SPATIAL AND TEMPORAL PATTERNS OF *PSEUDO-NITZSCHIA* SPP. IN CENTRAL CALIFORNIA RELATED TO REGIONAL OCEANOGRAPHY

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Spatial and temporal patterns of *Pseudo-nitzschia* species in central California related to regional oceanography

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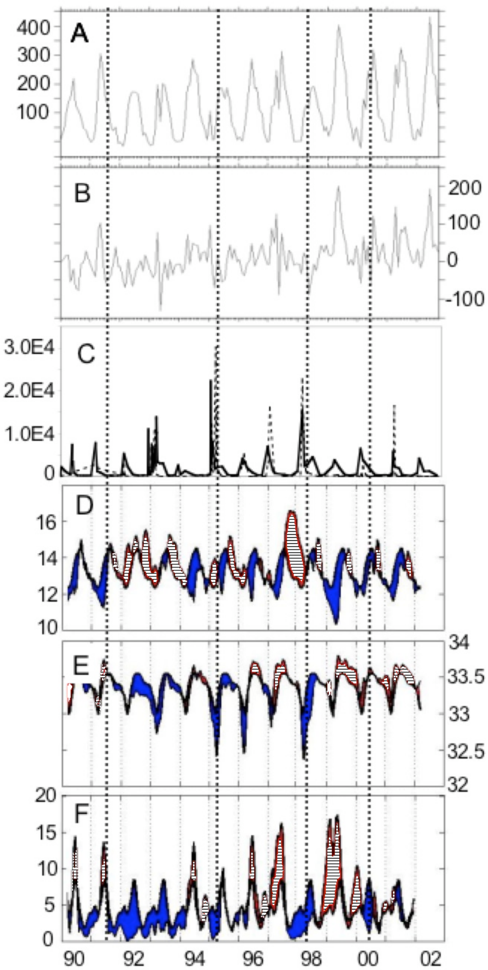

Figure 1. Time-series plots for A: upwelling index (m^3/s/100 m coastline); B: upwelling anomaly; C: Riverflow from San Francisco (solid line) and Salinas River (dashed line; cfs); D: temperature anomaly (deg C); E: Salinity anomaly (pss); F: nitrate anomaly (µM). For D-F, solid line s therunning mean, striped areas are positive anomalies, dark shaded areas are negative anomalies. Data are for Monterey Bay. The dashed vertical lines indicate major bloom events.

Abstract. We compare similarities and differences in oceanographic and environmental conditions during major HAB bloom events off the California coast, focusing on the Monterey Bay region from 1990-2002. During this period, there were five major events. In 1991, domoic acid was first reported in Monterey Bay. In 1995, a red *tide (Lingulodinium polyedrum*) extended from Baja to Monterey, CA. In 1998, 2000, and 2002, there were a series of widespread *Pseudo-nitzschia* blooms along the California coast. In many cases, these events were initially reported in the south, and appeared to propagate northward. Here we evaluate whether there are consistent environmental patterns associated with these events.

Introduction. Coastal California is typically viewed as an upwelling-dominated system, with strong equatorward and Ekman-dominated offshore flows, bounded to the west by the broad, meandering California Current. This implies that (1) biological and physical processes propagate predominantly southward, (2) coastal runoff has negligible impacts on the near-shore oceanographic conditions and (3) much of the biological activity is driven by seasonally intense spring upwelling. Recent observations, however, suggest that this view is misleading, and that the occurrence of infrequent but high-impact events such as precipitation-driven coastal runoff may dominate the biological signal over large spatial and temporal scales (e.g. Friederich et al., 2002). These events can "fertilize" the coastal ocean with anthropogenically derived nutrients, and may catalyze or exacerbate HAB conditions in the coastal ocean. Three past HAB events occurring in 1995, 1998 and 2000 exemplify the difficulties associated with monitoring, predicting, and understanding the origins and fate of HABs. In 1995, a massive red tide of the non-toxic dinoflagellate *Lingulodinium polyedrum* occurred off the coast of California, extending from the upper Baja peninsula to Monterey Bay, representing the largest and most widespread red tide observed off California since 1902. In spring 1998, field sampling identified toxic *Pseudo-nitzschia* species along much of the California coastline, at relatively low abundance. A series of bloom events again occurred in 2000 and 2002, extending along much of the California coastline. There were no consistent links to known or potential environmental triggers during the domoic acid events, but in all three cases (1995, 1998, and 2000), there was an apparent northward propagation of plankton assemblages. While intriguing, the possibility of predictable northward transport or of northward propagation of environmental conditions conducive to HABs has not been directly tested.

Here we address several specific questions. (1) Are mesoscale physical (e.g. upwelling, relaxation), or environmental (e.g. rainfall, runoff) events responsible for the large spatial/temporal toxigenic events in California? *Pseudo-nitzschia* spp. are cosmopolitan, and are always present in central California waters (based on long-term monitoring), but major toxin events often occur over large spatial scales (e.g. Southern California Bight to Monterey Bay, Trainer et al., 2000). This suggests that there must be large-scale forcing responsible for the otherwise coincidental timing of these major events. (2) Do nutrient concentrations trigger toxin production? If so, which nutrients? Various macro- and micro-nutrients have been implicated in the onset and maintenance of toxicity, primarily from laboratory studies. A partial listing includes: Si, P, Fe, Cu, Li, and N. Other hypothesized mechanisms include temperature, irradiance, and nutrient ratios (e.g. review by Bates, 1998). Despite these laboratory (and field) observations, no consistent pattern has been identified (3) Will regional, high-resolution

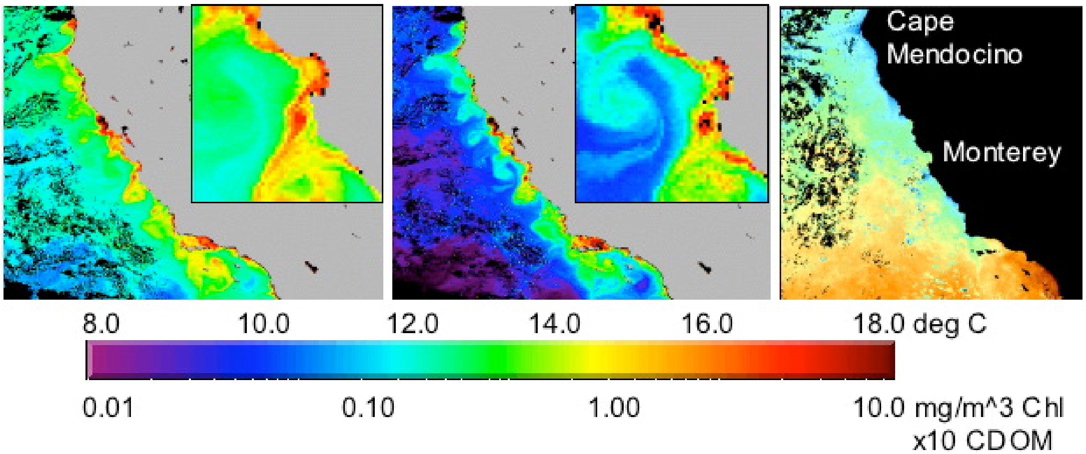

Figure 2. Chlorophyll (left), colored dissolved material (CDOM; middle) and sea surface temperature (right) for the west coast and for Monterey Bay (insets) during the 1998 toxigenic bloom event. Values for chl (mg/m^3), SST (deg. C), and CDOM (dimensionless) scaled by a factor of 10 are given.

monitoring programs provide predictive capabilities for larger scale (West Coast) monitoring programs? Recent evidence suggests that toxigenic events may be associated with persistent mesoscale physical features (e.g. Trainer et al., 2002, the Juan de Fuca Eddy) and "cryptic" blooms (e.g. Rines et al., 2002, thin layers). If the presence/absence of *Pseudo-nitzschia* is not a good indicator of toxigenic events, are there other measurements that can be incorporated into monitoring programs, and will they capture the scales of variability?

Methods and Materials. Time-series data for physical, biological, and chemical conditions in California (primarily Monterey Bay) were obtained from the Pacific Fisheries Environmental Laboratory (NOAA) database (upwelling indices), the USGS database (river flow), the Monterey Bay Aquarium Research Institute (MBARI; temperature, salinity, nutrients) and the TOPEX/Poseidon satellite system (sea surface height). For analysis of the 1998 bloom event, whole-cell hybridization techniques developed by Scholin et al., (1997) were used on samples collected from the Santa Cruz Wharf from Year Day 78-200, 1998. Nutrient values were determined by MBARI using standard colorimetric techniques. Remote sensing data were obtained from the NOAA CoastWatch program (sea surface temperature) and the NASA SeaWiFS program (ocean color).

During the 2000 Monterey Bay field experiment, water was collected from a nearly unialgal near-surface bloom of *Pseudo-nitzschia australis* (identified using microscopy and molecular probes), and enriched with either 20 µM nitrate, 20 µM silicate, 100 nM Desferol, which is an iron chelator (e.g. Wells, 1999), and no treatment (control) in 9 liter polycarbonate carboys. Water was collected using a trace-metal clean pumping system. The carboys were then maintained under simulated *in situ* conditions for six days, and changes in biomass were monitored using chlorophyll, biogenic silica, or *P. australis*-specific probes. Spatial variable fluorescence data were collected simultaneously (Chelsea FRR using night-time data).

Results and Discussion. Time-Series plots for oceanographic and environmental parameters centered on Monterey Bay are presented in Figure 1. Although the red tide event of 1995 was clearly linked to a heavy runoff event (e.g. Kudela and Cochlan, 2000), the trends for major *Pseudo-nitzschia* toxic blooms are less evident. In general, blooms occur during anomalously weak (but not absent) upwelling conditions, typically during a transition from excess to negative macronutrients relative to the climatological mean (black line). There is no evidence that *Pseudo-nitzschia* blooms are strongly correlated to runoff events. The observed south to north trend in bloom events (1991, 1995, 1998, 2000, 2002) is consistent with large-scale physical forcing, as evidenced by changes in sea surface height, which occur south to north at the same time scales (weeks to months), suggesting that the spatial pattern is indicative of a change in environmental conditions, rather than actual transport of seed populations.

During early summer 1998, a widespread DA event occurred along the entire West Coast, and has been well described elsewhere (Scholin et al., 2000, Trainer et al., 2000). Observations from this bloom include: its apparent propagation from south to north, starting in the Southern California Bight and extending to the Monterey region, with additional blooms occurring in the Pacific northwest. Toxic blooms were generally associated with headlands and upwelling centers, as reported by Trainer et al. (2000). There is some evidence (inconsistent) for bloom initiation to be associated with terrestrial runoff (Scholin et al., 2000). Macronutrients were generally elevated, but lower than the climatological mean (Figure 1). Conditions preceding and during the toxic bloom were generally indicative of weak upwelling (see SST, Figure 2), but highly productive (Chl a, Figure 2). However, prior to the bloom (March), the concentration of colored dissolved organic matter (CDOM) was very high, indicating substantial terrestrial input (runoff), particularly in central California off San Francisco and Monterey Bay, and in the Channel Islands. These areas were reported to be two bloom "hot spots" (Trainer et al., 2000), suggesting a correlation,

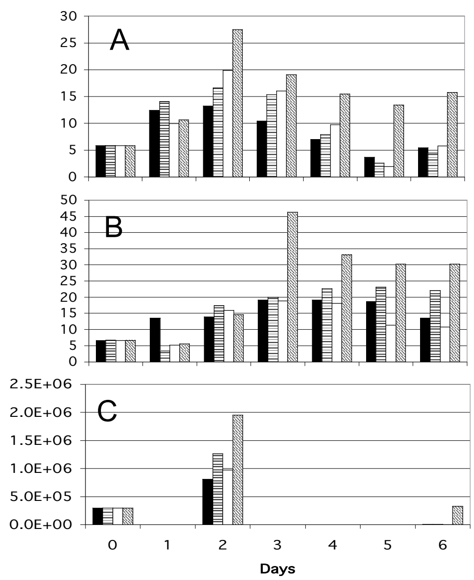

Figure 3. Large-volume grow-outs of whole water from a *P. australis* dominated bloom with nutrient amendments, Monterey Bay 2000. A: Chl a (mg/m^3). B: biogenic silica (µM). C: species-specific molecular probes for *P. australis* (cells/L). Solid fill: control. Horizontal fill: plus nitrate. White fill: plus silicate. Diagonal fill: plus Desferol.

although these regions are also associated with headlands, and therefore upwelled nutrients. During the peak toxicity in Monterey Bay (May) CDOM levels were still very elevated in these regions, suggesting continued influence from runoff (although CDOM is also produced by phytoplankton).

Based on possible nutrient-control of toxin production during 1998, we evaluated the importance of macro- and micronutrients during another widespread bloom in August 2000 in the Monterey Bay region. Large-volume grow-out experiments with amended macro- and micronutrients (Si, N, Fe), showed no evidence for iron limitation, and *Pseudo-nitzschia* biomass was nitrogen (not silicon) limited (Figure 3). Spatial surveys of surface variable fluorescence similarly suggested that there was no widespread iron stress during the bloom. A series of AUV and shipboard observations were also conducted (Ryan et al., 2002), providing a 3-D view of the water column. A subsurface bloom of *Pseudo-nitzschia australis* was mapped, and was associated with a density gradient. This bloom extended spatially for several kilometers, with very little surface expression. A 2-D slice of optical backscatter (data not shown) suggested that the phytoplankton bloom was being "fed" by a subsurface resuspension event, possibly providing a source of bio-available iron. During this period, DA values in both the particulate and dissolved phase were extremely high (> 20 pmol/cell particulate DA and µM concentrations of dissolved DA; G. Doucette, pers. comm.). The presence of extremely high DA levels during this period, despite a lack of Si-limitation of biomass accumulation or iron stress, suggests that neither macro- nor micronutrient limitation were the primary cause of this toxigenic event.

Conclusions. Large-scale HAB events in California are inconsistent in their oceanographic and environmental conditions. Although extensive runoff and weak upwelling conditions were clearly responsible for the 1995 red tide (*Lingulodinium*) event, rainfall is not a good indicator of DA production. Bloom conditions are generally associated with weak (but not absent) upwelling, fresher water, transitional periods between anomalously warm and cool waters, and generally low ambient concentrations of macronutrients. There is no consistent evidence for macronutrient or iron concentrations to be directly attributable to toxic events; when tested directly, *Pseudo-nitzschia* was generally nitrogen limited, with little or no iron stress (although it is possible that DA production and lack of Fe stess are correlated, if DA is a chelator (Rue and Bruland, 2001). *Pseudo-nitzschia* is likely often associated with thin-layers, as has been observed by others (e.g. Rines et al., 2002), which may make detection difficult prior to a major toxic event. Latitudinal changes in environmental conditions associated with seasonality are the likely cause for the apparent northward propagation of HAB events along the west coast.

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