature from Stillwater Cove and M1 were included as well (Figures 7, 8). The inverse correlation between chlorophyll and temperature at Wharf 2 is apparent during both summer periods examined (Figures 7 a,b and 8 a,b). Examining the subsequent panels, additional relationships are suggested by the data. During the summer of 2012, periods of increased chlorophyll and decreased temperature co-occur with decreases in equatorward flow of surface currents (Figure 8 c), and decreases in upwelling favorable wind stress (Figure 8 e). The relationship between regional wind stress, specifically alongshore wind stress, and chlorophyll measured at Wharf 2 is statistically significant for both summers studied (Table 1).

As the strongest correlation was observed between nearshore temperature and chlorophyll concentrations, additional correlation analyses were performed using Wharf 2 temperature as the response variable. These analyses provided significant results for the 2012 summer only, with the exception of M1 temperatures in the summer of 2013. The high correlation between nearshore temperatures and alongshore wind stress in 2012 is consistent with past research for this region (Figure 3, Paduan & Cook 1997); the sign of the R value indicates that, as winds become more upwelling favorable, temperature at Wharf 2 increases (Figures 7, 8 b). Such a correlation does not exist for nearshore temperature measured at the relatively exposed site of Stillwater Cove (Figures 7, 8 d). Both surface current components (Figure 7 c) showed significant correlations with temperature at Wharf 2. The correlation with alongshore surface currents can be attributed to wind stress (Figure 7 e), which has a stronger correlation with the same sign. The relationship between M1 and Wharf 2 was inconsistent throughout the study period. M1 temperatures were correlated with Wharf 2 chlorophyll in the winter/spring and summer of 2013 only, and in both seasons changes in chlorophyll at Wharf 2 occurred 2.5 days prior to the changes in temperature at M1 (Table 1). M1 temperatures and Wharf 2 temperatures correlated only in the summer of 2013 (Figure 8 d) with a negative R value.

Based on previous research along an exposed rocky coastline (McPhee-Shaw et al. 2011), surface waves were examined as an alternative physical factor influencing chlorophyll concentrations at Wharf 2. Wave height was only found to be significantly correlated with chlorophyll for one summer studied. However, this correlation had a positive lag, indicating that increases in chlorophyll preceded increases in wave height. During both summers studied, wave heights were not significantly correlated with ocean temperature, while being strongly correlated with upwelling-favorable alongshore wind stress (Figure 7, 8 f). This correlation between wave height and wind stress, along with a lack of correlation with temperature, suggest that any appearance of correlation between wave height and chlorophyll at Wharf 2 is likely the result of the relationship between wind stress and wave height.

Of all the factors considered above, the most consistent correlation was found between water temperature and chlorophyll at Wharf 2. During both summers studied, there was a strong negative correlation between these two variables and very little lag was evident. However, high chlorophyll concentrations at Wharf 2 lag upwelling favorable wind stress by 5-6 days (Table 1). The temporal lag and variance explained by wind stress is consistent between both summers studied despite the high inter-annual variability in wind conditions. Transitions to cold water and high chlorophyll conditions are preceded by relaxations in upwelling favorable conditions (Figure 7, 8). This suggests that circulation dynamics occurring during wind relaxation are responsible for advection of phytoplankton biomass and cold water from offshore to the Wharf 2 site in southern Monterey Bay.

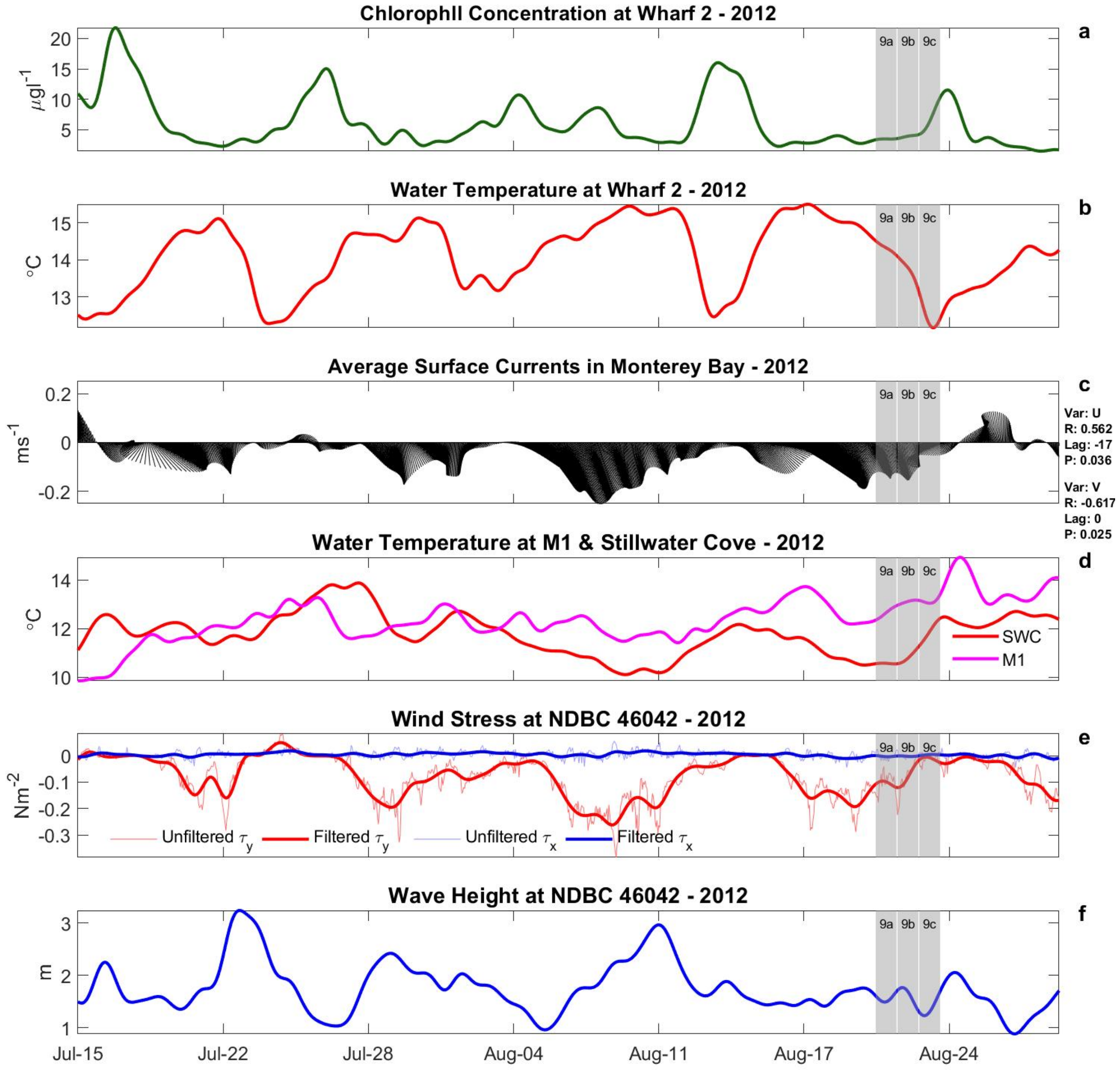

Figure 7. 2012 time series for (a) chlorophyll at Wharf 2, (b) water temperature at Wharf 2, (c) averaged surface currents, (d) water temperature at M1 and SWC, (e) alongshore wind stress, and (f) wave height. Shaded areas in each panel identify days used in surface current and SST maps in Figure 9. Surface current and wind stress coordinate plans have been rotated to align with the orientation of the coastline. Correlation results for physical mechanisms and Wharf 2 temperature are presented, where significant, in the text to the right of the relevant time series. Filtered and unfiltered wind stress components (e) follow those plotted in Figure (2)

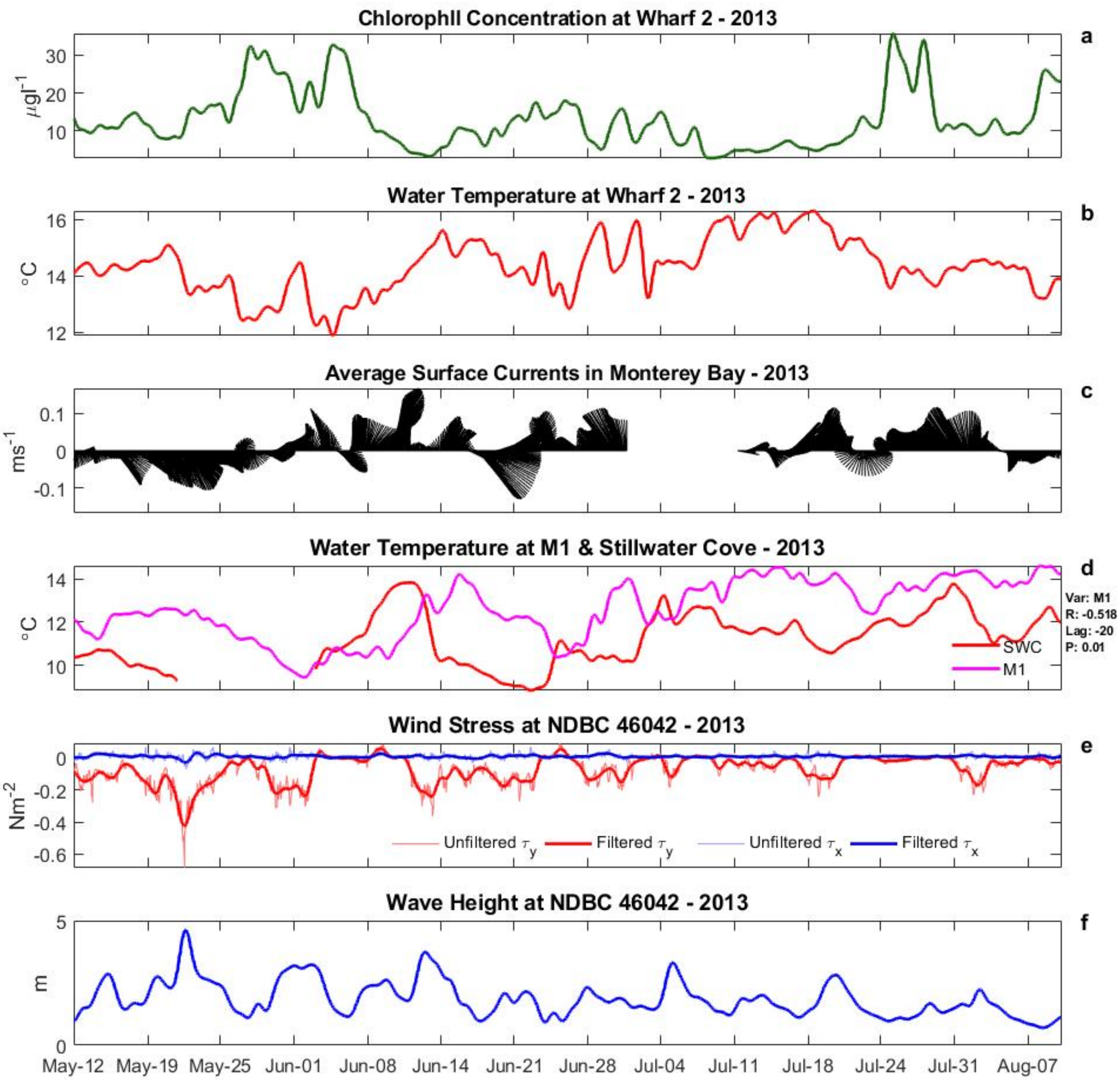

Figure 8. 2013 time series plots. Panel values and rotation of axes follow Figure 7. Y axes scales vary between years to display maximum variance for each parameter. X axes scales vary between years studied based on length of available data. Correlation results for physical mechanisms and Wharf 2 temperature are presented, where significant, in the text to the right of the relevant time series..

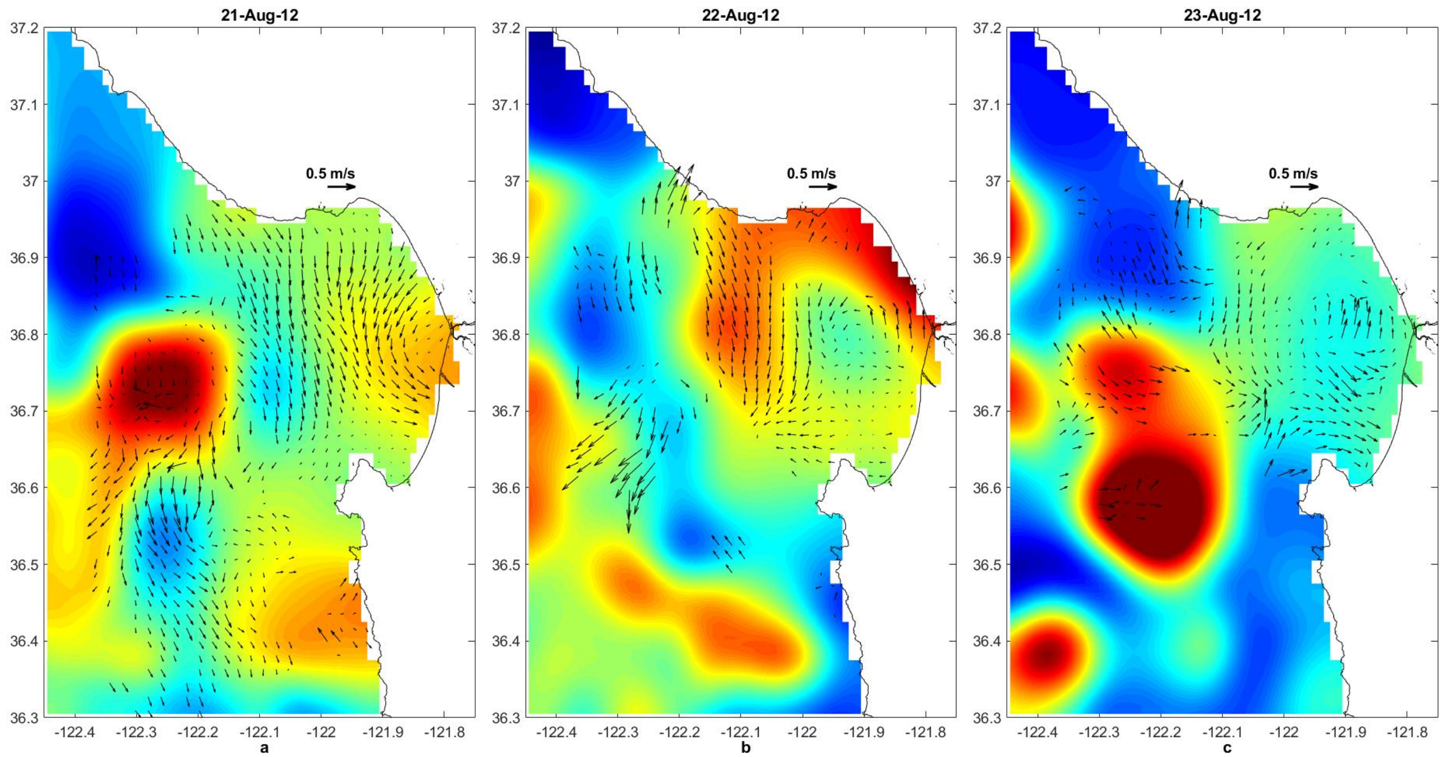

Figure 9. Plots of SST and average surface currents for a) August 21, b) August 22, and c) August 23 of 2012. Wharf 2 shore station is indicated by a red star on the inner coastline of the Monterey Peninsula

An example of the relationship between water temperature and surface currents during the persistent upwelling period is shown in maps of SST and daily averaged surface currents (with tidal velocities removed) over a 3-day time span in 2012 (Figure 9). Conditions transitioned from a high temperature, low chlorophyll condition at Wharf 2 (a) to a low temperature, high chlorophyll condition (c). This transition is slightly preceded by a shift in both wind stress and mean surface current flow and follows the downwelling/relaxation circulation patterns described in Paduan et al. (2016). The initial circulation is cyclonic within the Monterey Bay and anticyclonic without. Warm water retention within the bay is evident in the SST values. Cooler water is apparent near upwelling center to the north while warmer water is present to the south. After one day the cold waters at both upwelling centers are more pronounced, circulation within the bay is weaker, and a strong thermal gradient is present in the north of the bay. By the third day surface current patterns have broken down and cold water has now displaced much of the warm water in the bay.

4. DISCUSSION

The results of this study demonstrate a close relationship between temperature and chlorophyll in southern Monterey Bay which suggests that nearshore phytoplankton abundance is governed by advective mechanisms. Wind-driven surface current circulation is found to be an important driver of variability in water properties and phytoplankton biomass over the inner shelf of southern Monterey Bay, particularly during months when upwelling favorable conditions are persistent. High phytoplankton abundance was correlated with cold water and circulation patterns associated with weakening of upwelling conditions.

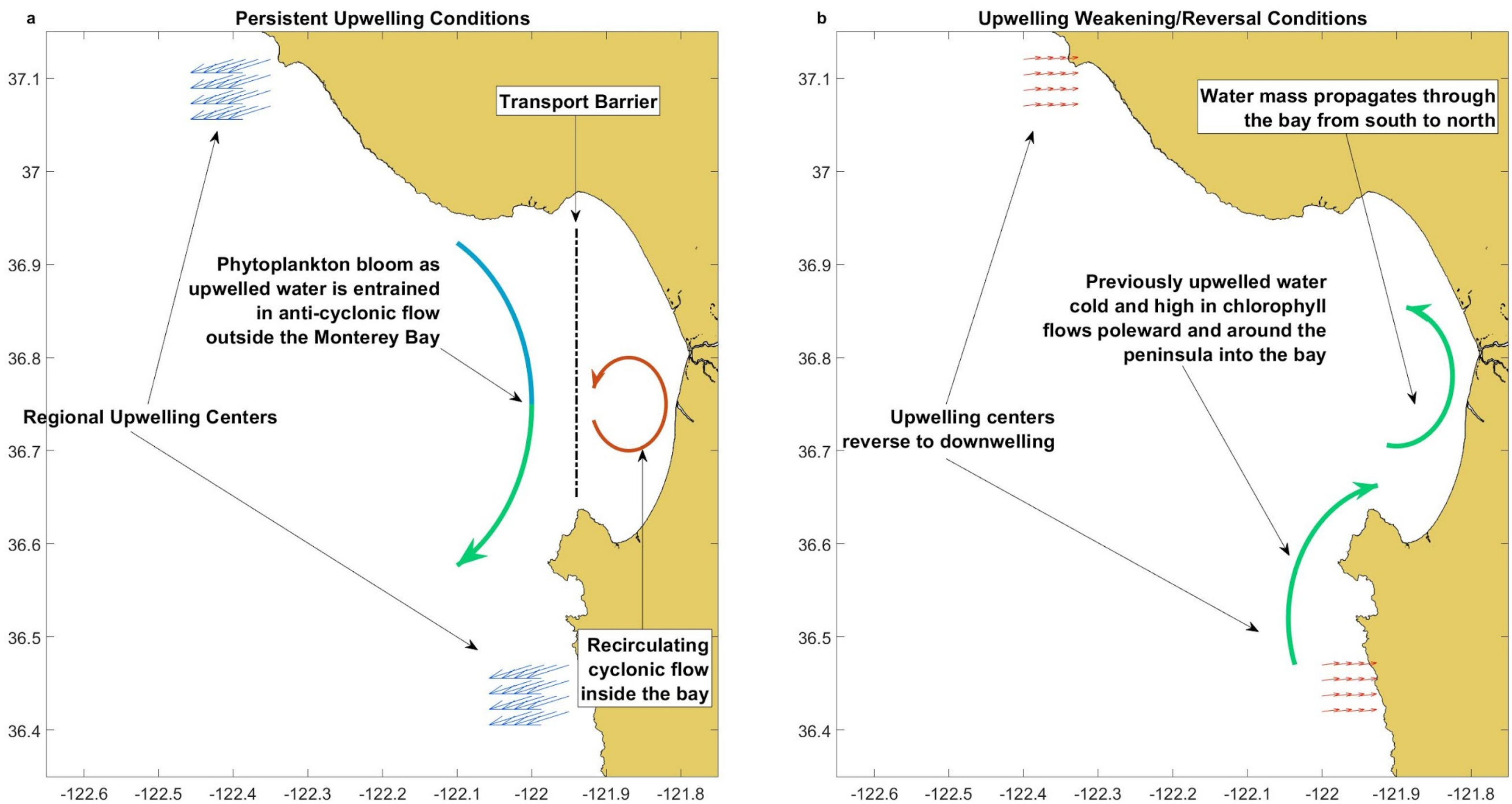

Figure 10. Proposed mechanism of water and phytoplankton transport during a) persistent upwelling events and b) wind reversals/relaxations.

A physical mechanism is proposed to account for the observed relationships between chlorophyll, nearshore temperature, alongshore wind stress and regional circulation in figure 10. Nutrient rich water is brought to the surface at two regional upwelling centers to the north and south of

Monterey Bay (Figure 10a). This water, initially low in chlorophyll, is advected offshore and equatorward as phytoplankton bloom. Warmer surface water circulates cyclonically within the bay while upwelled water is entrained in the anti-cyclonic circulation outside the bay (Paduan et al. 2016; Paduan & Cook 1997) and these two contrasting circulation patterns set up a transport barrier (dashed line, Figure 10 a). During upwelling relaxation or reversal (Figure 10 b), the alongshore flow at the mouth of the bay relaxes or reverses direction (poleward rather than equatorward) and the barrier between the inner area of the bay and the open ocean breaks down, causing surface water to advect from the south, flow into the southern Monterey Bay, and make its way north along the coast (Figure 10 b). The surface water being advected into the Monterey Bay, while still cooler than the water it is displacing, is at this point rich in phytoplankton. The surface flows shown by Paduan et al. (2016) suggest this flow will continue northward along the shore at a somewhat reduced velocity.

The proposed mechanism for phytoplankton delivery to the south Monterey Bay is supported by chlorophyll and temperature data from Wharf 2, regional wind stress measurements, regional average surface currents (Figure 7, 8), the documented phenomenon of cold upwelled water advecting northward around the Monterey Peninsula (Broenkow & Smethie 1978), and the circulation patterns described during upwelling and relaxation (Paduan et al. 2016). Upwelling favorable wind stress and corresponding equatorward mean surface currents are both observed during periods of increasing temperature at Wharf 2. This is consistent with Figure 9a, in which water recirculates and warms within the bay. The rapid decreases in temperature and subsequent increases in chlorophyll are accompanied by decreases or reversals in alongshore wind stress and mean surface currents. This suggests that, when upwelling favorable conditions are persistent, the circulation pattern described in Paduan et al. (2016) during weakening of upwelling conditions is the primary driver of phytoplankton to the coastal environment in south Monterey Bay. Considering the location of the points used in generating average surface current data (Figure 1) and the proposed circulation pattern (Figure 10), the correlation observed between cross shore currents and temperature at Wharf 2 (Table 1), westward currents correlating with increase in chlorophyll in the summer of 2013, also supports the mechanism proposed here. Decreases in temperature that coincide with westward shifts in surface currents(Figure 7c) can be explained by the downwelling circulation described in Paduan et al. (2016).

The timing of the relationships between upwelling, temperature and chlorophyll observed during May-September are consistent with previous observations in southern Monterey Bay. Cheriton et al. (2014) found that, during the 5 week study period occurring in mid-fall (September-October), two sustained upwelling favorable wind events occurred which caused shoaling of isotherms and isohalines as cold, high-salinity water filled the water column from below while the surface waters remained warm and well stratified. These periods of upwelling were punctuated by wind reversals associated with warm, low salinity water and reduced stratification. Both downwelling events were associated with increased surface chlorophyll down to 20m depth. In the nearshore region of southern Monterey Bay, temperature time series ~3 km to the northwest of Wharf 2 show a similar pattern of warm surface water associated with cold bottom water and stratification due to the combined influence of internal bores and upwelling (Drake et al. 2005; Walter et al. 2014) while the cross-shore exchange driven by wind and surface waves is relatively weak over the southern Monterey Bay inner shelf (Woodson 2013). The present study shows relationships between variables that are consistent with this previous work and proposes a new conceptual model for surface temperature and chlorophyll variability in southern Monterey Bay.

Wave-driven transport was examined as a potential mechanism for chlorophyll events at the study site, as has been previously documented on the exposed coast of California (McPhee-Shaw et al. 2011). However, at the Wharf 2 site in southern Monterey Bay, chlorophyll concentrations were more consistently correlated with cold water temperature than elevated wave heights. A study examining the impact of surface waves on chlorophyll concentrations farther north in the Monterey Bay region found that wave action contributed to increases in phytoplankton concentrations in the surf zone by redistributing phytoplankton originating from the inner shelf (Shanks et al. 2018). Additionally, breaking wave height as predicted by models shows a stark decrease between the middle and southern-most coastline of Monterey Bay (Orzech et al. 2010) resulting in dramatically lower wave energy at the site of the current study relative to areas northward. Thus, the lack of any predictive correlation between wave height and chlorophyll concentration is not surprising here. Additionally, Stokes drift would not account for the rapid changes in temperature that co-occur with changes in chlorophyll. Furthermore, if export from the shallow surf zone were the source of the phytoplankton increases observed, one would expect increases in shore station temperature to coincide with increases in phytoplankton, which is inconsistent with the observations. At a site near Stillwater Cove (Carmel River State Beach), inner shelf increases in phytoplankton followed reversals in upwelling conditions (Shanks et al. 2018). This reinforces the patterns observed in the current study and the proposed advective pattern.

Synoptic scale dynamics in nearshore regions are complex, often making it challenging to connect physical forcing mechanisms with key ecosystem parameters such as chlorophyll. The orientation and bathymetry of the Monterey Peninsula serve to increase this complexity. The relationship between coastal temperature and regional wind stress was only clearly discernible during a season of highly persistent upwelling favorable conditions. Observations from the outer mouth of the bay (M1) provided little insight into the mechanics except to highlight the difference between the two years studied. While the same degree of correlation between winds, surface currents, and nearshore temperature was not observed in 2013, the significant relationship between temperature and chlorophyll suggests that observed phytoplankton blooms are still the result of advection. It is likely that, due to the intermittency of upwelling favorable conditions in 2013, circulation patterns were not as clearly defined and thus harder to resolve. Previous work on the circulation patterns in Monterey Bay (Graham & Largier 1997; Paduan & Rosenfeld 1996; Rosenfeld et al. 1994) has attributed the source of upwelled water in Monterey Bay to Pt. Año Nuevo. While this may still be the case, the complexities of water advection presented here suggest further study on this topic may be warranted. Broenkow and Smethie (1978) concluded that recently upwelled water often flows poleward into Monterey Bay from an upwelling center to the south, or directly from the west when the direction of alongshore flow is not well defined. More recently, Ramp et al. (2009) observed cold water advecting poleward and offshore of the Monterey Peninsula during an upwelling relaxation event and hypothesized it may be the result of a poleward flow south of the peninsula interacting with equatorward surface currents across the mouth of the bay. This study did not set out to determine the geographic source of the relatively cold water associated with high chlorophyll at Wharf 2. However the potential alternative source for upwelled water could have implications in the composition of phytoplankton communities advected into the south Monterey Bay. A study of phytoplankton advection on the exposed coast of California found phytoplankton community compositions varied with the geographic sources of those communities (Paquin May, 2012) and on the coast of Washington state upwelling reversal conditions have been identified as sources for phytoplankton, and harmful algal blooms (HABs), to the nearshore environment (MacFadyen et al. 2005).

Despite a high degree of inter-annual variability during this study, the results demonstrate the importance of synoptic scale wind driven circulation events on phytoplankton abundance in nearshore ecosystems. The response of upwelling circulation patterns to even mild disturbances can have a dramatic effect in shifting the delivery of phytoplankton to the inner shelf. That observed phytoplankton abundance was significantly higher during the period of intermittent upwelling fits with previous work characterizing coastal ecosystems in various upwelling environments (Menge & Menge 2013). The results of this study indicate that, in order to better model phytoplankton delivery to the inner shelf in embayments with complex bathymetry, a more clear and nuanced understanding of the evolution of distinct water masses is required. Rather than simply examine the proximate advective mechanism preceding phytoplankton blooms, it is necessary to examine the complex interactions of multiple successive advective patterns.

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