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STUDY TITLE: Current-Topography Interaction and its Influence on Water Quality and Contaminant Transport over Shelf-Edge Banks

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BACKGROUND: A series of topographic banks topped by coral reefs, designated as the Flower Garden Banks National Marine Sanctuary (FGBNMS), and managed by the National Oceanic and Atmospheric Administration (NOAA), is located on the Texas-Louisiana continental shelf in the northwestern Gulf of Mexico. The footprints of the banks range from 2 km^2 to about 80 km^2 and the tops rise to within about 18 m of the sea surface from water depths of 100–150 m. The role of the banks and their interactions in modifying the circulation and transport of materials is poorly understood. The banks are large enough to alter the circulation on the outer shelf. Hydrodynamic processes on the reefs impact the dispersion and material transport of dissolved and particulate nutrients and of planktonic material (Wolanski et al., 1989). The role of dynamics of current and topography interactions in controlling the dispersion of the biological organisms and inorganic materials on the reefs and between the reefs are not well understood but may play a key role in reef habitat. Better understanding of the hydrodynamic processes that control material transport on reefs can provide marine managers information necessary for the successful management of coral reefs.

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OBJECTIVES:

1. To produce a 3-dimensional view of the flow fields around a selected bank and to extend those results to flow over other banks in the region.
2. To increase our understanding of the effects of topography and water stratification on circulation around the banks and the resulting energy subsidy to reef communities.
3. To assess pathways for potential oil and gas impacts on bank communities from adjacent shunting and surface discharge activities.
4. To examine oceanic response, over topographic bank (surface waves, bottom stresses, currents), to extreme, episodic atmospheric wind events, such as severe storms.
5. Expand understanding of non-hydrostatic processes over the reefs.
6. Expand understanding of diapycnal mixing over rough bottom topography and processes responsible for generating turbulence.
7. To understand lateral mixing process, topography induced wakes, and the resulting lateral eddy diffusivities.

DESCRIPTION: Measurements were made at various spatial and temporal scales for understanding the dynamics of flows over rough topography on the continental shelf in the Flower Garden Banks region. The processes that were examined over the East Flower Garden Bank (EFGB) are not limited to this particular bank but can be applicable to other banks in the FGBNMS and, in general, to other world ocean shelves. The field experiments used both long and short-term current moorings, and shipboard and autonomous underwater vehicle measurements during an intensive observation period. For the long-term, low-frequency measurements, five bottom-mounted acoustic Doppler current profiler (ADCP) moorings and four temperature/conductivity (TCP) string moorings were deployed in December, 2010 at the EFGB for approximately one year and hence provide coverage for all four seasons. These moorings were recovered while performing 18 days of intensive field observations in June 2011 from the R/V *Pelican*. Long-term moorings were then replaced by five new ADCP moorings and three string moorings. The fourth string mooring could not be redeployed due to time constraints. The intensive observation period, focused on higher frequency currents and mixing processes, and included short-term, fast sampling ADCP and TCP string moorings, towed ScanFish profiles, autonomous underwater vehicle measurements, vertical-microstructure-profiler observations, and dye releases. Final recovery of the long-term moorings was made using the R/V Pelican in December, 2011. The FGBNMS research vessel *Manta* was used for additional measurements during the June experiment with focus primarily on VMP and ship-mounted ADCP measurements. Standard CTD stations were conducted during the cruises. Additional observations of currents and microstructure at the EFGB were collected in November of 2011 by Mike Gregg (Applied Physics Laboratory, University of Washington) in a separate cruise in collaboration with the Naval Research Laboratory in a project funded by the Office of Naval Research. Some comparisons of the hydrography from the Navy Coastal Ocean Model (NCOM) were made with observed conductivity and temperature data. Plume forecasts were also made to estimate the dispersion of biota as well as sources of water that may impact the Flower Garden region.

SIGNIFICANT CONCLUSIONS: The EFGB interrupted the along-shelf current flow and resulted in a two-layer current system in the vicinity of the bank. Throughout the year, currents at the EFGB were generally eastward in the upper part of the water column above the sill of the bank but were reversed for periods from a day to a week or more by cyclonic eddies impinging on the edge of the shelf. These cyclonic eddies may have originated as Loop Current frontal eddies that were transferred to warm core rings upon separation. The bank impacted the flow in the lower water column and the flow followed the bathymetry. Near-bottom currents at the southwestern and southeastern corners of the bank were mostly directed offshore throughout the year in southeastward and southwestward directions, respectively, following the bathymetry. Average southward or offshore currents in the lower layer of the water column were sometimes comparable or larger than the east-west currents in the upper water column. The maximum observed offshore (onshore) velocity was 27 cm s^{-1} (20 cm s^{-1}). The region just south of the EFGB could be an area of convergence for the deep offshore flow. Integral time scales for the cross-shelf flows generally ranged from three to five days throughout the water column while the time scales for the along-shelf flows were longer and ranged from about a week to more than two weeks.

The main tidal components were M2, K1, and O1, but tidal currents were weak at the EFGB. However, near inertial currents (NICs; periods near the O1 tide) were often significant and could reverse the generally eastward low-frequency surface flows for a few hours when these background currents were weak. The inertial currents occur in bursts throughout the year but were enhanced (often exceeding 20 cm s^{-1}) during summer when in phase with wind modulations due to sea-breeze effects. The bank tends to modify NIC characteristics below the top of the bank. Typically, the vertical structure of the NICs followed a first-baroclinic mode with a 180° phase shift between upper and lower layers but was more complicated when waters were weakly stratified. NICs were generally stronger at the surface but sometimes were largest at mid-depth. Above the bank, NICs were highly coherent. Below the top of the bank, the NIC ellipses tended to align with the bathymetry and become more rectilinear while flowing around the bank. Counterclockwise rotation of the ellipse vector was common on the lee or eastern side of the bank below the top. NICs were often a significant part of the total current and could account for more than 50% of the total current energy throughout the water column. NICs are likely to be partially responsible for enhanced mixing of physical, biological, and geological properties. Characteristics of the NICs observed at the EFGB, as well as other physical processes, are expected to be similar at the other banks.

The southward deep flows at the southern edge of the EFGB in conjunction with the well-known westward motion of Loop Current warm core eddies, and associated cyclonic and anticyclonic eddies, may be a major conduit for shelf water exchange between the Flower Gardens and rest of the Gulf. Conversely, the less-frequent northward deep flows at the southern edge of the bank can transport deep ocean water onto the shelf and Flower Gardens. Offshore flows at the EFGB were largest in the October to December time period for 2011. Much of the cross-shelf exchange is likely to occur in the lower-water column and near the bottom. Eddies don't necessarily have to pass directly over the bank to transfer particulates that reside on the bank since they can entrain the offshore flow. Upwelling in response to storms can also transport cooler deeper waters onto the shelf. One such event was observed during a high wind period during September where 14°C water was upwelled from depths exceeding 200 m onto the shelf. In addition, shelf waves may contribute to the shoreward and offshore flows near the bottom. umerous other banks in the FGBNMS, as well as other regions in the Gulf and in the Atlantic Ocean, can then be affected through eddies and the Loop Current connectivity. Similar processes should also be common at the West Flower Garden Bank (WFGB), similarly located at the shelf edge. Upper layer currents generally did not reverse towards the west for long enough periods to connect the EFGB with the WFGB. However, connections between the EFGB to the WFGB can be made through the train of westward propagating eddies as discussed by Lugo-Fernández et al. (2001) using surface drifters. The WFGB can also connect with the EFGB through the generally eastward upper-layer flows. Connectivity between the banks is expected to be higher during Loop Current ring passages.

Wave-driven velocity fluctuations play an important role in mixing and vertical transports and, in addition, can strongly impact coral habitats over the EFGB. Our study reveals that such velocity fluctuations over the bank are closely related to surface wave conditions that can have strong localized variability due to wave focusing over the bank. Three-dimensional flows with frequencies ranging from 0.2 to 2 cycles per hour were observed in the mixed layer when wind speed and Stokes drift at the surface were large. These motions were stronger over the bank than outside the perimeter. The squared vertical velocity, w^2, was strongest near the surface and decayed exponentially with depth, and the e-folding length of w^2 was two times larger than that of Stokes drift. The two-hour averaged w^2 in the mixed layer, scaled by the squared friction velocity, was largest when the turbulent Langmuir number was less than unity and the mixed layer was shallow. It is suggested that Langmuir circulation is responsible for the generation of vertical flows in the mixed layer, and that the increase in kinetic energy is due to enhancement of Stokes drift by wave focusing. The lack of agreement with open-ocean Langmuir scaling arguments is likely due to the enhanced kinetic energy by wave focusing. Our findings indicate that the scaling of wave-induced mixed-layer currents over a shelf edge bank differs from the open ocean.

Form drag and bottom roughness lengths were estimated over the East Flower Garden Bank (EFGB) in the Gulf of Mexico by combining an array of bottom pressure measurements, and profiles of velocity and turbulent kinetic dissipation rates. Pressure differences across the bank generate a form drag, which opposes the flow in the water column, and viscous and pressure forces acting on roughness elements of the bank generate a frictional drag on the bottom. The average frictional drag coefficient over the entire bank was estimated as 0.006 using roughness lengths that ranged from 0.001 cm for relatively smooth portions of the bank to 1–10 cm for very rough portions over the corals. The measured form drag over the bank showed multiple time-scales variability.

Diurnal tides and low-frequency motions with periods ranging from 4 to 17 days generated form drag of about 2000 N m^{-1}–3000 N m^{-1} with average drag coefficients between 0.03 and 0.22, which are a factor of 5–35 times larger than the average frictional drag coefficient. Both linear wave drag and quadratic drag laws have similarities with the observed form drag. The form drag is an important flow retardation mechanism even in the presence of the large frictional drag associated with coral reefs, and requires parameterization.

Internal mode-2 hydraulic control was observed on crossings of the northern edge of the EFGB. Flow perturbations produced by the hydraulic response dominated the water column and included large vertical displacements in the weakly stratified surface layer overlaying the ridge. The mode-2 response differed in form from a hydraulic jump but produced turbulence one to two decades more intense than the local background. These observations demonstrate that hydraulic control of mode-2, and perhaps higher modes, can affect mixing over rough bottoms nearly as much as does mode-1 control. Hence, mixed layer studies over continental shelves cannot be conducted without considering the effect of relatively small bottom roughness.

Mixed layers at the EFGB often extended to the bottom on top of the bank and ranged from as shallow as 10 m to deeper than 80 m just off the bank. Mixed-layer depths changed rapidly and were observed to shallow from about 80 m to 20 m in less than two days due to an eddy passage that transported cooler shelf water over the bank. Mixed layers were deepest (60 to 80 m) during December and January and generally ranged between 20 and 40 m for much of the year. November was the transition month for the seasonal deepening of the mixed layer.

Observations clearly showed that flow structure and mixing were highly dependent on the direction and strength of the currents in the EFGB region; thus, they varied spatially and temporarily. Responses resulting from interactions between the free-stream flow and the bank were significantly different on the upstream and lee sides of the EFGB. For highly-stratified, subcritical flows over an obstacle, blocking and diverging of the flow is expected on its upstream side, and these flow features were observed on the upstream side of the EFGB for both mean eastward and westward current phases. On the downstream side of the bank, a wake developed, identified by past studies of flows with low Froude numbers. The current observations and estimated relative vorticity also implied that eddies developed on the lee side of the bank. Furthermore, turbulence was amplified over the EFGB top and on its lee side. Estimated total kinetic energy dissipation rates from current shear observations were as high as 10^{-6} W kg^{-1} resulting in measured rates of energy dissipation and mixing by turbulence per unit width over the bank as high as 40 W m^{-1}. Even for such weak flow conditions, mixing on the downstream side was also enhanced by a few orders of magnitude above the typical shelf value of 10^{-5} m^2 s^{-1}, and the eddy diffusivity there was as high as 10^{-3} m^2 s^{-1}. On the upstream side, its estimated values were close to that for continental shelf with gradually varying bathymetry and it was generally less than $0.5{\cdot}10^{-4}$ m^2 s^{-1}. Significantly stronger flows over the EFGB were recorded by the year-long moorings. Turbulence and mixing are expected to be more elevated during the more extreme but commonly observed currents in the EFGB region than turbulence and mixing observed during the intensive observations portion of the field experiment. Hence, the coral reefs can be probably considered as “hot spots” for mixing on the shelf in the northwestern Gulf of Mexico.

STUDY RESULTS: An extensive data set of currents, hydrography, microstructure, and pressure data were acquired at the EFGB. These data were used to understand the physical processes in and around the bank. The East Flower Garden Bank is one of a number of banks in the Flower Gardens and processes observed at this bank are expected to be similar at the other banks. The banks are all large enough to affect the impinging current flow. These topographic interactions can substantially modify advection and transport of water and matter over reef communities. Unlike nearshore reefs of shallower waters, which are wave dominated and strongly influenced by runoff, the ecology of shelf-edge bank communities seems to be dominated by current-topography interactions. The resulting flows provide an energy subsidy for nutrient uptake, waste removal, dispersal of larvae, and regulates the physical environment that allows these communities to grow. Our field observations, some of which are unique to this study, greatly expand our knowledge and understanding of the currents and current interactions with the topography at the EFGB, and the observed processes may be applicable to other banks and topographic features, in general. Better understanding of the hydrodynamic processes that control material transport on reefs were obtained from analyses of these data and can provide information to marine managers to aide in the management of coral reefs as natural resources.

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