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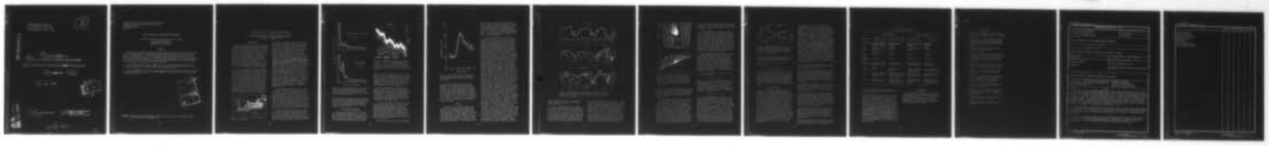

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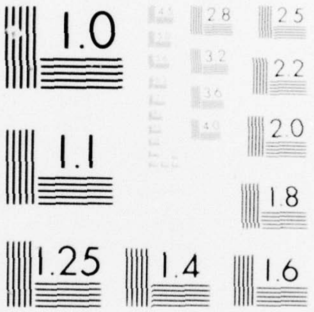

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⑨ Technical Report, No. 240

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PHYSICAL PROCESSES IN A FORE-REEF SHELF ENVIRONMENT.

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⑪ Dec[redacted]977 ⑫ 12p.

⑭ TR-240

Reprint from
Third International Coral Reef
Symposium, Miami,
Florida, May 1977

⑮ Office of Naval Research
N00014-75-C-0192
Project No. NR 388 002

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Proceedings, Third International Coral Reef Symposium
Rosenstiel School of Marine and Atmospheric Science
University of Miami
Miami, Florida 33149, U.S.A.
May 1977

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ABSTRACT

Wave and current measurements were made across a rough-bottomed fore-reef shelf along the south coast of Grand Cayman Island. Wave heights attenuated 20% and current speeds 30% from the shelf margin (≈ 22-meter depth) to a depth of approximately 8 meters, a distance of ≈ 0.4 km. Strong, rectilinear tidal currents (∿ 50 cm s^{-1}) dominated the deep shelf margin, but weak, directionally variable currents were characteristic of the shallow shelf. Attenuation of wave heights and current speeds across the shelf is attributed to frictional effects resulting from strong interactions with the unique boundary conditions of the extremely rough bottom.

A dye experiment illustrated that strong (≈ 35 cm s^{-1}) on-shelf flow is directed up the deep coral reef grooves at the shelf margin. High levels of turbulence (turbulence intensity ≈ 23 cm s^{-1} diffusion coefficient ≈ 2.4 x 10^3 cm^2 s^{-1}) characterize this process.

Wave force-dominated versus current force-dominated portions of the fore-reef shelf were defined from *in situ* measurements. Variations in organic communities, growth forms, and reef structure are consistent with these zones.

KEY WORDS: Waves, Currents, Bottom Roughness, Fore-Reef Shelf, Turbulence, Tidal Current, Wave-Dominated Zone, Current-Dominated Zone

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Introduction

General understanding of the magnitudes and spatial-temporal variations of physical processes (in particular waves and currents) on the seaward shelves of well-developed reefs is based on very few actual measurements. Recent work (1) has shown that the concept of tranquil conditions below the effective wave base on fore-reef shelves is not well founded. On the contrary, the margins of island shelves are commonly exposed to strong, periodic currents. The present paper is designed to present results of physical process studies conducted on the fore-reef shelf of Grand Cayman Island and to relate what we have learned about the physical environment to the reef and some of its constituents.

Figure 1 illustrates the central Caribbean location of Grand Cayman Island, where in situ data on waves and currents, as well as reef morphology, were collected. A site along the south coast was selected for study because of its well-developed reef morphology on the fore-reef shelf, its adequate exposure to dominant ocean waves, and its accessibility from our docking facility near Georgetown. As is characteristic of all fore-reef areas around the island, the shelf in the study area has a general stepped configuration and is very narrow (≈0.6 km wide). An abrupt break in slope at approximately 8 meters delineates the seaward edge of the shallow fore-reef terrace, and a second break in slope at approximately 20-22 meters marks the shelf edge and seaward margin of the deep fore-reef terrace. Along the south coast it is common for the shelf edge to display overhanging reef lobes or a near-vertical seaward-facing reef wall. This seaward reef face extends to various depths (commonly near 700-800 meters) where the deep island slope is encountered. Both the shallow and deep fore-reef terraces support coral communities that are viable but of somewhat different composition. The shallow terrace is dominated by Acropora palmata. Other corals, such as Diploria strigosa, Dichocoenia stokesii, Agaricia agaricites, Porites astreoides, and Montastrea annularis, are also common. In addition, Gorgonians and various alcyonarians are important members of the community. The deep fore-reef terrace can be divided into two zones based on composition of the coral communities: (1) an Acropora cervicornis zone and (2) a Montastrea annularis zone. Coral-covered ridges extend from the seaward extent of the shallow terrace to the buttress zone or shelf margin reef (2) at the shelf edge. These coral spurs are separated by sediment-floored grooves and larger open areas of sediment accumulation. Acropora cervicornis and Agaricia agaricites compose the dominant coral growth on the coral ridges, whereas Montastrea annularis, M. cavernosa, and Agaricia are the most important corals of the shelf margin reef.

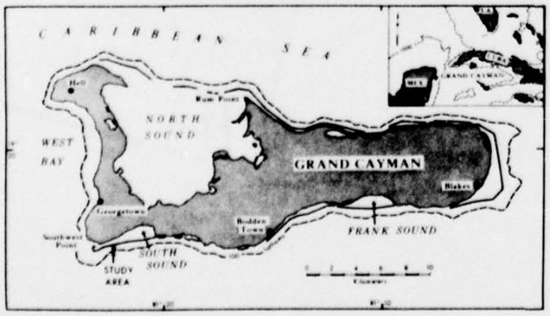

Figure 1. Location map of Grand Cayman Island and the area of study.

Bottom roughness of both the shallow and the deep terraces is primarily the result of coral-covered spurs oriented at a high angle to the coastline and separated by linear areas of sediment accumulation. The spurs and grooves of the shallow terrace generally have a shorter wavelength and smaller amplitude than similar features on the deep fore-reef terrace. Figure 2 quantitatively illustrates this relationship in the form of two bottom roughness spectra derived from the two bathymetric profiles run across the structural grain of the shelf at the approximate midpoints of the shallow and deep fore-reef terraces.

Because Grand Cayman is located in the central Caribbean region, it is sheltered by other land masses from strong storm swells that originate in high latitudes. Therefore, the trade wind system is the driving force behind the wave regime. The process climate in which Grand Cayman resides can be characterized as follows: (1) a

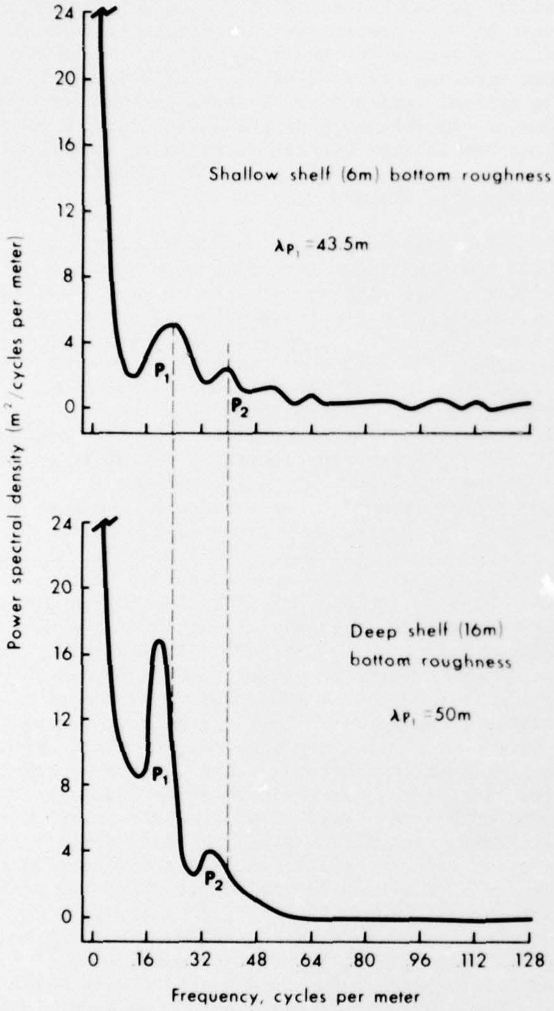

Figure 2. Bottom roughness spectra of the shallow and deep fore-reef terraces in the study area. Note the longer wavelengths and greater amplitude (related to peak heights) of the forms on the deep shelf terrace.

mixed diurnal and semidiurnal microtidal regime, (2) a moderately strong unidirectional trade wind and wave field, (3) moderate-strong oceanic currents, (4) a sheltered position with regard to high-latitude storm swell, and (5) occasional hurricane winds and waves.

Data Collection Methods

Wave and current data were collected from the instrument array shown in Fig. 3. Instrument positions are plotted on a bathymetric profile of the fore-reef shelf that illustrates the extreme irregularity of the bottom--i.e., the spur and groove morphology oriented across the shelf, plus the two submarine terraces positioned along the shelf. Instruments were positioned so that the modification of both waves and currents could be assessed as they impinged on the shelf and propagated over a surface of unusual bottom roughness. Tide measurements were made with a capacitance tide gage installed in the back-reef lagoon adjacent to the shelf study area.

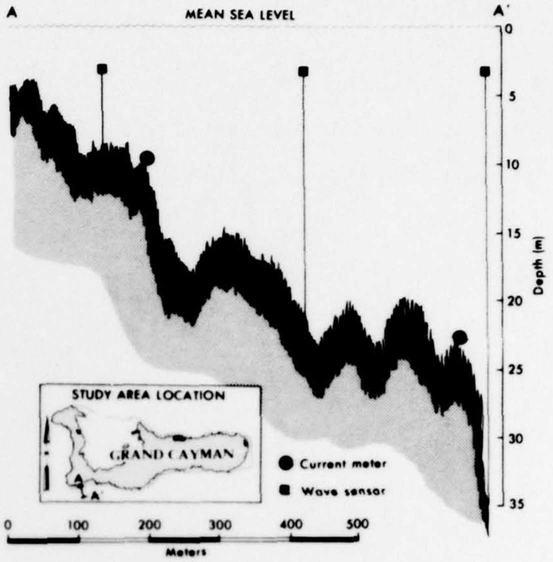

Figure 3. Bathymetric profile across the fore-reef shelf in the study area adjacent to South Sound (see Fig. 1). Note the extreme bottom roughness resulting from coral-covered spurs and intervening sand-floored grooves. Locations of wave and current sensors are plotted on the shelf profile.

In situ continuously recording, bottom-mounted current meters (Marine Advisors Q-16) were used. One current meter was deployed at the seaward margin of the shallow fore-reef terrace (≈8 meters). A second current meter was positioned on top of a coral spur at the shelf edge (≈21 meters), where unobstructed on-shelf currents could be monitored. Data collection was continuous over a 2-week period.

Current meters were not deployed in the deep grooves at the shelf margin. In order to measure the hydrodynamic activity levels in this environment, a dye experiment was designed. Time-lapse photographs were taken as dye (Rhodamine B) was diver released at a depth of ≈33 meters on the groove floor. The experiment was conducted during a peak in the current cycle to assess whether the grooves were active or passive structures with regard to the on-shelf movement of oceanic water.

Wave data were collected from three absolute

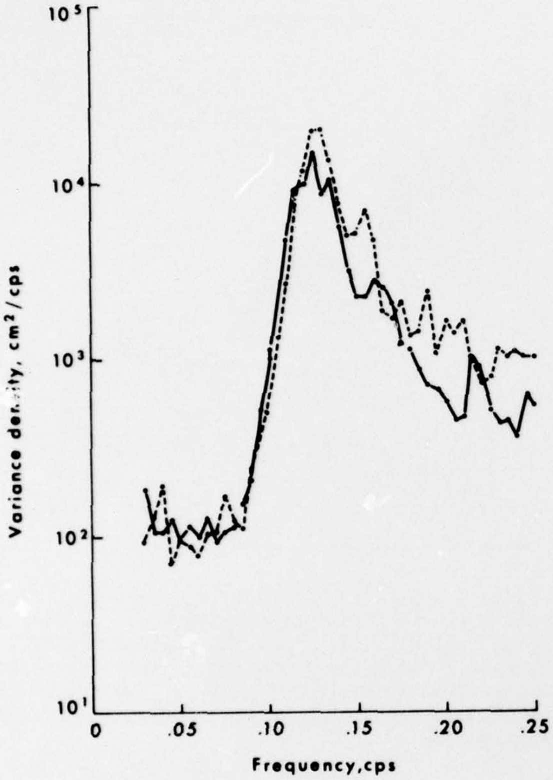

Figure 4. Wave spectra (variance density) from wave measurements at the shelf edge (dashed line) and near the shallow reef crest (dotted solid line).

pressure sensors buoyed at the shelf edge, mid-shelf, and mid-shallow fore-reef terrace positions. The output from each sensor was corrected to give surface measurements. Pressure changes caused by passing waves were registered on a boat-based Brush analog recorder. Sensor depth was read before each measurement by employing a low-pass filter. Data collection periods were ≈20 min at each sensor site. Multiple readings were taken. Data from the pressure sensors were used to define wave spectra at three locations on the shelf.

Results

Comparison of wave data collected at three points on the fore-reef shelf of Grand Cayman Island (Fig. 3) indicates that deepwater wave characteristics are significantly modified by reef morphology. An interesting point concerning these modifications is that changes occur over a very short lateral distance (≈0.4 km). Figure 4 illustrates data taken from the seaward (shelf edge) and landward (near the shallow reef crest) wave monitoring stations. In this figure, wave-induced pressure changes have been defined in terms of wave spectra which essentially show the variance density of the original data. The two most striking features of this comparison are (1) the general consistency of shape between the spectra and frequency relationships between major peaks and (2) the overall decrease in peak amplitudes or variance density of the landward as compared to the seaward spectra.

The dominant peak in each spectrum is at ≈0.13 cps, or a wave period of ≈7.6 s, which is typical of the area and appears to have remained constant between the two monitoring sites. A decrease in energy density of about 45% exists throughout the frequency range of the spectrum between the seaward and the landward stations. Translated into wave heights, this trend indicates that waves are reduced in height by about 20% as deepwater waves intersect the shelf and translate a distance of ≈0.4 km across it. This wave height reduction can arise from a number of combined processes, such as shoaling, refraction, reflection and scattering, and frictional attenuation. Because of the complex nature of fore-reef shelf morphology, the relative importance of each process is difficult to quantify; however, general estimates can be made. Frictional attenuation and scattering of wave energy depend to some extent on bottom roughness. For a bottom roughness amplitude averaging 2 meters (which is a very conservative estimate for the Grand Cayman shelf), wave scattering (3) and the bottom friction coefficient (4) would be about 10 times that found on a sandy shelf of equal width. This estimate means that it would take a sandy shelf 4 km wide to produce the same wave height reduction as results in 0.4 km over the highly irregular Grand Cayman shelf. As Munk and Sargent (5) pointed out with regard to Pacific atolls, the reefs are molded into natural breakwaters consisting of long ridges and channels that efficiently dissipate the energy of incoming waves. Although Munk and Sargent were primarily referring to shallow surge channels and their seaward extensions, the concept is valid for all depths where waves feel bottom and is the configuration common to the entire Grand Cayman shelf. Wave reflection could be significant in some circumstances, but because of the extreme complexity of the shelf morphology it is difficult to estimate. Taking the seaward face of the shallow fore-reef terrace alone, the reflection coefficient (4) is about 0.1 or 10%. Refraction and shoaling can also result in reduced wave heights. For the example given in Fig. 4 a reduction of about 10% is estimated; however, roughness of the fore-reef shelf may cause changes in the wave phase speed. Because of energy losses resulting from percolation and water movement into the reef matrix and sediment, this process cannot be estimated at the present time. Several studies (5), (2) have shown that the wave field plays a major role in determining reef morphology. From the present study it is also apparent that the reef morphology or bottom roughness strongly affects wave processes. Therefore, variability

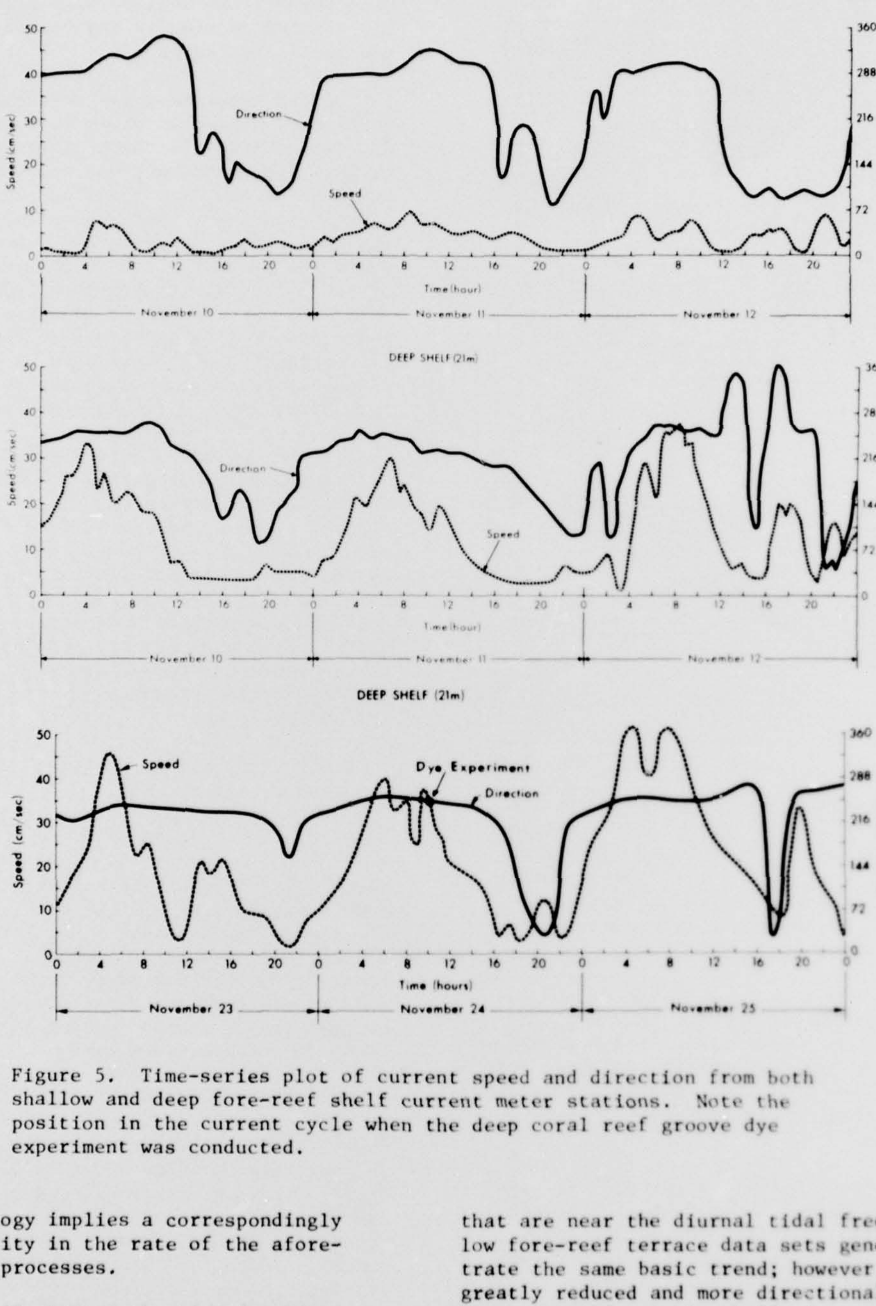

Figure 5. Time-series plot of current speed and direction from both shallow and deep fore-reef shelf current meter stations. Note the position in the current cycle when the deep coral reef groove dye experiment was conducted.

in reef morphology implies a correspondingly strong variability in the rate of the aforementioned wave processes.

Figure 5 illustrates the time-dependent behavior of currents monitored at both the edge of the shelf and the margin of the shallow fore-reef terrace (Fig. 3). Although these and other records from the Cayman shelf were collected in a region strongly influenced by the steady trade winds, currents display very distinct variations in both speed and direction. Records from the deep shelf current meter station clearly show periodicities in current magnitude and direction that are near the diurnal tidal frequency. Shallow fore-reef terrace data sets generally illustrate the same basic trend; however, currents are greatly reduced and more directionally variable. Current speeds at the shelf edge commonly were in excess of 50 cm s^{-1} at the peak in the current cycle, whereas currents on the shallow shelf rarely exceeded 15 cm s^{-1} and generally were <7.5 cm s^{-1}. Current speeds at the deep terrace are distinctly higher, averaging 21.9 cm s^{-1} over a selected 6-day period. A comparison of current speeds at the two monitoring sites over the same time period discloses a 60-70% speed reduction from the deep-shelf station, a distance of ≈0.4

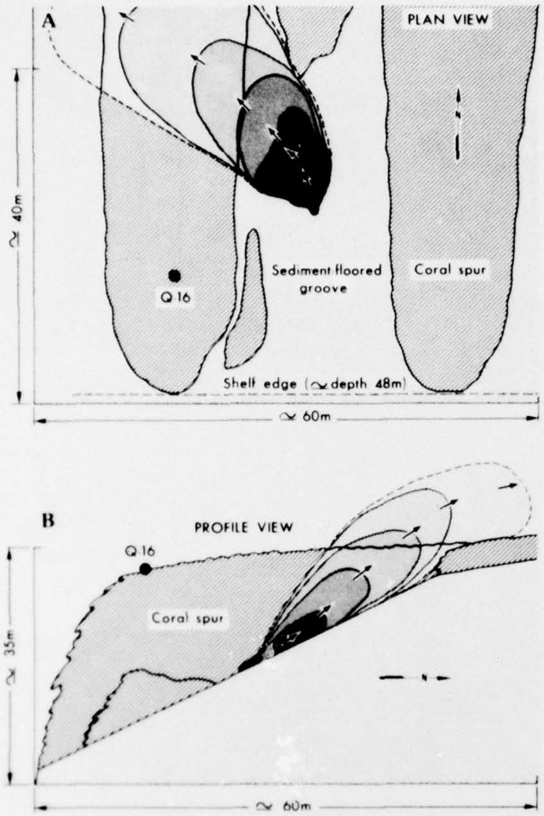

Figure 6. Schematic view of dye expansion in both plan (A) and profile (B) views as interpreted from time-lapse photographs and diver observations. See Fig. 5 for the relationship between the dye experiment and current cycle as monitored at the adjacent deep shelf current meter station.

km. Large vertical and lateral frictional forces associated with the shelf's reef induced extreme bottom roughness and wall roughness, which are probably responsible for the remarkable attenuation of the current speed over such a short expanse of shelf.

In addition to being considerably stronger, currents on the deep fore-reef shelf are much more unidirectional. West- (on-shelf) and slightly southwest- (along-shelf) setting currents account for ≈85% of the total bottom currents at this site. As can be seen in Fig. 5, the directional trace is characterized by long periods of unidirectional flow that are interrupted by short intervals of current reversal accompanied by minimums in the speed record. Currents on the shallow shelf are generally much more directionally variable, although this trend is not especially clear in the record selected for Fig. 5. As might be expected, the dominant shallow current is to the west (≈60%). A secondary east to southeast direction accounts for ≈29%, and 10% of the time the current flows south, directly off the shallow reef crest, and is probably related to tidally induced water exchange with the back-reef lagoon.

A dye experiment was conducted in a deep coral reef groove in order to determine the hydrodynamic activity in these distinct shelf-edge features. The experiment was conducted in a groove adjacent to the deep-shelf current meter mooring site. Time-lapse photography was used to track the dye expansion. Figure 6 schematically represents the history of the dye expansion over a time period of 105 s. Photographs taken at 15-s intervals from the top of the adjacent coral spurs, some 20 meters obliquely above the injection point (an angle of ≈70°), were used as a data base for calculations of mean advection speed, turbulence intensity, and a diffusion coefficient.

Plume boundaries were traced from the original time-lapse photographs and used to quantify the horizontal diffusion. Only the first four exposures (60-s) were used to quantify plume expansion because of perspective problems and source deterioration. Taylor (6) diffusion theory was used to analyze the dye expansion behavior. Details of application of this theory to the dye diffusion in a groove is given by Roberts et al. (7). Similar analyses have been successfully applied to the spreading of continuously emitted oil slicks at sea (8).

For brief diffusion times Taylor's (6) relation can be written as

$$d\sigma_y/dx = \langle V'^2\rangle^{1/2}/U \qquad (1)$$

where σ is the cross-stream standard deviation of particle spread (≈ visible outline of plume), x is the down-plume distance = U_t, U is the constant ambient speed across the source, measured by tracking the leading edge of the dye plume, V' is the cross-stream turbulent speed, and the angle bracket is the averaging operator. Long diffusion times can be expressed by

$$d\sigma_y{}^2/dx = 2\langle V'^2\rangle^{1/2}\,\ell^*/U \qquad (2)$$

where ℓ^*, the Lagrangian scale length, commonly is considered a representative eddy size. Thus $d\sigma_y/dx$ for short distances and $d\sigma_y{}^2/dx$ for long distances should be constants (all terms on the right side of eqs. 1 and 2 are known to be approximately constant). The tangent of half the angle of expansion of the plume ($d\sigma_y/dx$) can now be measured from the photographs, which give a turbulent intensity $\langle V'^2\rangle^{1/2} \approx 24$ cm s^{-1} from eq. 1, as U is already known from movement of the plume front (≈35 cm s^{-1}). Average values of the relative turbulent intensity, $\langle V'^2\rangle^{1/2}/U$, from both field and laboratory studies varies between 0.05 and 0.20. Murray (9) reported a value as high as 0.25 during a hurricane. An extremely high value of ≈0.7 was obtained from this study and appears to be the result of current and/or wave inter-

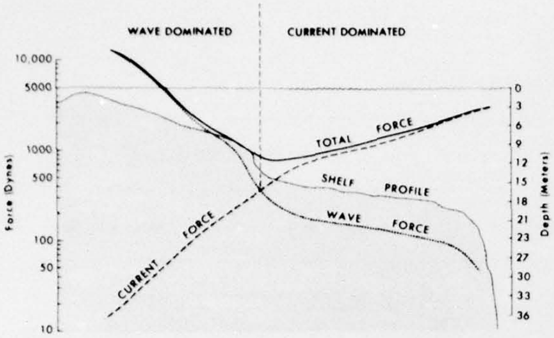

Figure 7. Distribution of wave and current forces across the fore-reef shelf calculated for a vertical surface oriented directly into the flow. Basic zonation of the reef is shown in relation to the force curves.

actions with the unusual wall roughness of the confining coral spurs. Other published values are from situations of unconfined flow.

A diffusion coefficient, K_y, can be expressed as

$$K_y = U/2\ (d\sigma_y{}^2/dx) = \langle V'^2 \rangle^{1/2}\ \ell^* \qquad (3)$$

For the groove experiment a value of 2.4×10^3 $cm^2\ s^{-1}$ was calculated. This value is an order of magnitude greater than might be expected from previous studies, summarized in Okubo's (10) diffusion diagram, if a 12-meter groove spacing is used as a diffusion scale. Both turbulence and turbulence intensity appear to be considerably stronger in the deep coral reef groove than any normal channelized or open ocean conditions would suggest.

Concluding Remarks

Results of physical process studies on a narrow fore-reef shelf are summarized in Fig. 7 and Table 1. Wave- and current-dominated parts of the shelf are defined in Fig. 7, where a common measure of their force across the reef profile is plotted. Representative current speeds, wave characteristics, and bathymetry from field data were used in the force, F, calculations. The common quadratic stress law, $F = 1/2\ \rho A C_d U^2$, was used, where ρ is the density of seawater, A is an exposed cross-sectional area (taken as 1 cm^2 on a vertical plane), C_d is the drag coefficient [taken as 1.95 (11)], and U is velocity ($cm\ s^{-1}$). A representative current speed of 50 $cm\ s^{-1}$ (includes both wind and tidal currents) was decreased linearly across the shelf following measured velocities at the shallow shelf current meter station and the fringing reef crest. Wave force calculations were made for typical trade wind generated waves ($T = 6$ s, $H = 75$ cm) by estimating maximum orbital speeds from linear wave theory.

It is interesting to note (Fig. 7) that current-induced forces at the shelf edge are approximately equal to wave-induced forces at a depth of ≈3 meters near the fringing reef crest. Crossing of the wave and current profiles (Fig. 7) delineates a position that separates the shallow wave-dominated portion of the shelf from the deeper current-dominated zones. Sediments have accumulated in abundance at this site and appear to be relatively stable, forming a mid-shelf sediment reservoir. Also, at this position on the shelf the coral community changes from a shallow, wave-resistant Acropora palmata dominated assemblage to a deeper group characterized by the intricately branched Acropora cervicornis (Table 1). Obviously, the manner in which the force is applied will help determine the response characteristics in the coral community. Periodic oscillatory perturbations by waves, for example, may result in quite different growth form responses from those produced by more steady, long-term current oscillations. These detailed interactions are, however, beyond the scope of this paper. Less detailed form-process relationships are summarized in Table 1.

In summary, the following statements can be made as a result of the physical process study of Grand Cayman's fore-reef shelf:

(1) A feedback relationship exists on the fore-reef shelf such that reef morphology and composition are somewhat dependent on the combinations, intensities, and spatial-temporal variations of physical processes while at the same time the rates of these processes are distinctly influenced by reef morphology and its associated bottom roughness.

(2) An interaction between deepwater waves and shelf morphology results in a 20% decrease in wave height over an ≈0.4-km width of shelf. This attenuation rate is about 10 times that expected for a sandy shelf.

(3) High-velocity (>50 $cm\ s^{-1}$), rather unidirectional currents that have a diurnal tidal frequency were found to dominate the deep fore-reef shelf. Shallow shelf currents were found to be weak and directionally variable. A current speed attenuation of 60-70% from the shelf edge to the shallow fore-reef shelf is attributed to lateral and vertical frictional attenuation associated with the unusual bottom roughness.

(4) A dye experiment conducted at the peak of the tidal current cycle in a deep shelf-edge groove illustrated that on-shelf flow is directed up-groove. Remarkably high levels of turbulence (turbulence intensity ≈23 $cm\ s^{-1}$, diffusion coefficient $\approx 2.4 \times 10^3\ cm^2\ s^{-1}$) characterize this channelized flow.

(5) Calculations illustrate the greater relative importance of current forces over wave forces on the deep fore-reef shelf. Current force on the

Table 1

Major Form-Process Relationships

	Wave Dominated		Current Dominated	
Parameters	Near-Reef Crest	Shallow Terrace Margin	Deep Terrace	Shelf-Edge Reef
Zonation	*Acropora palmata* *Millepora alcicornis*	*Acropora palmata* *Agaricia*	*Acropora cervicornis* *Agaricia*	*Montastrea* *Agaricia*
Growth Forms	Thickly branched Bladed Encrusting	Branched Bladed	Delicately branched Massive	Massive Platelike
Coral Cover	Moderate	Moderate	Abundant	Abundant
Bottom Roughness	<2 meters	<5 meters	<4 meters	<30 meters
Shelf Morphology	Limestone pavement, low-relief spurs and grooves	Moderate-relief spurs and grooves	Moderate-low-relief spurs and grooves	High-relief spurs and grooves
Sediment	Sparse	Thin veneer in grooves	Extensive impounded sediment plains	Off-shelf mass movement down grooves
Waves	Breaking, high turbulence, high wave force	Moderate wave forces, 20% height reduction from shelf edge	Moderate-low wave force, small-scale turbulence	Low wave force, small-scale turbulence
Currents	Weak, multidirectional flow	Multidirectional flow, 60-70% speed reduction from shelf	Moderate on-shelf rectilinear tidal currents	Strong on-shelf rectilinear tidal currents (>50 cm s^{-1})

reef at the shelf edge is approximately equivalent to wave forces on the shallow shelf at a depth of ≈3 meters.

(6) Position of the boundary between wave-dominated and current-dominated zones on the fore-reef shelf, as defined by the crossing of wave and current force curves, corresponds to the position on the shelf where the coral community undergoes a distinct compositional change. The wave-dominated zone is characterized by thickly branched, bladed, and encrusting growth forms and is dominated by the wave-adaptable coral *Acropora palmata*. Delicately branched, massive, and platelike growth forms are common in the current-dominated zone. *Acropora cervicornis* and *Montastrea* represent this coral community. This latter zone, which is subject to minimal wave forces yet experiences considerable current force and associated high levels of turbulence, displays the most thriving coral communities on the fore-reef shelf.

Acknowledgments

This research was performed under a contract with Geography Programs, Office of Naval Research, Arlington, Virginia 22217. Technical assistance in the field and laboratory was provided by Norwood Rector, Rodney Fredericks, and Manuel Hernandez-Avila. Ms. Gerry Dunn is acknowledged for preparation of illustrations.

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Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Coastal Studies Institute Louisiana State University Baton Rouge, Louisiana 70803	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP Unclassified

3. REPORT TITLE

PHYSICAL PROCESSES IN A FORE-REEF SHELF ENVIRONMENT

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Harry H. Roberts, Stephen P. Murray, and Joseph N. Suhayda

6. REPORT DATE December 1977	7a. TOTAL NO. OF PAGES 9	7b. NO. OF REFS 11

8a. CONTRACT OR GRANT NO. N00014-75-C-0192 b. PROJECT NO. NR 388 002 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report No. 240 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES Reprint from Proceedings, Third International Coral Reef Symposium, Miami, Florida, May 1977	12. SPONSORING MILITARY ACTIVITY Geography Programs Office of Naval Research Arlington, Virginia 22217

13. ABSTRACT

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DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6811

Unclassified

Security Classification

A-31408

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Wavesand currents						
Fore-reef shelf						
Grand Cayman Island						
Bottom roughness						
Turbulence						
Tidal current						
Wave-dominated zone						
Current-dominated zone						

DD FORM 1 NOV 65 1473 (BACK)
S/N 0101-807-6821

Unclassified
Security Classification

A-31409