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Detecting toxic diatom blooms from ocean color and a regional ocean model

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[1] An apparent link between upwelling-related physical signatures, macronutrients, and toxic diatom blooms in the various “hotspots” throughout California has motivated attempts to forecast harmful algal blooms (HABs) as a function of select environmental variables. Empirical models for predicting toxic *Pseudo-nitzschia* blooms in one such region, the Santa Barbara Channel (SBC), are tested in a nowcast mode using predictions based on merging data from MODIS ocean color geophysical products and the Regional Ocean Modeling System (ROMS) applied to the Southern California Bight. Thresholds for each model generate event forecasts. Spatially-explicit, monthly HAB maps are compared to ship-board observations and California monitoring data, demonstrating that the models predict offshore events otherwise undetected by nearshore monitoring. The use of mechanistic hydrodynamic models in concert with empirical, biological models facilitates future process studies on the effects of coastal eutrophication and climate change on regional HAB dynamics. **Citation:** Anderson, C. R., R. M. Kudela, C. Benitez-Nelson, E. Sekula-Wood, C. T. Burrell, Y. Chao, G. Langlois, J. Goodman, and D. A. Siegel (2011), Detecting toxic diatom blooms from ocean color and a regional ocean model, *Geophys. Res. Lett.*, 38, L04603, doi:10.1029/2010GL045858.

1. Introduction

[2] Since 2000, the Santa Barbara Channel (SBC) has become a seasonal “hot spot” of HAB activity in coastal California (CA). The toxin-producing diatom *Pseudo-nitzschia* is the dominant HAB genus in the region, reaching densities above 10^6 cells L^{-1} and toxin loads near $10 \mu g L^{-1}$ during bloom events [Anderson et al., 2006; Trainer et al., 2000]. These blooms can negatively impact marine wildlife [Fritz et al., 1992; Lefebvre et al., 1999; Scholin et al., 2000] and put humans at risk of amnesic shellfish poisoning [Perl et al., 1990] when the neurotoxin domoic acid (DA) is produced and transferred through the marine foodweb. Spring and summer upwelling in coastal California pumps

essential macro- and micronutrients to surface waters, fuelling mixed-assemblage diatom blooms that include *Pseudo-nitzschia*. The challenge is to identify the physical and chemical environment required to provide toxigenic species of *Pseudo-nitzschia* a greater competitive advantage over other diatoms and define the role that DA production plays in bloom regulation. Researchers have applied statistical modeling approaches to identify the *in situ* conditions associated with DA-producing blooms in the SBC and Monterey Bay [Anderson et al., 2009; Lane et al., 2009] with results alluding to the important role of limiting macronutrients, particularly silicic acid, in both upwelling regions. In the present paper, bloom likelihoods are modeled in a spatially explicit manner in order to provide additional value to the successful nearshore monitoring already provided by the California Department of Public Health (CDPH). We demonstrate the combined use of empirical HAB models, satellite ocean color data, and a Regional Ocean Modeling System (ROMS) for the ecological prediction of both *Pseudo-nitzschia* blooms and DA events in the SBC region (Figure 1), emphasizing the interplay of physical transport/retention and macronutrient availability.

2. Satellite Data and ROMS

[3] For 2009-2010, 1-km MODIS-Aqua data were acquired from NASA’s Ocean Biology Processing Group (<http://oceancolor.gsfc.nasa.gov/>) for the central California region, processed to Level 2 (SeaDAS v. 6.1), and further sub-scened for the SBC region. The high-resolution ocean model is based on a ROMS framework, a community-based hydrodynamic model designed for regional applications [Shchepetkin and McWilliams, 2005]. For HAB predictions, we employ a hydrostatic ROMS configuration over the Southern California Bight (SCB) with a 1-km spatial resolution that has been running in real-time since April 2007 from NASA’s Jet Propulsion Laboratory (<http://our.ocean.jpl.nasa.gov/SCB>) using a three-dimensional variational data assimilation (3DVAR) method for improved model skill [Chao et al., 2009; Li et al., 2008a; Li et al., 2008b]. Comparisons with observational data demonstrate that the SCB ROMS realistically captures the mean ocean circulation state as well as interannual, seasonal, and eddy-scale variability but may have limited skill at reproducing submesoscale circulation [Dong et al., 2009].

3. Empirical HAB Models

[4] We updated existing statistical threshold models for predicting blooms of *Pseudo-nitzschia*, particulate domoic

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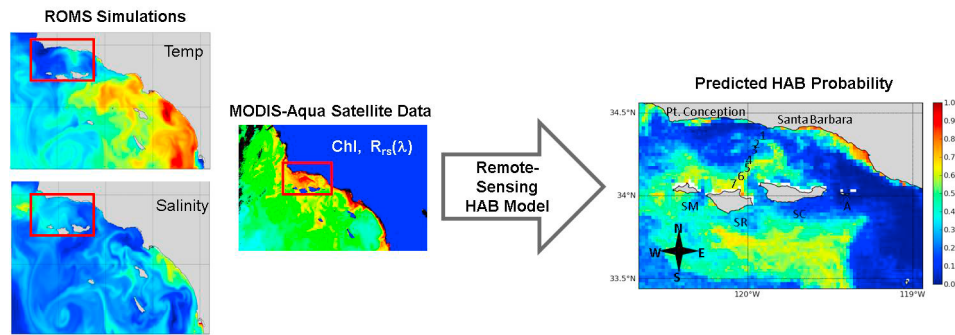


Figure 1. Schematic of ROMS model and MODIS satellite products used to compute the “Remote-Sensing” HAB Models (Table S2 of the auxiliary material) for predicting the probability of elevated *Pseudo-nitzschia* abundance and toxin concentrations in the SBC off the coast of central California. Numbers in the far right map denote monthly “Plumes and Blooms” sampling stations 1–7 with station 1 nearest the mainland and station 7 off the shelf of Santa Rosa Is. The Santa Barbara Channel Islands from west to east are: San Miguel Is. (SM), Santa Rosa Is. (SR), Santa Cruz Is. (SC), and Anacapa Is. (A).

acid (pDA), and cellular domoic acid (cDA) using 2009–2010 hydrographic, optical, and chemical observations. The results yield two sets of logistic generalized linear models (GLMs): i) best-fit *full* models where all available parameters were tested for inclusion [Anderson et al., 2010; Lane et al., 2009], and ii) a set termed *remote-sensing* models that only test parameters available from satellite or other remote platform. Model development and skill are fully described in the auxiliary material containing Tables S1 and S2.¹ The environmental variables retained in the new GLMs generally agree with previous models [Anderson et al., 2009], indicating a consistent set of predictors for the SBC related to enhanced chlorophyll, macronutrient depletion, and upwelling signatures. The most significant among these predictors include R_{rs} (510/555), the silicic acid to nitrate+nitrite ratio (Si:N), the silicic acid to phosphate ratio (Si:P), temperature, and salinity. Despite the better overall skill of the *full* models versus the *remote-sensing* models for all response variables [skill score $range_{full} = 0.49–0.74$; skill score $range_{rs} = 0.42–0.54$], current HAB predictions are only possible using the remote-sensing models due to the lack of a biogeochemical model within our local ROMS, precluding prediction of nutrient and chlorophyll fields. The probability of detection ranges are less distinguishable with 76 to 95% detection rate for full models (Table S1) versus 83 to 90% detection rate for remote-sensing models (Table S2). Thus, from the remote-sensing set of models for *Pseudo-nitzschia*, pDA, and cDA (Table S2), we developed spatially-explicit probability maps (Figures 1 and 2) for predictions in near real-time from satellite ocean color data and numerical simulations of temperature and salinity.

4. HAB Nowcasts and Monitoring Data

[5] Since the spatial and temporal resolution of HAB nowcasts are both limited by the availability of cloud-free MODIS imagery from low satellite zenith angles, only the mean for monthly predictions is shown (Figures 2 and 3). We evaluate our predictions by comparing shipboard observa-

tions collected monthly at seven stations on a single day and monitoring data from the CDPH (Figures 3a–3e) with monthly averaged probabilities at those seven sampling stations (Figures 3f–3h) and maps of spatially explicit probabilities at 1-km resolution throughout the SBC (Figure 2). In January and February, when no offshore data were collected (Figure 3), high *Pseudo-nitzschia* bloom probabilities were predicted (Figures 2 and 3) in disagreement with a low nearshore *Pseudo-nitzschia* Relative Abundance Index (RAI) [Langlois, 2009] pooled for three nearshore sites (Ellwood Pier, Goleta Pier, and aquaculture lease site M-653-02; Figure 3d). Probabilities of pDA and cDA (0–50%) from January to February are in better agreement with low shellfish DA levels used by the CDPH (Figure 3e). With the ramping up of the annual spring bloom, April predictions of *Pseudo-nitzschia* and cDA reached 70–100% (Figures 3g–3h) in correspondence with an increase in the RAI and shellfish DA levels above the regulatory limit of $20 \mu\text{g g}^{-1}$ (Figures 3d, 3e, and 2). Shipboard measurements of *Pseudo-nitzschia* abundance and DA were well below all thresholds (Figures 3a–3c), indicating model overestimation of offshore April bloom conditions in the mid-channel zone. Modeled cDA probabilities were highest in May 2009 when the RAI was at its peak for the year (Figure 3h) and shellfish DA reached almost $40 \mu\text{g g}^{-1}$ (Figure 3e), however, no mid-channel shipboard data were collected during this month (Figures 3a–3c). In July, models predict high bloom probabilities of *Pseudo-nitzschia* (Figures 2 and 3) corresponding with bloom levels of *Pseudo-nitzschia* ($\mu_{pn} = 1.2 \times 10^5 \text{ cells L}^{-1}$; Figure 3a) at all shipboard stations and elevated mean RAI at the three state monitoring sites ($\mu_{RAI} = 0.17$; Figure 3d). Conversely, elevated probabilities of pDA (mostly nearshore) and cDA (in the western channel) in July are inconsistent with low nearshore shellfish and offshore phytoplankton samples ($\mu_{pDA} = 0.019 \text{ mg/L}$; $\mu_{cDA} = 0.13 \text{ pg/cell}$). Given the often patchy nature of toxin distributions [Anderson et al., 2006], this mismatch is likely due to the high spatial variability predicted by the HAB models (Figure 2).

[6] Toxic *Pseudo-nitzschia* blooms have generally been spring and sometimes summer events in the SBC [Anderson et al., 2008, 2009; Trainer et al., 2000], but during the 2009

¹Auxiliary materials are available in the HTML. doi:10.1029/2010GL045858.

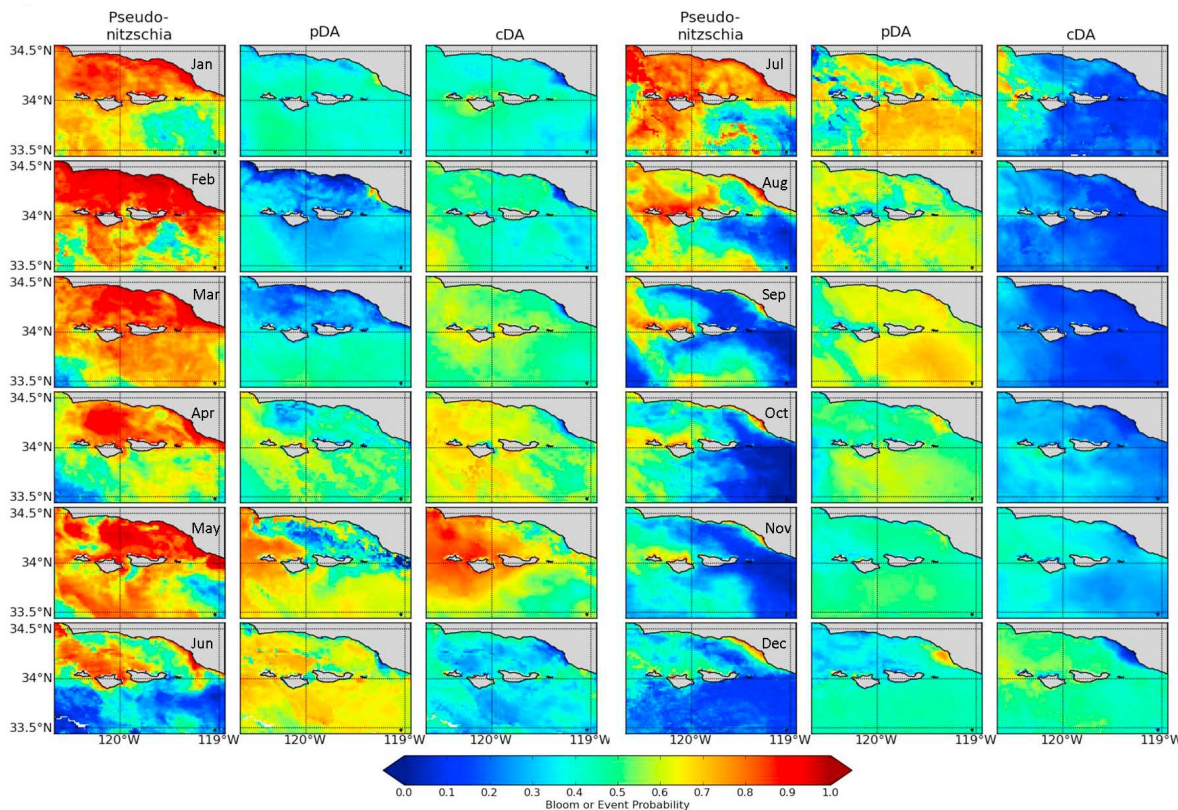


Figure 2. Monthly probability maps of *Pseudo-nitzschia* blooms ($\geq 10^4$ cells L^{-1}), elevated pDA (≥ 0.5 $\mu g L^{-1}$) and cDA (≥ 10 pg cell $^{-1}$) for January to December 2009.

El Niño summer to fall transition, we observed what may have been a single, prolonged DA event on monthly SBC cruises in October and November (Figures 3a–3c), similar to the large DA event observed in a sediment trap study of the SBC during the 1997–1998 ENSO event (E. Sekula-Wood et al., *Pseudo-nitzschia* and domoic acid fluxes in Santa Barbara Basin (CA) from 1993 to 2008, submitted to *Harmful Algae*, 2010). Cellular DA in November 2009 reached 121 pg cell $^{-1}$ at a mid-channel offshore station, and offshore particulate levels exceeded 5 $\mu g L^{-1}$ (Figure 3). Curiously, DA-related mammal strandings for 2009 in the SBC region did not peak in fall (M. Bermann, Santa Barbara Museum of Natural History, personal communication, 2010) nor did isolated shellfish test positive for DA after May (Figure 3e). In contrast to nearshore observations, predictions in November do reflect the observed increase in toxins (Figure 3). Daily DA event probabilities hovered between 60 and 80% from October to December with intermittent spikes up to 100% (daily imagery for the entire month not shown). This mismatch between onshore and offshore observations is again consistent with the high spatial variability associated with seasonal mesoscale eddies that may serve as transient retentive zones for HABs [Anderson et al., 2006]. In summary, model predictions generally agree with monthly phytoplankton observations and California monitoring data despite the varying spatial scales. HAB models generated nowcasts of elevated probabilities for *Pseudo-nitzschia* and DA in Fall 2009 that were consistent with offshore shipboard observations yet not aligned with nearshore shellfish monitoring data. Moreover, the seasonal

predictions for cellular DA, a measure of a bloom's toxicity, agreed well with offshore observations of toxic events in 2009.

5. Conclusions

[7] It is now recognized that predictive models of HABs are necessary to supplement limited time-series data and identify characteristic physical-biological interactions that may influence HAB formation over regional scales [McGillicuddy, 2010]. Future efforts will combine mechanistic and statistical approaches for making robust, reliable forecasts in response to a diverse range of environmental processes. Toxic blooms that are not observed by standard monitoring methods nor noted by a rise in animal strandings still threaten wildlife populations, for example, via vertical export of toxins to benthic biota [Sekula-Wood et al., 2009]. Spatially-explicit models of HAB probabilities provide a complementary tool for assessing public health risk, predicting ecosystem disturbance, and warning resource managers of offshore blooms.

[8] The conditions that lead to *Pseudo-nitzschia* blooms and the subsequent production of DA may differ as evidenced in laboratory and field experiments linking toxin production to varying forms of macro and micro-nutrient limitation [Bates et al., 1998; Fehling et al., 2004; Kudela et al., 2004, 2010; Maldonado et al., 2002; Pan et al., 1996; Wells et al., 2005]. As a result, the accuracy of current statistical HAB models that are not based on unique optical signatures [Cannizzaro et al., 2008; Tomlinson et al., 2009] is gener-

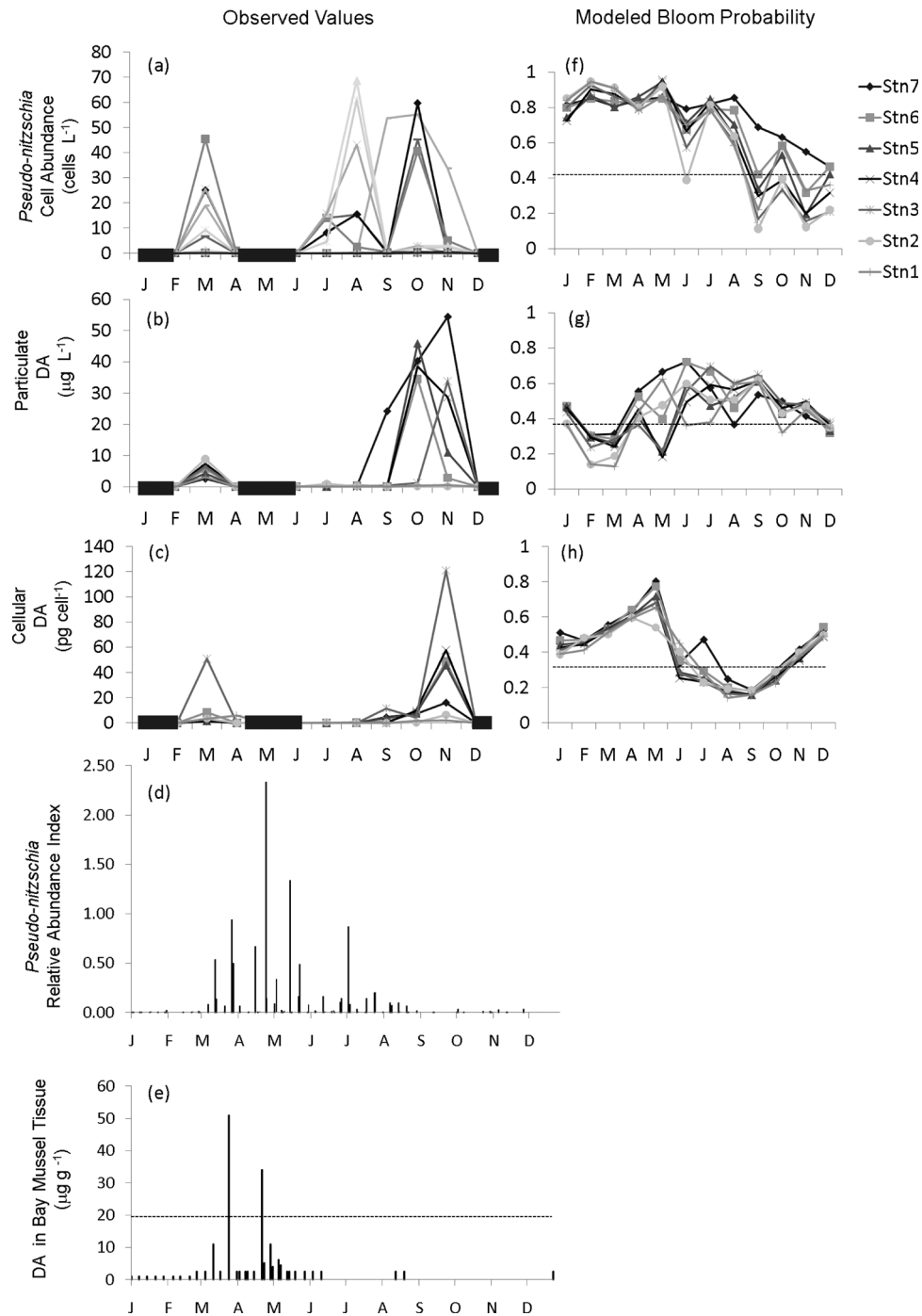


Figure 3. Monthly observations of (a) *Pseudo-nitzschia* abundance, (b) pDA, and (c) cDA from shipboard sampling transect (see Figure 1) measured on a single day; grey bars represent no offshore data collection in the months of Jan, Feb, May, June, and December 2009 and horizontal dashed lines indicate optimized probability thresholds (see Tables S1 and S2 of the auxiliary material). Observations of (d) Relative Abundance Index (RAI) for *Pseudo-nitzschia* spp. and (e) DA in mussel tissue; horizontal dashed line marks the $20 \mu\text{g g}^{-1}$ regulatory limit for DA-contaminated shellfish. (DA in mussel samples from August to December was categorized as “non-detect” in field kits.) Modeled probabilities of (f) *Pseudo-nitzschia* blooms, (g) pDA events, and (h) cDA events at each station are monthly means calculated within a 4-pixel area surrounding each sampling station.

ally constrained by estimation of the key environmental fields necessary to predict blooms and toxin production, both fundamentally a response to nutrient type and availability [McGillicuddy *et al.*, 2003, 2005]. Application of the

better-performing *full* HAB models that combine relevant physical and chemical fields ultimately requires a validated ROMS and biogeochemical model nested within ROMS to produce daily, high resolution simulations of chlorophyll,

silicic acid, nitrate, and phosphate [Moore *et al.*, 2001] as well as the increasingly-recognized organic nitrogen sources that trigger toxin production in *Pseudo-nitzschia* [Cochlan *et al.*, 2008; Howard *et al.*, 2007; Thessen *et al.*, 2009]. The remote-sensing models in this study miss important dynamics linked to the nutrient environment, and this likely contributes to an inflated rate of false positive predictions. Separating the *Pseudo-nitzschia* model, for instance, into spring/summer and fall/winter models (data not shown) suggests it may be possible to distinguish *Pseudo-nitzschia* blooms in fall/winter using a chlorophyll anomaly method from MODIS data [e.g., Tomlinson *et al.*, 2009], while in spring and summer, using simulations of nutrient levels to distinguish *Pseudo-nitzschia* from other blooms in the SBC. The additional information provided by nutrient ratios and concentrations from biogeochemical model-to-ROMS coupling, particularly at subsurface depths within the euphotic zone, will greatly aid in forecasting surface to subsurface blooms. Ideally, the more inclusive approach using ecosystem models that parameterize nutrients and differentiate carbon species will not only facilitate better predictions for resource managers but allow for experimental exploration of eutrophication and ocean acidification effects on HAB variability in the California Current System.

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