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Convergent blooms of *Karenia brevis* along the Texas coast

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[1] A numerical model of wind-driven surface flow in the Gulf of Mexico is used to examine physical controls on harmful algal bloom formation along the Texas coast. *Karenia brevis*, which blooms frequently in the Gulf of Mexico, has a relatively slow growth rate (doubling times of 2–3 days). Increases in *K. brevis* concentration cannot be explained simply in terms of growth. We hypothesize that the primary mechanism responsible for bloom formation in the western Gulf of Mexico is convergence due to downwelling at the coast. Convergence along the Texas coast caused by seasonal downwelling winds can concentrate the plankton up to 1000 times. This is surprising because the modeled cells do not grow; the simulated increase in concentration is due to physical processes alone. The numerical model qualitatively reproduces both the timing and magnitude of bloom initiation along the coast, but does not predict the details of the migration of the bloom along the coast after it has formed, or the destruction of the bloom. The result of this simulation is significant because it implies that *K. brevis* blooms may be caused primarily by physical processes and that cell division is not an important factor in bloom formation. **Citation:** Hetland, R. D., and L. Campbell (2007), Convergent blooms of *Karenia brevis* along the Texas coast, *Geophys. Res. Lett.*, *34*, L19604, doi:10.1029/2007GL030474.

1. Introduction

[2] Harmful algal blooms (HABs) are increasing in frequency worldwide and pose a significant threat to human and environmental health. The toxic dinoflagellate Karenia brevis is the primary HAB species in the Gulf of Mexico where it appears to be ubiquitous at background levels of <1 cell ml^{-1} [*Steidinger et al.*, 1998]. Accumulations, or blooms (>10 cells ml^{-1}), of *K. brevis* occur almost annually off the west coast of Florida, but historically have occurred less frequently along the Texas coast. Factors responsible for blooms has been a central question in HAB research. In Florida, *K. brevis* bloom populations are thought to originate 20–75 km offshore [*Steidinger and Ingle*, 1972; *Steidinger et al.*, 1998].

[3] The mechanism for formation in Texas is not known. *Villareal et al.* [2001] suggested blooms also originate offshore and are transported inshore, perhaps in association with Loop Current eddies. Local populations do not appear to be a likely source. Measured growth rates for *K. brevis*, at most doubling every two to three days, are insufficient to create observed blooms [*Steidinger et al.*, 1998]. *K. brevis* growth rate is slow enough that other physical factors may be important in bloom formation and maintenance. *Steidinger and Ingle* [1972] previously noted growth alone could not account for accumulations and that physical processes must act to concentrate cells for bloom initiation.

[4] Whereas this study focuses on *K. brevis* in the western Gulf of Mexico, two other studies have demonstrated that *K. brevis* concentrations are also influenced by physical processes in the eastern Gulf of Mexico, along the West Florida Shelf [*Janowitz and Kamykowski*, 2006; *Stumpf et al.*, 2007]. In particular, *Stumpf et al.* [2007] show increases in *K. brevis* concentrations inferred from satellite observations that were greater than can be explained by growth rate alone.

[5] This paper explores a novel mechanism for *K. brevis* bloom formation along the Texas coast: a combination of a coastal convergence due to downwelling and upward swimming of the plankton. This mechanism of bloom formation is examined using a numerical simulation of surface currents in the Gulf of Mexico to demonstrate that increases in algal concentrations due to downwelling circulation may be comparable to population increases due to growth alone. The model explicitly excludes growth from the calculation and is used to isolate the influence of coastal circulation patterns in concentrating *K. brevis* along the coast.

2. Conceptual Model

[6] The basis of the conceptual model presented in this paper is that during downwelling conditions plankton are concentrated near the coast due to an interaction between the downwelling circulation and plankton swimming. Downwelling circulation creates a convergence near the coast. Plankton are concentrated by this convergence because they may swim upward against the downward currents near the coast. Plankton enter the near-shore region in the shoreward currents of the upper layer, but do not leave the region in the deeper, offshore return flow. This results in a concentration of algae near the coast proportional to the net amount of shoreward transport in the Ekman layer.

[7] Seasonal winds over the Texas-Louisiana coastal region are typically upwelling in the summer and downwelling the rest of the year. However, because of the curved coastline, the transitions between upwelling and downwelling occur at different times [*Morey et al.*, 2005]. In the spring, upwelling starts in the south along the Mexican coast, and moves northward along the Texas, and eventually, Louisiana. In fall, downwelling starts in the north over the Texas-Louisiana continental shelf and translates southward. Of course, the details of this transition vary from year to year. This study focuses on the Fall transition to downwelling winds in 2005. South of Galveston Bay, downwelling began in August 2005 and progressed from north to south similar to the climatological winds.

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[8] Many recent studies have suggested that plankton may aggregate along frontal boundaries due to the interaction between the physical flow field and plankton swimming [e.g., *Tyler and Seliger*, 1978; *Olson and Backus*, 1985; *Franks*, 1992, 1997; *Epstein and Beardsley*, 2001; *Hetland et al.*, 2002]. Although these reports are useful for a general understanding of the interactions between plankton and circulation, the spatial scales of frontal circulation are considerably smaller than those of coastal downwelling, and are thus not directly applicable to the case of coastal downwelling. The scales of motion in the vicinity of fronts may be quite small, and as a consequence, vertical motions may be substantial when compared to plankton swimming rates. However, vertical velocities associated with downwelling along the Texas coast are similar to plankton swimming rates during frontal passages and are much smaller when averaged over longer time periods. Thus, whereas we expect that plankton could possibly be subducted beneath a front, we expect plankton to stay near the surface during downwelling.

[9] The primary assumption in this conceptual model is that the plankton swim fast enough to stay near the surface. This assumption can be checked by comparing estimated vertical flow velocities with the swimming rate of the plankton. The magnitude of the vertical flow velocity, w, near the coast during downwelling is approximately $w = \frac{\tau}{\rho_o f L}$, where ρ_o is a reference water density, f is the local Coreolis parameter, and L is the width of the coastal current (here approximately 20 km). Given a 10 m s^{-1} downwelling wind ($\tau/\rho_o \sim 10^{-4}$ m^2 s^{-2}), the average downward velocity in the coastal current region would be slightly less than 10 m day^{-1}, which is similar to *K. brevis* swimming speeds. Stronger winds occur less than 10% of the time annually, and are even more rare in summer when winds are typically weaker. Also note that a decrease in the wind speed, or advection in the deep layer offshore will cause a decrease in the vertical velocity that would allow the plankton to re-enter the surface water if they are temporarily subducted by sporadic stronger wind events. Although the model does not account for this type of temporary subduction, we expect that the effect is small. Finally, this temporary subduction will not alter our primary result that plankton aggregate near-shore due to downwelling circulation.

3. Numerical Methods

[10] The hydrodynamic simulations were performed using the Regional Ocean Modeling [*Shchepetkin and McWilliams*, 2005]. The model configuration is identical to that used for the Texas Automated Buoy System (TABS) modeling effort, a real-time nowcast/forecast of surface currents over the Texas-Louisiana continental shelf. (Real-time model results are available at http://seawater.tamu.edu/tglo). The model domain covers the entire Gulf of Mexico, with the grid focused in the north-western section of the Gulf where grid resolution is about 5 km. The model is forced with winds from the National Centers for Environmental Prediction (NCEP) and climatological heat fluxes [*da Silva et al.*, 1994]. The model does not include forcing from the Loop Current or from rivers. Currents in regions shallower than 50 m over the Texas-Louisiana shelf are driven primarily by wind stress, so the coarse coastal circulation features are reproduced by the model [*Nowlin et al.*, 2005]. The simulation began on 1 June 2005 and continued until the end of the year.

[11] Surface currents were extracted from the hydrodynamic simulation, and these surface currents were used to advect a tracer representing *K. brevis* concentration, initialized to be 1 cell ml^{-1}. The tracer simulation begins 1 August 2005, after the circulation in the model has spun up, and this tracer is carried laterally by the simulated flow field. Thus, as the model is a two-dimensional (horizontal) model, there is no explicit swimming. This is equivalent to saying that the plankton swim fast enough to always remain in the upper mixed layer, so that the plankton concentrations here represent the total plankton contained in the upper water column and that these plankton are advected laterally with the surface currents. Although the three-dimensional flow field is non-divergent, the two-dimensional surface current field may be convergent or divergent due to, for example, downwelling and upwelling circulation. During downwelling there is a surface convergence near the coast, which concentrates the *K. brevis* tracer.

4. Data

[12] Surface current observations from the Texas Automated Buoy System (TABS) are shown in Figure 1. TABS is a real-time ocean observing system funded by the Texas General Land Office to aid in oil spill trajectory analysis [*Guinasso et al.*, 2001]. Data are available at http://tabs.gerg.tamu.edu/. Buoys J and D were chosen for the comparison because they are close to the coast, and within the area along the coast that has been affected by *K. brevis* blooms.

[13] *K. brevis* abundance in Corpus Christi Bay was determined from Lugol's preserved samples collected weekly by the Texas Parks & Wildlife Department (TPWD) from October through November. Samples were stored at 4°C and enumerated using a Sedgwick-Rafter counting chamber. Data for Brownsville were obtained from daily cell counts (T. Reisinger, unpublished data, 2005) conducted from 15 September through 11 November 2005 by TPWD.

5. Results and Discussion

[14] Observations of along-shore surface currents are compared with currents predicted by the numerical model. The model reproduces along-shore currents with a correlation coefficient of $r^2 \geq .60$ in both cases. Model correlations with coastal sea-level (not shown) are significant, and correlated with along-shore wind stress as expected. Both along-shore currents and coastal sea level are related to cross-shore currents through the dynamics of the wind driven coastal jet [e.g., *Csanady*, 1982; *Mitchum and Clarke*, 1986]. The model does not predict offshore surface currents well, as these currents are strongly influenced by deep ocean circulation features, such as Loop Current Eddies, that are not included in the numerical simulation. The model does better in the winter than in the summer, most likely due to the effects of stratification from fresh water inputs and solar heating. However, the model does reproduce the salient features of the coastal current system.

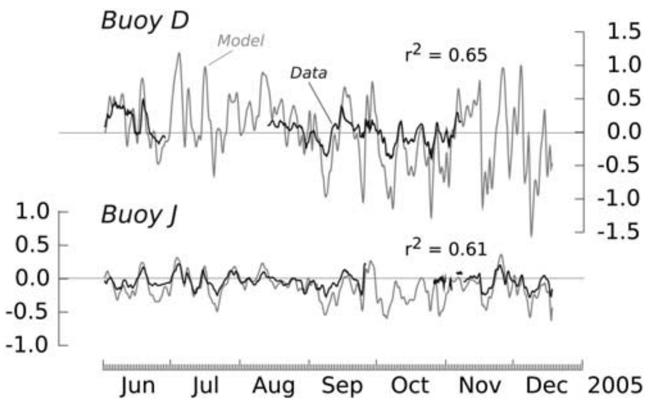

Figure 1. Simulated and observed along-shore surface currents are shown for two TABS mooring locations (Buoy D at 27°56.0′N 96°48.5′W, and Buoy J at 26°11.3′N 97°3.1′W).

[15] The circulation along the Texas-Louisiana coast is typically upwelling in the summer (approximately June, July, and August) and downwelling during the rest of the year, although the magnitude and duration of the upwelling winds change both along the coast and from year to year. Further to the south along the South Texas coast, mean winds are downwelling nearly all of the time, although this also varies considerably between different years. During 2005, the seasonal downwelling circulation begins first in the north, and progresses to the south.

[16] The downwelling is associated with an increase in *K. brevis* concentration near the coast. During downwelling, plankton in the surface layer are advected shoreward due to Ekman transport. At the coast there is a convergence in the surface waters that cause a downwelling circulation. Plankton may swim against this downward current, and remain near the surface. During upwelling, plankton are carried seaward with the offshore Ekman transport. A patch of plankton near the coast would be transported seaward roughly intact. Note that the response of the system is not symmetric, as plankton only swim against vertical currents during downwelling.

[17] Figure 2 shows a plan view of the concentration of *K. brevis* in the numerical simulation. The increase in the southward migration of the simulated bloom throughout the fall of 2005 is apparent. High concentrations of *K. brevis* are localized within about 20 km of the coast, in the wind-drive coastal current regime.

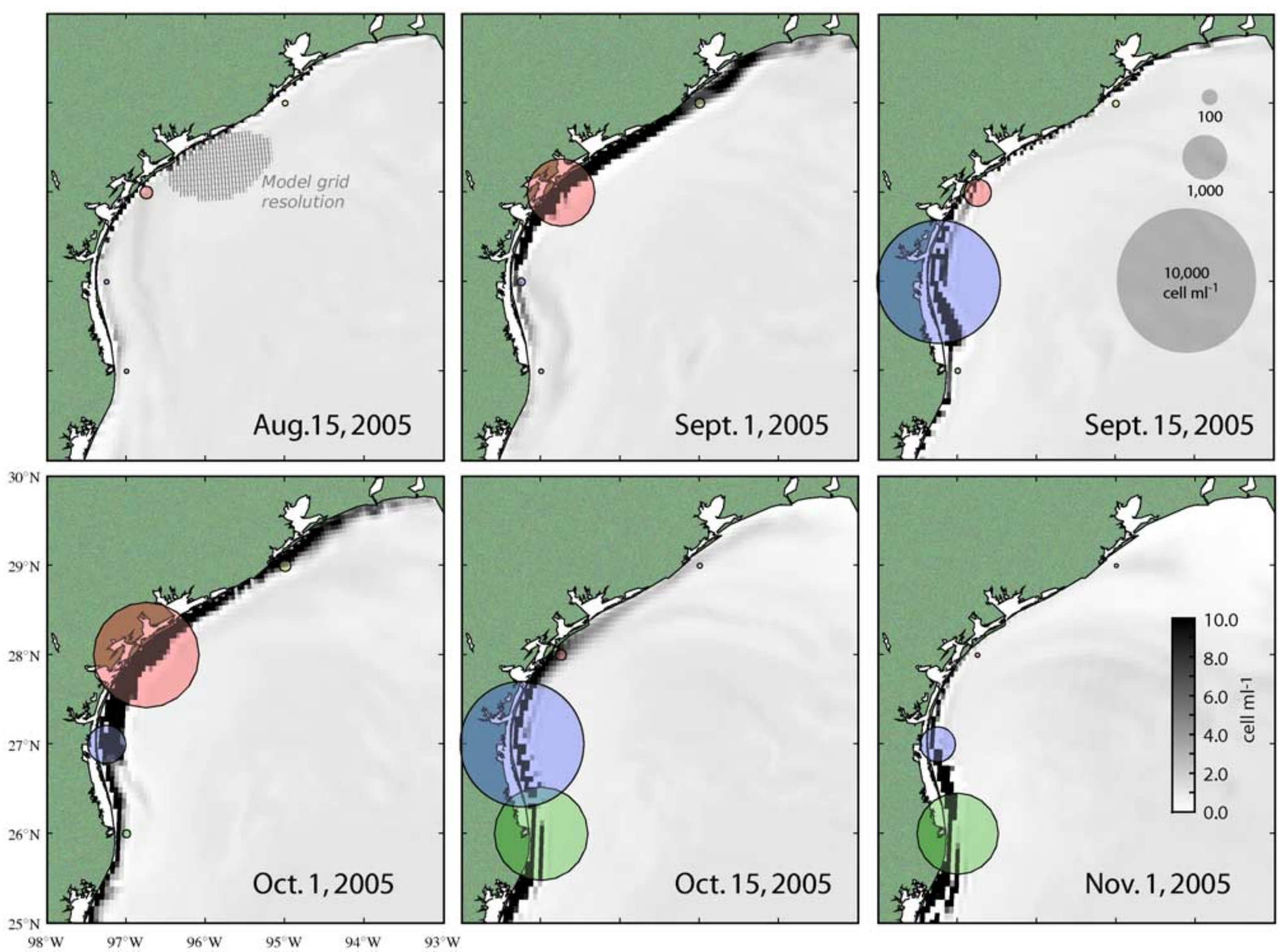

Figure 2. Concentrations of a conservative tracer representing *K. brevis* advected by surface currents are shown in grayscale (for lower concentrations) and circles at points along the coast (for higher concentrations). Point estimates (the shaded circles) show average concentrations in a 20 km radius around the center of the circle, and thus represent a coastal region rather than a single point.

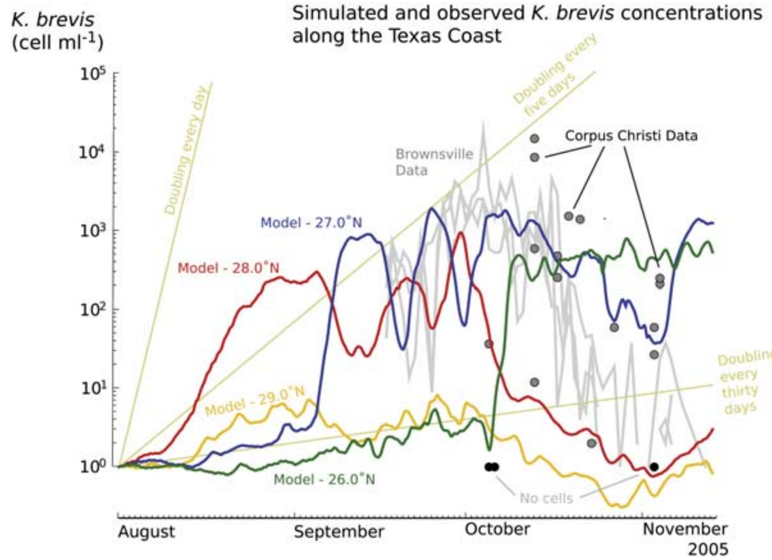

Figure 3. The shaded lines show the simulated *K. brevis* concentrations, and the grey lines show observed *K. brevis* concentrations at Brownsville, Texas, and near Corpus Christi Bay.

[18] Figure 3 shows a time series of simulated plankton at the four locations marked in Figure 2. Although the numerical model is initialized with a low, uniform concentration of 1 cell ml^{-1}, convergence along the Texas coast caused by seasonal downwelling winds can concentrate the plankton up to 1000 times, similar to observed values of 1000 cell ml^{-1}. The numerical model predicts the timing and magnitude of bloom initiation along the coast, but does not predict the details of the migration of the bloom along the coast after it has formed, or the destruction of the bloom. Simulated plankton concentrations are similar to those observed, despite the fact that the tracer representing the plankton concentration is conservative, with a growth rate of zero. This result is significant because it implies that *K. brevis* blooms may be caused primarily by convergence due to coastal downwelling, with cell division a secondary factor in bloom formation. The changes in concentration of the simulated plankton are due only to physical convergence.

[19] Some of the uncertainties in the hydrodynamic model include errors in the wind field product, lack of fresh water discharge, and absence of the Loop Current. Although the dominant physical process on the shelf is wind stress, these small errors may become substantial when integrated for a long period. The position of a tracer patch, in particular, is caused by the history of the flow field it has traveled through. Thus, we do not expect this simple hydrodynamic model to be predictive without data assimilation of either the flow field or plankton concentration. However, the general features of the simulation are correct, as suggested by the high correlation between simulated and observed currents (Figure 1). Chemotaxis also plays an important role in accumulating cells in frontal regions [*Janowitz and Kamykowski*, 2006].

6. Conclusions

[20] This paper reports on a simple numerical experiment that demonstrates the potential importance of surface convergence due to Ekman transport in forming blooms of *K. Abrevis* along the Texas coast. *K. brevis* is of particular concern here because it is a harmful algal species, but this theory should also hold for any algal species with upward swimming behavior. Furthermore, if growth rates are low, the physical aggregation may outpace biological growth rates during seasons with net downwelling conditions. It is clear from Figure 3 that the convergence due to downwelling may account for increases in plankton concentration comparable to growth rates of one doubling per day. Results presented here demonstrate the importance of physical processes in concentrating slow-growing plankton by simulating plankton using an advective model without growth. Thus, changes in the plankton concentration can be uniquely attributed to physical processes that cause convergence and divergence. Model results show that increases in concentration due to coastal downwelling may be as large as increases in concentration expected from typical *K. brevis* growth rates, doubling approximately every one to five days. Although plankton growth is certainly important in bloom dynamics, concentration due to physical properties may be more significant in determining when and where blooms occur. Finally, growth rates estimated from in-situ measurements of cell abundance may have large errors if horizontal convergence is not taken into account. This model also points to the importance of understanding bloom destruction as much as bloom formation. Although increases in plankton concentration may be roughly reproduced through physical processes alone, the collapse of the bloom is not. Understanding biological processes that affect mortality are then perhaps more critical in predicting *K. brevis* blooms than understanding of *K. brevis* growth. Finally, if the magnitude of downwelling is a primary factor in bloom formation, it should be possible to create a downwelling index, an index proportional to the alongshore wind-stress that is proportional to the predicted concentration of plankton along the coast due to Ekman transport convergence. Although this index would only

have predictive ability in line with our ability to forecast weather systems (i.e., not much beyond a few days), it could help managers decide how likely a bloom is before deciding to sample coastal waters.

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