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Evidence for strong currents and turbulence in a deep coral reef groove¹

Abstract—High levels of turbulence (turbulence intensity $\approx 23 \text{ cm s}^{-1}$, diffusion coefficient $\approx 2.4 \times 10^8 \text{ cm}^2 \text{ s}^{-1}$), and strong currents ($\approx 35 \text{ cm s}^{-1}$) were found in a deep coral reef groove ($\approx 33 \text{ m}$). This unexpected turbulence is likely related to the ambient current acting on reef roughness elements, e.g. coral heads. Well developed coral communities that commonly occur at the deep margins of island shelves may in part be associated with these unusual levels of turbulent diffusion.

Below 20 m, coral reefs are generally considered rather passive environments hydrodynamically. However, recent research (Roberts et al. 1975) has shown that the narrow shelves of steep-sided coral islands are subject to strong currents and that the reef is influenced to a significant degree by the interaction of waves and currents with reef morphology. The question then arises: Do the deep grooves so characteristic of the edges of coralline shelves also show such high hydrodynamic activity levels? To approach an answer, we conducted a dye experiment in a deep coral reef groove and showed that, rather than being quiescent, this environmental setting is characterized by swift currents ($\approx 35 \text{ cm s}^{-1}$) and extremely high turbulence intensity (23.7 cm s^{-1}).

The unusual sea floor configurations associated with well developed reef systems (Roberts et al. 1975; Shinn 1963), commonly referred to as spurs and grooves or buttress formations, create a bottom roughness boundary condition for physical processes which is seldom equalled in other natural environments. Relief of 10–20 m between the tops of coral-covered spurs and the floors of adjacent grooves is not uncommon at the deep shelf margin of well structured Caribbean reefs (Goreau and Goreau 1973; Roberts 1974). These deep spur-and-groove structures are large-

scale (up to 20-m amplitude), quasi-periodic corrugations in the forereef shelf which are generally oriented at a high angle to the coast. Circulation and diffusion in atoll lagoons have been measured (von Arx 1948; Munk et al. 1949), as well as flow over reef crests (Odum and Odum 1955; Kohn and Helfrich 1957), but few physical measurements have been made for deep reef environments (Roberts et al. 1975). Our initial study (Roberts et al. 1975), which was conducted on Grand Cayman Island in the central Caribbean Sea, examined the detailed structure of the currents on the forereef shelf and indicated that strong currents at the shelf edge above the reef surface are frequently directed onto the shelf. The role of deep grooves in this forereef shelf circulation remained unknown because no physical measurements, to our knowledge, had ever been made in such a setting.

The dye experiment was conducted on 24 November 1972, at the end of an extensive 5-week study of the forereef shelf adjacent to South Sound, Grand Cayman Island (about $19^{\circ}20'N$, $81^{\circ}15'W$), described by Roberts et al. (1975). The island, in the northeast tradewind belt, is subject to a moderate wave field (typical waves have a significant height of 1 m and a period of 6 s) and low tidal regime (average range $\approx 30 \text{ cm}$). A narrow forereef shelf (about 0.5 km wide) displaying bottom roughness elements of 3–5 m is typical of the study area.

At the shelf edge, spurs or coral ridges have developed into massive reef lobes which are separated by deep sediment-floored grooves ($\approx 20\text{-m}$ average amplitude). The seaward edge of this deep reef terminates in a very steep surface which descends several hundred meters to the main island slope.

As background for the groove circulation and turbulence experiment, ambient current data (Fig. 1) were obtained from a current meter (Marine Advisers Q-16) positioned (*see Fig. 2*) on top of the ad-

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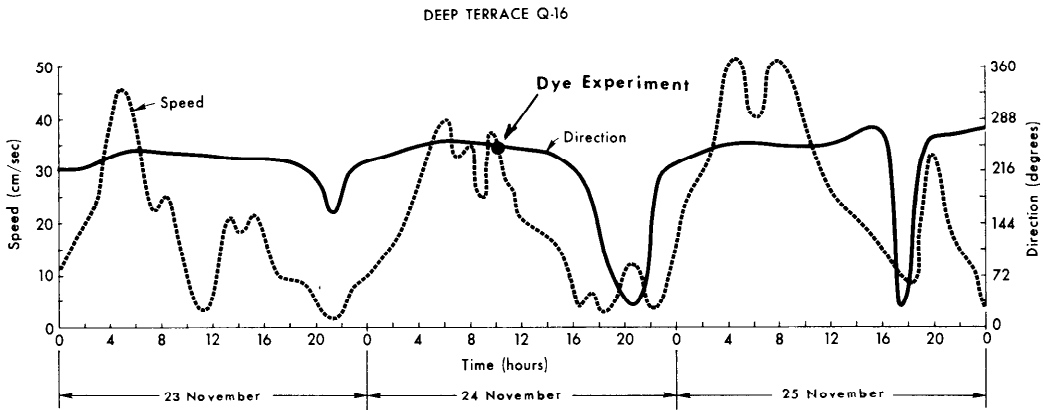


Fig. 1. Time series plot of speed and direction from a bottom-mounted current meter positioned on top of a coral spur about 20 m above the groove study site. Dye-diffusion study was executed during a peak in the current cycle.

adjacent coral spur some 20 m above the groove study site. The segment of the current record spanning the groove study presented in Fig. 1 shows a current of about 35 cm s^{-1} flowing westerly. Periodicity near the diurnal tidal frequency is apparent in the speed signal, with maximum velocities exceeding 50 cm s^{-1} . Long periods of relatively steady westerly flow, roughly along the shelf edge with a slight onshore heading, are most common. Current reversals to the east are short-lived events characterized by erratic low velocity flow.

Dye (rhodamine B) was placed on the sediment-covered groove floor ($\approx 33 \text{ m}$) by a diver. A perforated dye-filled plastic bag served as a quasi-continuous source of tracer for the duration of the experiment. Photos taken at 15-s intervals from the top of the coral spur adjacent to and some 20 m obliquely above the injection point (an angle of about 70°) provided a time-lapse method for tracking dye plume expansion.

In schematic form, Fig. 2 illustrates the expansion history of the dye plume over a period of 105 s. Initially the plume expanded both laterally and along the upslope axis of the groove with very little vertical mixing. Then vertical displacement became evident. After about 45 s the plume was moving swiftly upslope and

expanding rapidly. At the end of the first minute the plume had expanded vertically out of the confines of the groove; however, the bulk of the tracer was confined to the western half of the groove. Upon reaching the height of the coral spurs, the plume was advected onto the shelf by a current moving obliquely across the spurs in a landward direction. The plume then expanded further both horizontally and vertically as it moved across the adjacent spur and onto the shelf.

We estimated the horizontal mean flow on the groove floor, U , to be 31 cm s^{-1} from the time-lapse photographs by tracking the leading edge of the plume over a given time interval. Only the first three intervals (T_1 to T_3) were used in the calculation (Fig. 3). During this period the dye was highly concentrated and the leading edge of the plume was distinct. This procedure minimized the problems of defining the leading plume boundary and uncertainties in calculation of U , as discussed by Okubo (1962).

For quantitative analysis of horizontal diffusion, the plume boundaries were traced from enlargements of the original photographs to illustrate the history of the dye plume expansion during the first 60 s after injection. Only the first four ex-

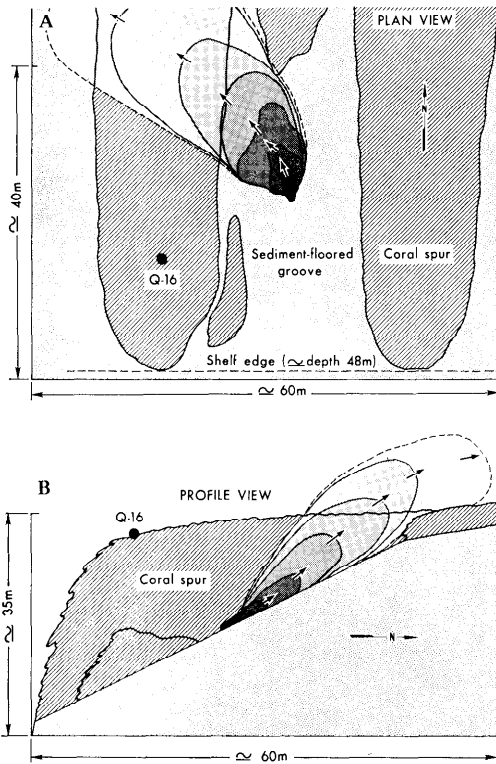


Fig. 2. Schematic representation of dye expansion in plan (A) and profile (B) views as interpreted from time-lapse photographs and diver observations.

posures were considered because of source deterioration and perspective problems as the dye plume moved upslope and onto the shelf. The photographs are not suitable for quantitative estimates of vertical diffusion, nor do estimates of horizontal diffusion warrant the slight correction to a vertical perspective. Note first that the expansion angle of the plume in the immediate vicinity of the injection point (source) is nearly identical throughout all four time-lapse traces, and second that the plume boundaries tend to be nearly coincident (Fig. 3). These two observations strongly suggest that an approximately steady-state plume has formed and that these early and later phases are indicative of the linear and parabolic expansion regimes predicted by the basic Taylor (1921)

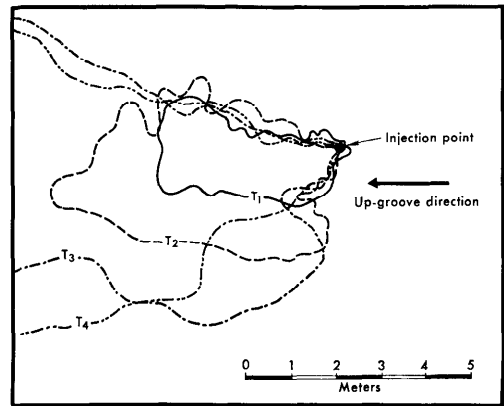


Fig. 3. Dye plume expansion showing plume boundaries for first 60 s after injection as traced from original time-lapse photographs. Time intervals represent 15 s. Photographs, uncorrected for perspective, were taken at a slightly oblique angle (about 70°) from top of an adjacent coral spur (20 m above injection point).

diffusion theorem. However, with the limitation of only one data set, this conclusion obviously needs further verification.

The Taylor relations provide the framework for numerous studies of smoke plume and dye diffusion (Slade 1968) and have also been used successfully in studying the spreading of continuously emitted oil slicks at sea (Murray 1972).

For brief diffusion times Taylor's relation can be transformed into

$$d\sigma_y/dx = \langle v'^2 \rangle^{1/2} / U, \quad (1)$$

where σ is the cross-stream standard deviation of particle spread (or visible outline of plumes as a rough approximation), x is the downplume distance $= Ut$, U is the constant ambient current speed across the source, v is the cross-stream turbulent speed, and the angle bracket is the averaging operator. A limiting equation for long diffusion times is also readily written

$$d\sigma_y^2/dx = 2\langle v'^2 \rangle^{1/2} l^* / U, \quad (2)$$

where l^* , the Lagrangian scale length, is usually thought of as a representative eddy size. Thus $d\sigma_y/dx$ for short distances and $d\sigma_y^2/dx$ for long distances should both be constants, as all terms on the right-hand

side of Eq. 1 and 2 are known to be approximately constant. Now, $d\sigma_y/dx$ is the tangent of half the angle of expansion of the plume from the source and can be measured directly from the plume photographs, which give a value of the turbulent intensity $\langle v'^2 \rangle^{1/2} \approx 24 \text{ cm s}^{-1}$ from Eq. 1, as U is already known from the movement of the plume front. Numerous laboratory and field observations (Okubo and Farlow 1967) indicate that the relative turbulent intensity $\langle v'^2 \rangle^{1/2}/U$ varies between 0.05 and 0.20. In the extreme conditions of a hurricane (Murray 1971), values as high as 0.25 were reported. As all these published values are from situations of unconstrained flow, the exceptionally high value of relative turbulent intensity reported here from the groove floor of $24/31 \approx 0.7$ is related to current or wave interaction with the extreme wall roughness described earlier.

Tabulation of σ_y^2 (the square of the plume half-width) as a function of distance downplume allows us to use a standard linear regression technique to determine the value of l^* from Eq. 2, as all other variables are now known. Beyond a distance of 5.5 m downplume, the σ_y^2-x relation is indeed linear, as predicted by the theory with a regression coefficient of $r = 0.97$, $df = 15$, and the calculation from Eq. 2 shows $l^* \approx 1.0 \text{ m}$.

Assumption of the exponential form of the autocorrelation function as frequently observed in the laboratory and in nature (Hinze 1957) and performance of the double integration of the basic Taylor equation allows l^* to be estimated by a second and independent method (Murray 1972). This slope-intercept technique indicates that the linear portion of the integrated Taylor equation should have an ordinate intercept $= -2l^{*2}$. The mean of the value of l^* calculated by this independent technique from three time lapses gives $l^* \approx 1.1 \text{ m}$. The good agreement between the two different methods for calculating l^* , while somewhat fortuitous, does strengthen our confidence that the plume dispersion

in the groove is indeed following a Taylor diffusion process.

Taylor has further shown that a diffusion coefficient K_y can be expressed as

$$K_y = U/2(d\sigma_y^2)/dx = \langle v'^2 \rangle^{1/2} l^*, \quad (3)$$

which determines a value of $2.4 \times 10^3 \text{ cm}^2 \text{ s}^{-1}$ for the experiment in the deep groove. This is a full order of magnitude greater than might be expected from Okubo's (1971) diffusion diagram if one takes groove spacing (12 m) as a diffusion scale. All indications, then, are that both the turbulence and the turbulent diffusion are considerably stronger in the groove than any normal channelized or open oceanic conditions would suggest.

The above observations of hydrodynamics in a deep island margin environment have been of a preliminary nature. Thorough quantitative analyses must await the acquisition of more complete data sets. However, analysis of time-lapse photographs of dye diffusion in a deep coral reef groove indicates strong turbulent diffusion processes are operative, as evidenced by a diffusion coefficient of $2.4 \times 10^3 \text{ cm}^2 \text{ s}^{-1}$. Characteristics of this diffusive process include a small eddy size ($\approx 1.1 \text{ m}$) and an extremely high turbulence intensity ($\approx 24 \text{ cm s}^{-1}$). The large turbulence intensity value suggests that interaction of currents with the coral spurs and their constituent coral heads may be of paramount importance in the turbulence generation.

In terms of reef growth and development, strong turbulent diffusion is generally considered in a qualitative way to be a process which is most important in the shallow, wave-dominated portions of a reef. This study has shown that deep areas of a modern coral reef system may experience a high level of turbulence during part of the tidal cycle owing to interactions between strong currents and reef geometry. The luxuriant coral communities and well formed reefs which commonly occur at the deep margins of island shelves may in fact be associated with the

presence of these unusual levels of turbulent diffusion.

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A simplified expression for calculating cohort production

Abstract—A simplified method for calculating the production of a cohort is given in terms of readily measured parameters involving ΔB , the observed change in biomass, m the mortality of individuals, and g the observed growth rate of the biomass.

Winberg et al. (1971) gave a method for calculating the average finite growth and mortality of a population if both the number and weight of individuals at times t_0 and t_1 are known. In order to calculate production, they used average number and weight estimates over the time period $t_1 - t_0$. They did not specify whether these are arithmetic or geometric averages, and, further, it appears to us that this is an unnecessary step in calculating cohort production.

Using the same symbols as in Winberg et al. (1971), we can write the rate of change of biomass as

$$\frac{d}{dt}[N(t)w(t)] = N(t)\frac{dw(t)}{dt} + w(t)\frac{dN(t)}{dt}, \quad (1)$$

where $N(t)$ is the number of organisms and $w(t)$ the weight of an individual organism; their product is the total biomass present at any one time, denoted by $B(t) = N(t)w(t)$. The total production (assuming of course that no reproduction occurs in the chosen time interval) is given by