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The impact of coastal runoff on ocean color during an El Niño year in Central California

Raphael M. Kudela[a,*], Francisco P. Chavez[b]

[a]Ocean Sciences Department, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA
[b]Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039, USA

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Abstract

The introduction of the SeaWiFS ocean-color instrument in the autumn of 1997 coincided with the onset of perhaps the largest El Niño event of the century, providing us with the opportunity to monitor the impact of such events on biological and bio-optical properties in central California. The increased importance of coastal runoff (both sediments and fresh water) during the winter of 1998 have been striking. Here we evaluate the effects of riverine input to central California immediately following the largest El Niño-influenced winter storm event in central California of February 1998 using shipboard, mooring, and satellite observations from the sea-viewing wide field-of-view sensor (SeaWiFS). Two models were employed to estimate colored dissolved organic matter, (CDOM), which provided similar spatial and temporal patterns of CDOM, but differing absolute concentrations. We observed a 5-fold increase in SeaWiFS-derived chlorophyll concentrations, with a corresponding CDOM signal (estimated absorption at 300 nm greater than $0.30\,m^{-1}$) extending to approximately 300 km offshore. This event, while anomalous, demonstrates the potential influence of riverine input on the bio-optical properties of the coastal environment extending to several hundred kilometers offshore.

1. Introduction

Monterey Bay, California, is located on the eastern edge of the California Current system, and is classified as an eastern boundary current regime. Monterey Bay typically will exhibit several strong upwelling-favorable wind pulses lasting for several days during the upwelling season (March–September), followed by periods of weaker winds or even wind reversals (Breaker and Broenkow, 1994; Rosenfeld et al., 1994). During weak upwelling there is typically a persistent source of upwelled waters to the north of Monterey Bay near Davenport, California. The spatial and temporal extent of these upwelling plumes is highly variable, and warm, nutrient-depleted waters can still occur in this region during the upwelling season (Pennington and Chavez, 2000). However, under

*Corresponding author. Tel.: +1-831-459-3290, fax: +1-831-459-4882.
E-mail address: kudela@ucsc.edu (R.M. Kudela).

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normal conditions, this region is dominated by coastal transport and largely unaffected by fluvial inputs.

Associated with these upwelled waters are elevated macro and micronutrients, which feed a high-biomass, high-productivity diatom-dominated system from about March–October (Wilkerson et al., 2000). During El Niño events, this seasonal increase in productivity and subsequent export of organic material is greatly reduced, with less upwelling-favorable conditions and anomalously warm (nutrient-depleted) waters upwelled and advected towards shore (Chavez, 1996; Kudela and Chavez, 2000).

The introduction of the Sea-viewing wide field-of-view sensor (SeaWiFS) ocean-color instrument in the autumn of 1997 occurred shortly after the onset of one of the largest El Niño events of the century (McPhaden, 1999). The onset of the 1997–1998 El Niño event was observed in Monterey Bay initially as an anomalous increase in late June 1997 of sea-surface height, followed approximately a month later by sea-surface temperature (Chavez et al., 2002). Temperature anomalies peaked in autumn 1997, and there were generally weaker upwelling-favorable or downwelling winds during the 1997–1998 El Niño (Schwing et al., 2002). These anomalous conditions largely returned to normal in early 1998 (February–April; Collins et al., 2002 and references therein), but temperature anomalies remained in Monterey until October 1998 (Chavez et al., 2002). The recovery in spring 1998 was characterized by a rapid freshening of coastal waters attributed to river runoff (Wilkerson et al., 2002; Friederich et al., 2002). Based on river flow and salinity/nutrient characteristics, it is probable that the surface river-freshened waters were overlying a larger body of Subarctic Pacific (offshore) waters normally found further offshore (Collins et al., 2002; Castro et al., 2002).

The physical anomalies associated with the El Niño resulted in dramatic changes in biological productivity offshore, with a significant decline in both primary production (Chavez et al., 2002) and new primary production (Kudela and Chavez,

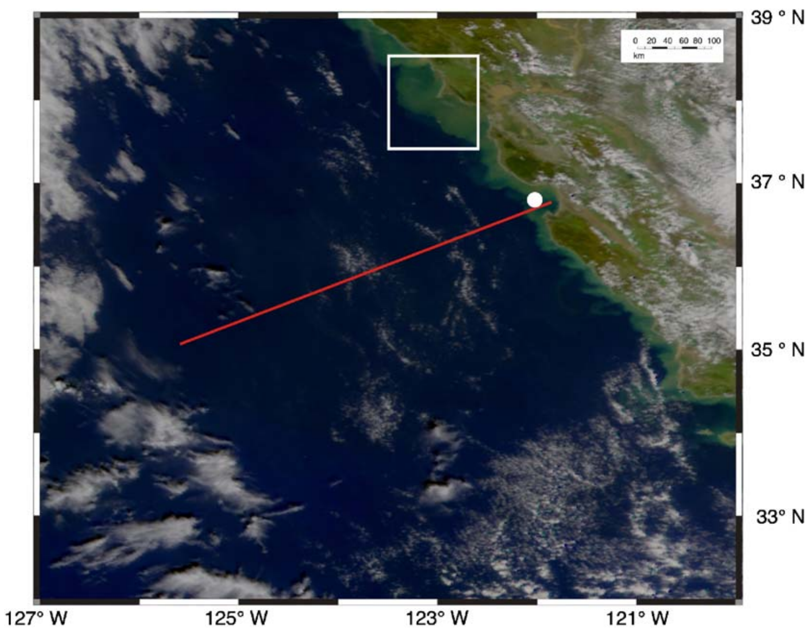

Fig. 1. SeaWiFS quasi-true color image (bands 6, 5, 1) of the region of interest from February 9, 1998. The red line indicates the cruise track of CalCOFI Line 67. The white circle is the approximate location of the MBARI M1 mooring. The white box denotes the CoOP WEST study region, which was used for CDOM measurements. Note the extensive coastal runoff visible in the true-color image. Data source: SeaWiFS file S1998040204831.L1A_HMBR.

2002). Nearshore, however, at locations such as the Monterey Bay Aquarium Research Institute (MBARI) time series, phytoplankton productivity is relatively unaffected by El Niño events due to the continuing presence of weak upwelling (Siegel et al., 1995; Chavez, 1996; Kudela and Chavez, 2000, 2002; Chavez et al. 2002).

During 1998, rainfall in California increased dramatically as the 1997–1998 El Niño event transitioned to La Niña conditions. The storm of February 1–9 resulted in rainfall exceeding the previous records for a period ranging from 10 to 100 years, depending on location (Monterey was the site of a ''100-year event''), with anywhere from 200% to 400% of average monthly rainfall (Mertes and Warrick, 2001 and references therein). Despite this heavy runoff, the suspended-sediment signal as estimated from SeaWiFS typically extended less than 30 km from the coast (Fig. 1; Mertes and Warrick, 2001). Here we demonstrate that this fluvial input impacted the bio-optical properties of the central California coast considerably further than the ca. 30 km evident for sediment transport, likely extending as a low-salinity, high colored dissolved organic material (CDOM) field upwards of 300 km from the coast. This outflow likely provided a significant source of macronutrients (Wilkerson et al., 2002) to the nutrient-poor surface waters associated with coastal California during this time period (Castro et al., 2002), and may have served as a trigger for the development of toxic phytoplankton blooms (Scholin et al., 2000). The general effects of sediment outflow events (Mertes and Warrick, 2001; Ruhl et al., 2001) and CDOM variability (Kahru and Mitchell, 2001) have been described for central California, and will not be further discussed here, except in relation to the extreme flow event of February 1998.

2. Methods

2.1. Shipboard measurements

Approximately monthly time-series cruises (since 1989) have been conducted at several nearshore stations in Monterey Bay, with discrete samples collected for estimates of nutrient concentration, chlorophyll concentration, primary production, and species composition, as described in Pennington and Chavez (2000). To augment these measurements, an ongoing series of cruises along CalCoFI line 67 (Fig. 1) have been added, with four cruises in 1997 and nine cruises completed in 1998. For CDOM validation, additional data were collected as part of the Coastal Ocean Processes program Wind Events and Shelf Transport (CoOP WEST), during four cruises between 2000 and 2002 (May–June 2000, June 2001, January 2002 and June 2002), predominantly in a region between 37° 30' and 38° 30' N, 122° 30' and 124° W. No CDOM measurements were collected during the 1997–1998 field program.

Sampling for optical properties included in situ profiling to measure both inherent and apparent optical properties, as well as discrete water samples for more detailed laboratory measurements. Downwelling irradiance (412, 443, 490, 510, 555 and 670 nm, spectral bandwith, 10 nm; and broadband PAR) and upwelling radiance (412, 443, 490, 510, 555, 683) were measured using a hand-lowered Biospherical Instruments PRR-600 with matching deck reference PRR-610 (412, 443, 490, 510, 555, 670, PAR), with post-processing following the methods of Siegel (1985). Data from central California (predominantly within 400 km of the coast, with $>50\%$ of the optical casts within 100 km of the coast) collected between 1989 and 2000 were used for algorithm performance estimates. Approximately 27% of the spectral data were from 1997 to 1998, including multiple data points from January, March, and May 1998.

CDOM is operationally defined as the volume absorption coefficient at 300 nm after filtration with 0.2 μm membrane filters, normalized to deionized water (cf. Kahru and Mitchell, 2001). These values are sometimes referred to as colored dissolved material (CDM; Maritorena et al., 2002), since it is not generally possible to separate the effects of dissolved and <0.2μm particles; we consider CDM and CDOM to be interchangeable for the purposes of this study. Samples were collected from Niskin bottles on a standard CTD rosette system and run fresh (within 12 hours) from multiple depths on a Varian Cary 50 spectrophotometer with a 10 cm quartz cuvette. The exponential slope, *s*, of the spectral shape was determined (e.g. Bricaud et al., 1981), for comparison with other data sets. Other parameters (chlorophyll, conductivity, temperature, nutrients) were measured following the same protocols as described above.

2.2. Moorings

Continuous records of oceanographic and atmospheric conditions in Monterey Bay including salinity, temperature, fluorescence, bio-optical parameters, and winds data are made on a routine basis on the MBARI M1 mooring, located in 15 km from shore in 1000 m water within the Monterey Canyon (Chavez et al., 1997). At 10 m, a Biospherical PRR-600 spectroradiometer records downwelling irradiance at 412, 443, 490, 510, 555, and 656 nm plus PAR, and upwelling radiance at 412, 443, 490, 510, 555, 670, and 683 nm. At approximately 1.5 m depth, a WETLabs miniature fluorometer records in vivo fluorescence from which chlorophyll concentration can be determined. Beam attenuation was measured at approximately the same depth with a WETLabs C-Star 25-cm pathlength beam transmissometer (660 nm). Data from the PRR were used to calculate in situ remote-sensing reflectance (R_{rs}), determined as the ratio between upwelling and downwelling light. Because the radiometer was at 10 m depth, and there were no estimates of vertical attenuation, it is not possible to extrapolate the in situ reflectance measurements to the equivalent surface reflectance values, and the in situ R_{rs} values are not directly comparable to satellite remote-sensing values. These data can be used for algorithm performance testing and comparison of trends, however. Data from the moored beam transmissometer were discarded prior to an instrument swap on year day 22 (1998) because of obvious fouling. Fluorometer and transmissometer data from year day 70 to 79 also were discarded because of data quality issues (the instruments were functional, but the recorded data were erroneous). On year days 50 and 62, the optical instruments were cleaned as part of mooring servicing. Riverflow data were obtained from the California Department of Water Resources.

2.3. Algorithms

Chlorophyll and CDOM values were calculated from the SeaWiFS data using the OC2v2 band-ratio algorithm (O'Reilly et al., 2000) and the CDOM algorithms of Kahru and Mitchell (2001), hereafter referred to as KM01, and the Garver–-Siegel–Maritorena algorithm (Garver and Siegel, 1997; Maritorena et al., 2002), hereafter referred to as GSM01. Cellular pigment-packaging effects, which could influence the CDOM algorithm, were evaluated using the algorithms described by Carder et al. (1997). Since the KM01 and GSM01 models report CDOM absorption (m^{-1}) at differing wavelengths, the CDOM values from the two models were normalized to 300 nm as described below. Moored radiometer data were used to estimate chlorophyll using the OC2v2 algorithm; this was chosen over the OC4v4 algorithm because fewer radiance bands are required, minimizing artificial changes in estimated chlorophyll from selective drift in the radiometer channels.

2.4. SeaWiFS data

Ocean-color (SeaWiFS) data were obtained from the MBARI High Resolution Picture Transmission (HRPT) station, and processed at UCSC using the SeaDAS package (version 4.3; Fu et al., 1998) to produce Level 2 data using the default values for reprocessing 4. The OC4v4 chlorophyll algorithm and the GSM01 colored dissolved material (CDM) algorithm (Maritorena et al., 2002) were applied to the normalized water leaving radiance (*nLw*) L2 data using the standard settings for SeaDAS, which includes a near-infrared iterative atmospheric correction for coastal waters (Siegel et al., 2000); the CDOM algorithm of Kahru and Mitchell (2001) was calculated from the *nLw* fields for the same images. There are known issues with atmospheric correction in turbid or high-biomass waters that may influence the CDOM algorithms (e.g., Kahru and Mitchell, 1999). To minimize this problem, an additional quality flag was applied to the CDOM images (Fig. 3) as implemented by Siegel et al. (1995). Pixels with *nLw* (412) values less than $0.2\,\mu W\,cm^{-2}\,nm^{-1}\,sr^{-1}$ were masked in the CDOM (but not chlorophyll) imagery. This had negligible effects on the January and February imagery, but removed a substantial subset of high-biomass pixels from the March image (Fig. 3, inset). For comparison to a climatological mean, a composite image for OC4v4 chlorophyll, KM01 CDOM, and GSM01 CDM were created using a geometric mean for February (year days 32–59) from the years 1999–2002. A quasi-true color composite image was created (Fig. 1) using the SeaDAS program, with bands 6, 5, and 1 (670, 555, and 412 nm). SeaDAS applies Rayleigh corrections to the top-of-the atmosphere L1A data prior to the generation of these true-color composites. All images were mapped to a cylindrical projection, with a nominal resolution of 1 km per pixel.

3. Results

3.1. Algorithm performance

Because we did not have field samples from shipboard data during February 1998, it is important to verify that the algorithms used to estimate chlorophyll and CDOM for this study are reasonably accurate. To determine whether the SeaWiFS data significantly bias biomass estimates, we tested the OC2v2 and OC4v4 chlorophyll algorithms with a regional dataset of bio-optical and chlorophyll measurements. There are known biases in the OC2v2 algorithm for central California compared to other oceanic provinces, with a slight underestimate at moderate ($1-10\,mg\,m^{-3}$) chlorophyll levels and overestimates at the extremes (0.1–1.0, $>10\,mg\,m^{-3}$ Chl, Fig. 2; see also Kahru and Mitchell, 1999). Compared to the global data set used to parameterize the original OC2 and OC4 algorithms (O'Reilly et al., 1998), our data exhibit a factor of 5–10 more variance. The OC4v4 algorithm performed similarly to OC2v2 with our regional data set, with a slightly better overall r^2 value (0.35 versus 0.30). Although the statistical fit to our data is poor relative to the global data set, the percent root mean square (%RMS) error is similar, with approximately 21% for the regional data set, and 35–45% for the most recent evaluation of the global OC4v4 algorithm (O'Reilly et al., 2000). We also tested this regional database against several other published algorithms including CAL-P6 (Kahru and Mitchell, 1999). All of these algorithms performed similarly in terms of RMS error, providing retrieved chlorophyll values within $0.16\,mg\,m^{-3}$ chl (mean square prediction error).

For testing the CDOM algorithms, we compared the spectral shape functions from a large (225 discrete measurements) dataset of near-surface samples. The spectral slope (s) for our data ($s=0.0173$) was within the expected range of reported values ($s=0.0185$, Kahru and Mitchell, 2001; $s=0.025$, Carder et al., 1999), as was the range of values ($0.1<a_{cdom}(300)<0.85$, mean$\,=0.25\pm0.04\,m^{-1}$). We did not have a large enough data set of in situ CDOM and reflectance measurements to directly test the retrieval from optical data; however, given the similarity of our data to that reported for California by Kahru and Mitchell (2001) for the same time period, we are confident that the reported trends are accurate.

To directly compare the results of the GSM01 and KM01 models it is necessary to normalize the CDOM results to the same wavelength (GSM01 estimates CDOM absorption at 443 nm while the KM01 model estimates values at 300 nm). Based on previous comparison methods (Kahru and Mitchell, 2001), we used the average spectral slope from our field data ($s=0.0173$) to extrapolate the GSM01 values to 300 nm. Kahru and Mitchell (2001) estimate that at 300 nm, only about 4.5% of the retrieved absorption signal is due to particulate, rather than dissolved, material. In contrast, Siegel et al. (1995) report that 22.7% of the CDM signal at 440 nm is detrital for California Current waters, suggesting that, after normalizing to 300 nm, there will still be a consistent overestimate of CDM by GSM01 relative to KM01.

It is apparent from the estimated CDOM values (Fig. 3) that the GSM01 model consistently overestimates CDM relative to the KM01 model.

While part of this discrepancy can be attributed to the relative contribution of detrital material at 440 versus 300 nm, the magnitude of the offset suggests that this is not the only issue (i.e. there is more than a 25% offset between algorithms). As discussed by Kahru and Mitchell (2001), KM01 is a band-ratio algorithm using *nLw* values at 443 and 510 nm. It is expected that KM01 would be relatively more insensitive to atmospheric correction issues than GSM01, which is a semianalytic model that inverts the water-leaving radiance data from all bands to solve simultaneously for multiple parameters (for details, see Garver and Siegel, 1997; Maritorena et al., 2002). There are substantial atmospheric correction issues for coastal waters on the US west coast (Siegel, pers. comm.). Kahru and Mitchell (1999) reported artificially low *nLw* values extending from 412 to 490 nm, however, so the potential for atmospheric correction issues affecting both models exists. Both Kahru and Mitchell (2001) and Siegel et al. (2000) report that, despite the potential for atmospheric correction issues, the respective algorithms perform well in coastal waters.

Although these models were not directly compared by the authors, Kahru and Mitchell (2001) did compare the KM01 model to another semianalytic model (Carder et al., 1999). That comparison demonstrated a consistent bias (overestimate) of the Carder model relative to KM01, similar to what we report. Kahru and Mitchell attributed some of this bias to atmospheric correction, and also reported a relatively high failure rate for the semianalytic model. In our application of the GSM01 model we also found that it had a much higher failure rate in coastal waters for chlorophyll retrievals relative to the OC4v4 algorithm (data not shown), suggesting that the GSM01 model is much more sensitive to initial parameterization and atmospheric correction errors. The GSM01 model assumes that water leaving radiance spectra

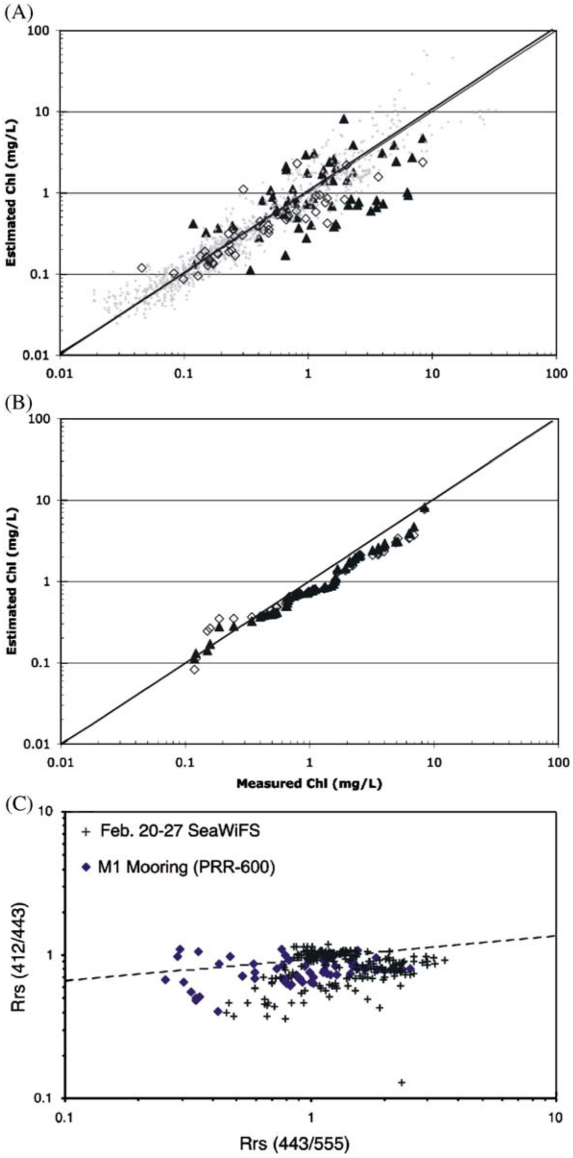

Fig. 2. Modeled versus measured chlorophyll *a* values from the MBARI bio-optical database (in situ measurements) using the OC2v2 (filled diamonds) and OC4v4 (open triangles) chlorophyll algorithm. (A) a scatter plot of the data, overlayed on the original SeaBAM global dataset used to parameterize OC2 and OC4 (O'Reilly et al. 1998). (B) quantile–quantile plot of the data. Statistical parameters for these data are: slope, 1.042; intercept, −0.70; RMS error, 0.398; MSPE, 0.158 mg Chl m^{-3} (OC2v2), and slope, 1.049; intercept, −0.392; RMS error, 0.403; MSPE, 0.163 mg Chl m^{-3} (OC4v4). The MSPE value represents the error in chlorophyll units. (C) moored (diamonds) versus SeaWIFS *nLw* values ('+') values from February 20–27, 1998. SeaWiFS values represent the transect data plotted in Fig. 4. The dashed line corresponds to $r12 = 0.95[r25]^{0}.16$. Values below the line represent ''packaged'' pigments and/or CDOM (Carder et al., 1997).

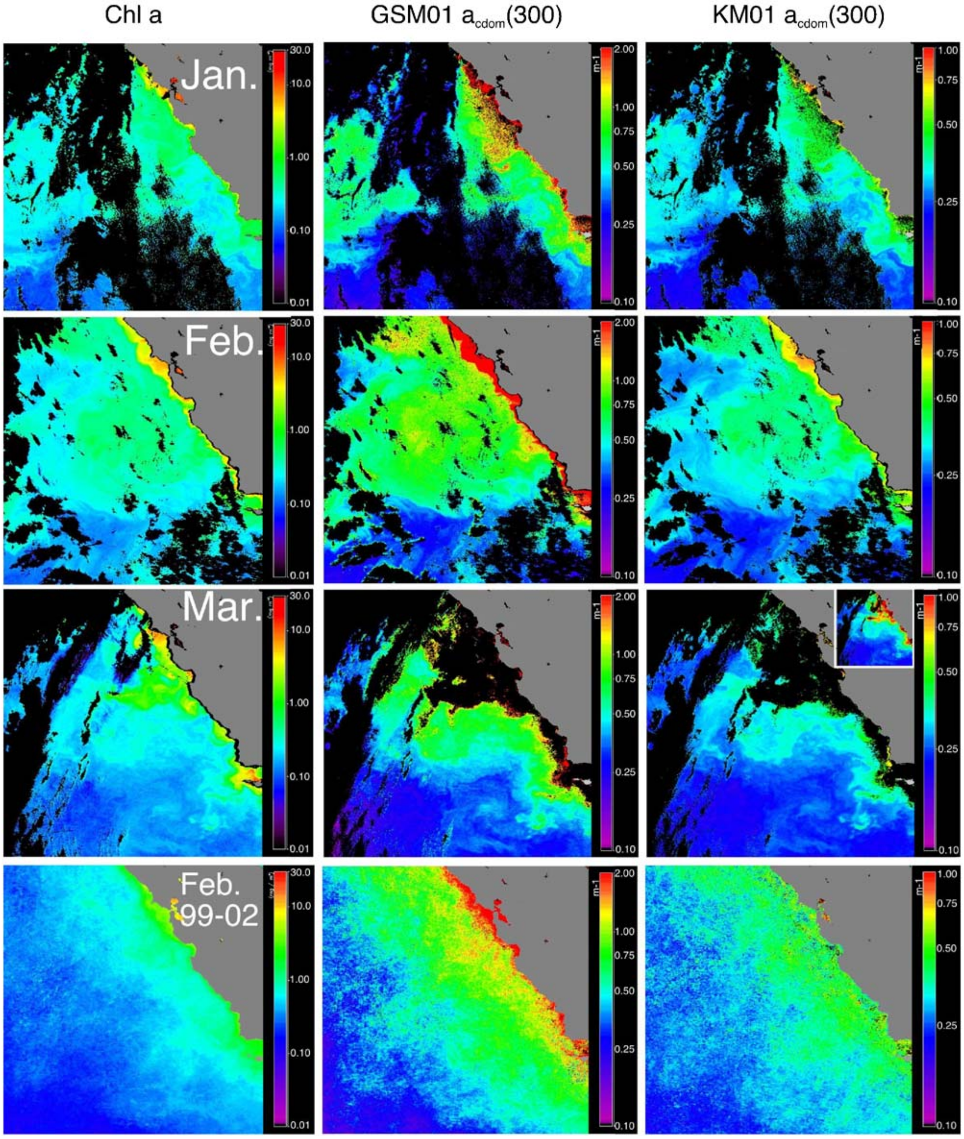

Fig. 3. Chlorophyll, CDM (GSM01 model) and $a_{cdom}(300)$ (Kahru and Mitchell model) from SeaWiFS data. The GSM01 model output was normalized to 300 nm as described in the text. Top row: January 22, 1998 (S1998022203253.L2 _ HMBR); Second row: February 9, 1998 (S1998040204831.L2 _ HMBR); Third ROW: March 10, 1998 (S1998069210316.L2 _ HMBR). The inset graph for March KM01 shows the same image without the *nLw*(412) atmospheric correction applied. Bottom Row: geometric mean values for the month of February from 1999–2002. Note the difference in scale between the GSM01 and KM01 models. January and March images correspond to the shipboard pigment measurements in Fig. 4.

can be deconvolved into a small number of seawater constituents, and that the spectral shapes are known. The sensitivity of the model output to these shape functions varies from coastal to open-ocean waters (Garver and Siegel, 1997; Siegel et al., 2002), and is optimized in GSM01 to a global data set. Therefore, it is likely that the GSM01 model is not as highly tuned to coastal

California waters as is the KM01 algorithm, which was parameterized exclusively with California data. A comparison of the 412/443 nm ratio from moored radiometers and SeaWiFS (Fig. 2C) also demonstrates that SeaWiFS values exhibit more variance, and also a wider range of low values, than in situ data collected from the M1 mooring. These observations are consistent with either the SeaWiFS data being retrieved from areas with more pigment packaging and/or CDOM absorption, or atmospheric correction issues.

Despite the discrepancy between models, the relative spatial and temporal patterns are similar (Fig. 3). Kahru and Mitchell (2001) reported that the comparison between Carder et al.'s (1999) semianalytic model and KM01 also had an offset in magnitude, but was consistent with the KM01 results within (but not necessarily between) seasons. For this study, we are examining data from a single season, over a relatively narrow time scale. We cannot determine which model output is more accurate for our data set, but believe that the observed patterns are consistent with an enhanced CDOM signal from coastal runoff and that the relative patterns are consistent between models.

3.2. SeaWiFS observations

During the extreme rainfall event of February 1998, satellite imagery was generally poor due to persistent cloud cover. On February 9, however, a predominantly cloud-free image was obtained (Fig. 1). The influence of suspended sediments associated with fluvial input is apparent from the true-color composite, as has been previously reported (Mertes and Warrick, 2001). Also apparent in these images is a large plume of "chlorophyll" and CDOM extending several hundred km offshore centered on Monterey Bay, with a band of elevated values nearshore, particularly north of San Francisco Bay (Fig. 3).

The chlorophyll and CDOM values offshore in the February image are substantially higher than the mean chlorophyll and CDOM values for this region (Kahru and Mitchell, 2001), although the onshore gradient is similar to the February average from 1999 to 2002 (Fig. 3). The February 1998 plume is especially evident as an intensification of nearshore CDOM values, corresponding to the visible sediment plumes (Fig. 1), and an intensification and sharper boundary between the low ($a_{cdom}(300) < 0.25\,m^{-1}$) offshore CDOM concentrations versus the elevated coastal values. Chlorophyll values from February 9 are also elevated relative to the climatological mean in the near offshore. For comparison, shipboard chlorophyll values for January and March 1998 and for the mean of all cruises (1997–1998) along CalCOFI Line 67 are plotted in Fig. 4. These patterns, together with the unusually high (20–100 year events) precipitation during the week immediately preceding this image, suggest that coastal runoff is the primary cause for the anomalous bio-optical signals.

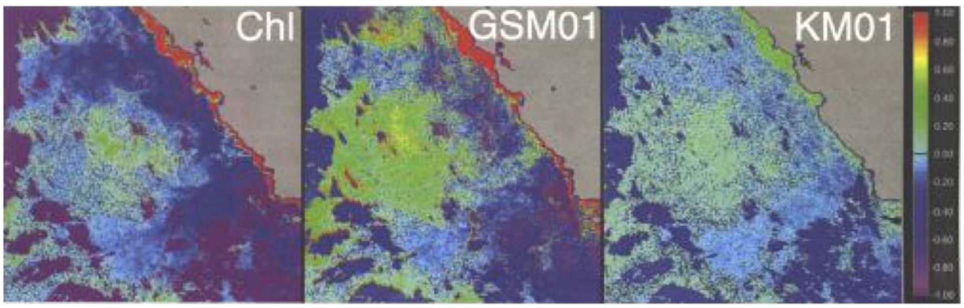

Fig. 4. SeaWiFS-derived and shipboard chlorophylls for January and March 1998 are plotted versus longitude (upper and lower panels). February SeaWiFS data versus. the mean shipboard chlorophyll concentrations (± 1 SD) for all cruises are plotted in the middle panel. Overall, there is a good correlation between the SeaWiFS and shipboard measurements. Note that during February there is a broad region of elevated chlorophylls relative to the mean values from shipboard measurements. No shipboard chlorophyll data were available in February 1998.

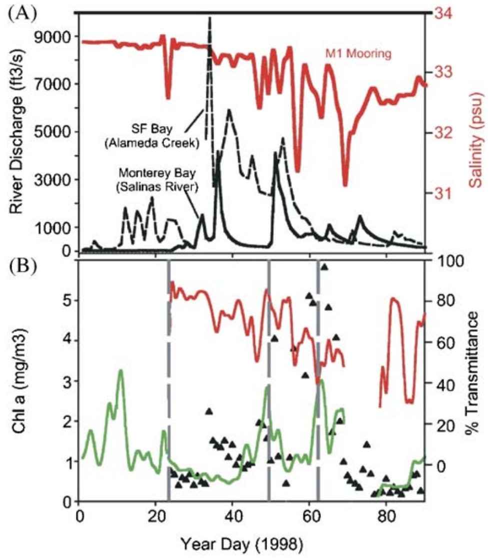

Fig. 5. Panel A: salinity at the M1 mooring and river outflow for San Francisco (Alameda Creek) and Monterey Bay (Salinas River). Panel B: transmissometer (red solid line) and fluorometer data (green solid line; converted to chl units) from the M1 mooring in Monterey Bay. Black triangles represent OC2v2 estimates (PRR-600 1 m depth). The first vertical grey line represent an instrument swap, while the second two vertical grey lines were mooring servicing deployments. Note that the OC2v2 chl, transmittance, and salinity all weakly covary, suggesting the runoff events beginning in February 1998 caused the anomalous SeaWiFS estimates offshore.

Although the spatial extent of the elevated CDOM was greatest in February, the images from January and March also suggest pronounced offshore transport of CDOM, with a general increase in concentration as the images progress temporally. This is consistent with the river flow data (Fig. 5). Although the storm event during the week of February 9 was the most spectacular (coinciding with the greatest offshore extent of elevated CDOM and the greatest impact on derived chlorophylls), much of the spring of 1998 was characterized by persistent, episodic flow events, and there were elevated CDOM concentrations offshore throughout the period (Fig. 3).

3.3. Mooring observations

During the winter storm event (February 1–9) immediately preceding the satellite image shown in Fig. 1, most precipitation recording stations in central California reached a 10–20 year high, while Monterey recorded a 100-year precipitation record (Mertes and Warrick, 2001 and references therein). This time period was characterized as an extensive runoff event all along the central California coastline, resulting in sediment discharges observable from SeaWiFS extending to approximately 30 km (average) from the coast. To further determine whether the origins of the anomalous CDOM signal (ca. 300 km from the coast) observed in the February 9 image from SeaWiFS are consistent with a large-scale coastal runoff event, we evaluated a time-series of bio-optical data from the M1 mooring in Monterey Bay.

The M1 mooring is approximately 15 km from the coast, and is generally considered to be representative of the chemical and biological conditions in Monterey Bay (e.g., Pennington and Chavez, 2000). Its proximity to shore and the Salinas River means that it should also be well within the ca. 30 km extent of the February 1998 sediment plumes observed by Mertes and Warrick (2001). Data from January to March 1998 for river flow from the Salinas River (Monterey Bay) and Alameda Creek (San Francisco Bay) are presented in Fig. 5. Mooring data suggest that there was some influence from river-induced runoff (i.e., the large excursions in salinity), although much of the variability in physical and optical measurements could not be directly attributed to increased river flow. Flows from Alameda Creek increased throughout January, while Salinas River (which is seasonal, and has zero flow for much of the year) did not begin to increase until late January into early February (approximately year day 25–30). Peak discharge occurred on February 3 (year day 34) for Alameda Creek. The Salinas River lagged in peak flow, with maximum discharge on February 8 (year day 39).

Mooring observations (Fig. 5) show a gradual decline in surface salinity from initial (January 1998) values within climatological conditions (33.2–33.5; Pennington and Chavez 2000) to less than 33, with excursions to nearly 31, generally tracking the riverflow data. Accompanying the decrease in salinity was a general trend downward in beam transmission from mid-January to mid-March, followed by a recovery towards the end of the time-series. The decreases in transmittance were accompanied by a trend upwards in fluorescence (biomass), which would be expected if the transmittance values were tracking biogenic particle load. Calculated chlorophyll values from the radiometer generally track the fluorescence data, with two exceptions. From year day 35–41, the bio-optical estimates increase substantially relative to the fluorometer, and again from, approximately, year day 55 to 65. These deviations suggest a change in the optical characteristics of the water column that affected the radiometer but not the fluorometer. Although the apparent correlation between these excursions and either salinity or transmittance is relatively weak, we hypothesize that the large deviations in radiometer-derived chlorophyll may be attributed to increases in river-induced CDOM. The initial deviations (year day 35–41) occurred during the peak rainfall event of February 1–9; the second time period (year day 55–65) immediately followed a large negative salinity anomaly at the M1 mooring (but note that the second large anomaly did not result in a significant deviation in calculated chlorophyll versus the fluorometer).

The remote sensing reflectance ratios for 412, 443 nm and 443, 555 nm from the February SeaWiFS image and the mooring PRR data are also plotted (Fig. 2C). As described by Carder et al. (1997), values that fall below a threshold represented by

$$R_{rs}\,(412/443) = 0.95 \bullet [R_{rs}\,(443/555)]\hat{}0.16 \qquad (1)$$

are indicative of either pigment packaging effects within the phytoplankton cells, or CDOM absorption. A third possibility for the SeaWiFS data is that the 412 nm data are artifactually low due to atmospheric correction issues. We do not directly evaluate this, but the generally good correspondence between the SeaWiFS and mooring values suggest that atmospheric correction problems would affect a subset of the remotely sensed data (e.g., the very low SeaWiFS values in Fig. 2C). These data again suggest that there was a significant CDOM contribution to the bio-optical signals observed at the mooring and in the SeaWiFS imagery for February. Although pigment packaging effects can not be ruled out, the preponderance of evidence suggests that the extreme rainfall events of 1998 resulted in elevated CDOM values in the coastal ocean from fluvial inputs.

4. Discussion

Using a combination of data from SeaWiFS, moored platforms, and shipboard measurements, we demonstrated that the plume observed on February 9, 1998 in central California was likely dominated by CDOM absorption, extending approximately a factor 10 further offshore than the previously reported suspended sediment signal. The large-scale impact of this event on the coastal bio-optical properties of central California was unusual, and resulted from a combination of unseasonal (400% above normal) rainfall and a suppression of biological productivity offshore caused by the El Niño. These results indicate that under the right conditions, fluvial input can impact the coastal ocean in this region over a much greater spatial extent than previously observed.

These inputs also may have significant biological and chemical effects on the coastal ocean. During 1998, significant drawdown of pCO_2 was observed coincident with low-salinity waters centered ca. 100 km offshore in the high-CDOM waters. Friederich et al. (2002) speculated that this drawdown was due to the input of nutrients associated with freshwater discharge, acting as a "fertilizer" for the otherwise nutrient-depleted waters characteristic of an El Niño time period, and recorded a coincident increase in chlorophyll from a background level of ca. 0.02–0.16 mg m^{-3} chl in the low salinity, low-pCO_2 plume. This is supported by Wilkerson et al. (2002), who reported a strong gradient in macronutrient concentrations extending from the Golden Gate Bridge in San Francisco Bay (ca. 30 μM nitrate) into the California Current (sub-detection levels of nitrate). The Salinas River and Elkhorn Slough, which drain into Monterey Bay, can have nitrate concentrations in excess of 1000 μM prior to the first flush from seasonal rainfall (Caffrey et al., 1997, 1998). Macronutrients were below detection to within less than 50 km of the coast during February–April 1998, while the strongest negative nutrient anomalies were observed between 100 and 200 km offshore at 60 m depth in April 1998 (Castro et al., 2002). Even with significant dilution and mixing, the unusually high riverine flow of spring 1998 would provide a significant source of nitrate to the coastal ocean, particularly during February 1998, when waters off the central California coast were substantially depleted of inorganic nutrients (Kudela and Chavez, 2000).

Friederich et al. (2002) calculated that, from January to April 1998, outflow from San Francisco Bay could produce a $450\,km^2\,day^{-1}$ low-salinity, low-pCO_2 anomaly in the coastal ocean, assuming a mean depth of ca. 20 m. Shipboard transects during this time period (January–March) showed salinity anomalies a much as 300 km offshore (Asanuma et al., 1999), consistent with these calculations. Assuming the San Francisco Bay outflow was the primary riverine source contributing to the offshore anomalies observed on February 9, and that the mean anomaly production rate of $450\,km^2\,day^{-1}$ is a conservative estimate of the outflow during the winter storm of February 1–9, 1998, the offshore extent of a riverine anomaly could reasonably be expected to be approximately 170 km (8 days of flow at $21\,km\,day^{-1}$). This is about half of the observed distance from the SeaWiFS imagery of February 9. It is more likely that the elevated riverine inputs, which began in early January and continued through mid April, built up an anomalous CDOM signal offshore over a period of weeks. The CDOM signal in conjunction with the increased biomass observed in February, but not January or March (Fig. 4), suggests however that the peak flow of early February was the primary cause of these anomalies.

Although spatial and temporal patterns of CDOM are often similar to chlorophyll (Fig. 3; Kahru and Mitchell 2001) and are frequently correlated to salinity in coastal waters (Jerlov, 1953), our understanding of global patterns of CDOM are not well constrained (Siegel et al., 2002). We observed anomalously high chlorophyll in conjunction with the elevated CDOM from the February 9 image (Figs. 3 and 4). Kahru and Mitchell (2001) reported that CDOM was well correlated to chlorophyll offshore, but not correlated nearshore and over the shelf. Kahru and Mitchell (2001) also reported average offshore CDOM absorption values of ca. $a_{cdom}(300) = 0.2–0.3\,m^{-1}$, substantially below the values observed in the plume (ca. $0.30 < a_{cdom}(300) < 1\,m^{-1}$), implying that it is unlikely the observed CDOM signal was transported onshore from the California Current. While it is possible that the CDOM signal advected equatorward, the shape of the plume, then onshore gradient in CDOM, and the dominance of the San Francisco Bay outflow in central California's freshwater input suggests that the signal originated from the coastal runoff nearby. We cannot rule out the possibility that the CDOM signal was associated, with rather than the cause of, the apparently elevated chlorophyll signal offshore. Offshore chlorophyll values from the February image were approximately five times higher than the average (Fig. 4), of the same magnitude ($8\times$) as the nutrient-induced increase observed by Friederich et al. (2002). Whether the observed signals in CDOM and chlorophyll are attributed directly to CDOM absorption (artificially increasing the retrieved chlorophyll concentrations) or were caused by a "fertilization" of the coastal ocean by riverine input of nutrients, we are reasonably confident that these observations were a direct result of the increased river flow during this time period.

During the 1997–1998 El Niño, there were pronounced physical and biological repercussions caused by the suppression of seasonal upwelling and elevated temperatures. Biologically, these repercussions were most evident offshore, in the region between the California Current and the nearshore source of coastal upwelling (e.g., Kudela and Chavez, 2000, 2002; Chavez et al. 2002). Bio-optical measurements from ships, satellites and mooring can help to determine these effects. SeaWiFS imagery, although generally very well correlated to shipboard and mooring measurements, appears to have been influenced by the extensive coastal runoff, which was enhanced by a lack of strong coastal upwelling, during at least one period in 1998. This event was likely anomalous, but demonstrates the potential impact of coastal properties on bio-optical measurements.

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