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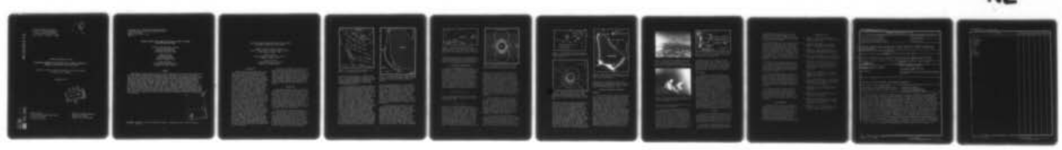

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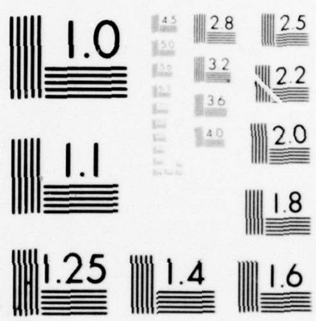

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NEARSHORE CURRENT FIELDS AROUND CORAL ISLANDS: CONTROL ON SEDIMENT ACCUMULATION AND REEF GROWTH

Stephen P. Murray, Harry H. Roberts, Dennis M. Conlon,
and Geoffrey M. Rudder

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Stephen P. Murray and Harry H. Roberts
Coastal Studies Institute
Louisiana State University
Baton Rouge, Louiaiana 70803

Dennis M. Conlon
Geography Programs
Office of Naval Research
Arlington, Virginia 22217

Geoffrey M. Rudder
Caribbean Meteorological Institute
Husbands, St. James, Barbados

ABSTRACT

Observations of drogues drifting with the current, combined with current meter data from Barbados and Grand Cayman Islands, indicate that zones of high current speed (jets or rips, 50-80 cm/sec) and zones of weak, disorganized flow (stagnation zones, 2-10 cm/sec) are systematically located around these islands. Theoretical models of the flow around islands predict the existence, strength, and location of these current zones with reasonable accuracy. Net circulations around the islands as observed by several other investigators play an important role in the location and number of jets or stagnation zones around a specific island. Extensive volumes of sediment accumulate to the lee of high-speed current zones. These sediments appear to be deposited as the carrying capacity of the current rapidly diminishes as it leaves the jet zone. Subsequent reworking of the sediment along the shore is produced by wave and current action. This process of accumulation and shifting of sediments on the lee sides of islands restricts substrate areas suitable for coral colonization and subsequent reef growth. Therefore, interplay between "around-the-island" circulations and sediment transport appears to be significant in producing sites favorable for sediment accumulation but unfavorable for reef growth.

KEY WORDS: Currents, Circulation, Sediments, Transport, Islands, Reef, Coral, Theory, Siltation, Shoaling

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Introduction

The large-scale current flow around oceanic islands has attracted considerable attention in recent years from physical oceanographers primarily interested in the effect of an island on the interior of the surrounding ocean. Hogg (1), for example, explained the vertical displacement (~100 m) of isopycnals observed around the periphery of the Bermuda platform with a theoretical model of steady, frictionless, stratified flow past a circular island. Observations of stagnation points, or zones of very low speed, on the northern and southern flanks of the bank were consistent with the theory. In a similar study of the flow past an equatorial island Hendry and Wunsch (2) reported that the frictionless equations of flow past a cylindrical obstacle described deformations in the density field observed around Jarvis Island (160° 01' W, 0° 23' S). In these cases only a few current measurements were obtained, and they were restricted to distances of more than an island diameter away from the coast and water depths greater than 400 m. Direct measurements of currents were made, however, by Knox (3) about 10 km off Addu Atoll, another isolated island in the equatorial Pacific. Knox reported westerly speeds of 20-30 cm/sec in the surface layer and easterly speeds of 75-100 cm/sec below 70 m. His data showed that the flow does tend to stagnate upstream of the atoll and that current speeds are increased along the atoll flanks, as expected from theory. None of these studies was designed to provide understanding of the dynamics of the currents affecting the coasts and shelves of the islands themselves; rather, they were intended to determine the perturbations introduced into the main flow by the island, which acts as an obstacle.

In contrast, the purpose of this paper is to present data and theoretical deductions concerned with currents within a few kilometres of the coastline. Both observations and theory show that zones of intense currents (jets or rips) and zones of weak currents (stagnation zones) are systematically distributed around the shores of islands and that prisms of sediment tend to accumulate in response to the deceleration of high-speed currents, providing substrate unfavorable for reef growth.

Observations

Our program to assess the role of currents on the shelves of steep-sided islands began in 1972 on the southwestern coast of Grand Cayman, in the Caribbean. By instrumenting in detail one particular transect across the shelf, much was learned (4) about the variability in time of the mean drift current along the shelf and the unexpectedly strong tidal current signal at the shelf edge. It subsequently became apparent that large and systematic along-the-shore gradients in current activity might exert considerable influence on the location and nature of coastal and shelf sediment accumulation forms and reef growth.

Observations of currents moving in space entail the tracking of drifters or drogues with a drag collector such as a parachute or biplane set at a prescribed depth below the sea surface. To locate the surface marker we have used various electromagnetic techniques, such as (a) visually locating drifting drogues with a ship and then locating the position with respect to the island by ship radar, (b) tracking the drogues from shore by radar [in this method an active target (transponder) is attached to the drogue pole which

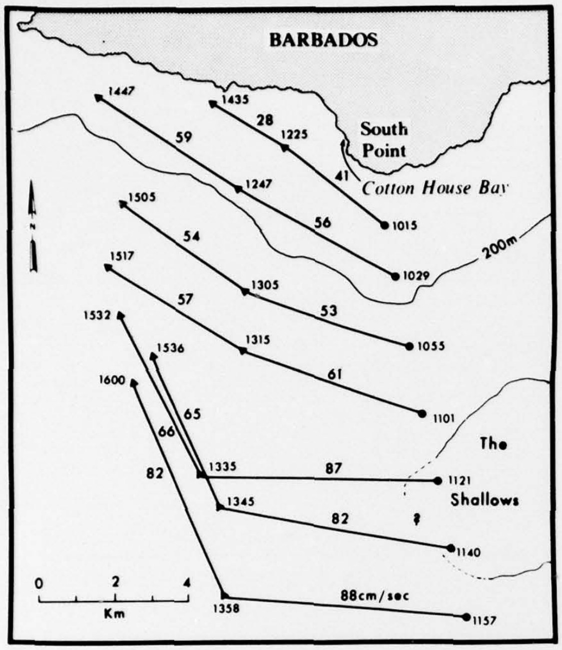


Figure 1. Current tracks from drogues off the south coast of Barbados July 25, 1973.

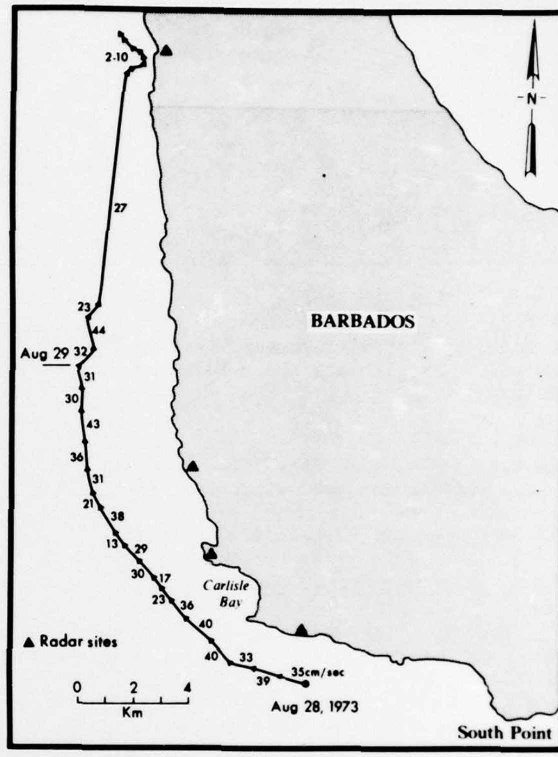


Figure 2. A current track from a drogue equipped with an x band radar transponder, August 28, 1974. A portable radar ashore is used to locate the drogue.

replies to the radar signal at a frequency different from that transmitted to avoid sea clutter, and (c) tracking the drogues by attaching an over-the-horizon type transmitter to the pole and triangulating from the shore by two portable direction-finding units (5).

Such techniques have been employed repeatedly on Barbados, Grand Cayman, and several other islands to determine the strength and characteristics of currents along the shelf. Figure 1 shows a field of drogues moving with the current at the 9-m depth level off the southwestern coast of Barbados. Although Warsh et al. (6) reported that current speeds in the open waters 25 km east of Barbados have a mean of 20 cm/sec and rarely exceed 25 cm/sec, these drogues show quite high speeds of 40-80 cm/sec. Currents just off South Point are in the range of 40-60 cm/sec and are capable of moving grains 1-2 mm in diameter on the bottom. The decrease in speed toward the island suggests the presence of a frictional boundary layer of about 5-km thickness along the coast. The sharp turn toward the island of the outer three drogues is perhaps related to a flow readjustment after they have traversed The Shallows, a 10-km-long bank whose western edge is seen in Fig. 1. From South Point the currents generally flow northward all along the western coast of Barbados. For example, Fig. 2 shows a drogue track of about 26 km along the western coast. Speeds gradually decrease along the northward track from about 40 cm/sec at the onset to 2-10 cm/sec at the end of the track, where the drogue is likely trapped in the frictional boundary layer. A track that is similar but farther offshore was shown in Murray et al. (5). Our observations on Barbados and on Grand Cayman show that reversing tidal currents became increasingly important in the immediate vicinity of the coast (within a few hundred metres). It appears that the long-term drift decays rapidly across the shelf while the tidal current is correspondingly amplified. Observation by Peck (7) clearly showed the dominance of the tidal current over the mean drift inside Carlisle Bay (Fig. 2).

At the northern end of Barbados the current structure was studied by both in situ current meters and drogue techniques. A current meter located about 800 m off Harrison Point consistently showed a weak, extremely disorganized flow in which the tidal currents (clearly seen in the records from other locations around the island) could not easily be identified. Figure 3 shows five drogue tracks around North Point obtained only 18 hours after the data seen in Fig. 1. All other data suggest that the same current patterns were in force around the island on July 26 as on July 25. This weak, oscillating,

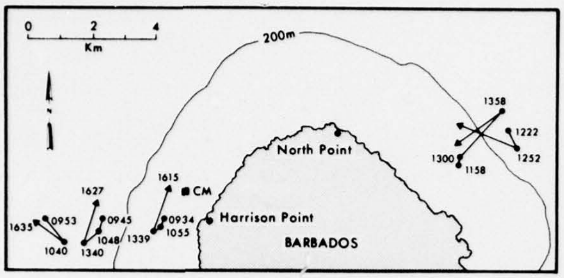


Figure 3. Current tracks off North Point, Barbados, July 26, 1973 showing the intermittent confused current pattern that is also present in the current meter data whose location is noted by CM.

disorganized flow in Fig. 3 is in marked contrast to the well-developed, swift flow persistently seen along the southern and western flanks of the island. These differences are explained below.

Theoretical Considerations

The flow patterns produced by current streaming past a submerged circular cylinder with no friction is a well-known topic in elementary hydrodynamics (8). White (9) gave the solution for the more realistic physical situation of current streaming past a circular island that pierces the water's surface on a rotating earth. The solution for the stream function Ψ is given in terms of an infinite series of modified Bessel functions of the first and second kind as shown in White's equation 17. This solution allows calculation of the radial U_r and tangential U_T components of the current velocity by differentiating Ψ with respect to θ and r; i.e.,

$$U_r = 1/r \frac{\partial \Psi}{\partial \theta} , \; U_T = - \frac{\partial \Psi}{\partial r} .$$

Thus we calculate the direction of the streamlines from the stream function and the absolute current speed from

$$V = (U_r^2 + U_T^2)^{1/2} .$$

To apply the theory two parameters must be set. First, one must specify the far-field current speed U_o, i.e., the upstream current speed beyond the influence of the island. Warsh et al. (6) provide a good estimate of 20 cm/sec, which we will use for computational purposes. Secondly, the value of the stream function on the island boundary must be set. A value of $\Psi = 0$ on the boundary implies symmetry across the flow axis, which hydrodynamically means there is no net circulation around the island. Figure 4 shows the flow predicted for this case with $U_o = 20$ cm/sec. Stagnation zones (weak currents) form on

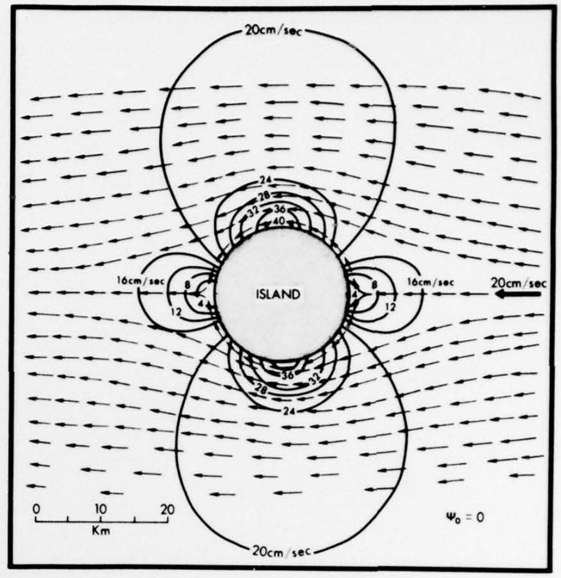


Figure 4. Theoretical prediction of current speed and direction around a circular island with a far field current speed of 20 cm/sec.

the nose of the island and directly behind it, whereas zones of very strong currents (jets or rips) form on the flanks. It is recalled that this general pattern of stagnation zones and accelerated currents was observed by Hendry and Wunsch (2) off Jarvis Island and Knox (3) off Addu Atoll, and it agrees with our current meter observations on Grand Cayman (4). The departure of the flow directly behind the island and the current jet at the top (northern) end of island in this model do not agree, however, with our observations around Barbados. These observations (Fig. 1, 2, 3) show northerly flow all along the back side of the island and departure at the northern end in or near a zone of weak, confused currents.

There are, however, a number of studies in the literature that definitely indicate the presence of clockwise net circulations around islands. Patzert (10) shows this phenomenon to be common in the Hawaiian Islands. One example, in Fig. 5 (replotted from his data), shows a strong clockwise flow around Kauai. The net clockwise speed of 30 cm/sec for 15 days on the southern coast is particularly striking. The geophysical mechanisms that produce these net clockwise circulations remain unclear.

A net circulation around an island such as observed by Patzert (10) and others can be produced in White's (9) theoretical model by setting Ψ unequal to zero on the boundary. Figure 6 is the solution predicted by the theory with $\Psi_o = 0.5 \times 10^8$ cm^2/sec for an island diameter of 20 km and a far-field speed of 20 cm/sec; the current

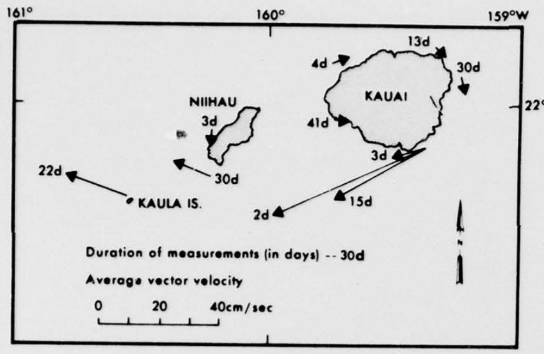
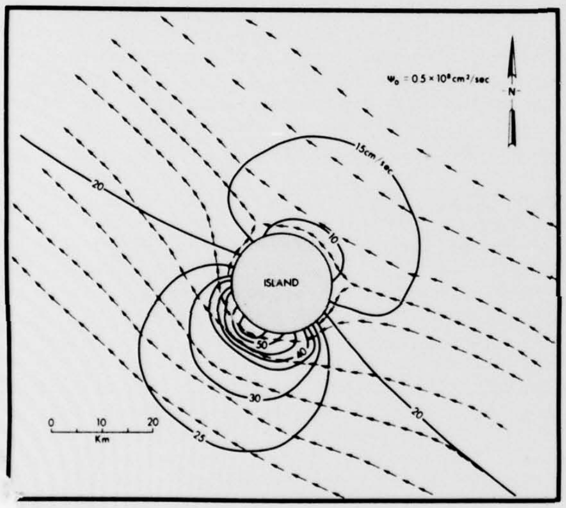


Figure 5. Net clockwise circulation around the island of Kauai observed by Patzert (10) from current meter data.



gure 6. Theoretical prediction of current ,peed and direction around a circular island exhibiting a net clockwise ciculation. The far field current speed is 20 cm/sec from the southeast.

approaches the island from the east-southeast, as is the usual case off Barbados. This value of Ψ_o is simply a best fit to the data selection. Notice that (a) the two stagnation zones have migrated northward and coalesced to form a zone of weak currents off the northern end of the circular island, (b) the flow is all northerly along the back of the island (western coast), and (c) there is a belt of extremely high speeds concentrated at the southwestern corner. These three features are essentially in agreement with the flow patterns depicted by our numerous drogue experiments off Barbados. Also note that our observations indicate that the superimposed oscillatory tidal current is on the order of 10 cm/sec. Thus drogues at the northern end of the island should be weakly oscillated back and forth

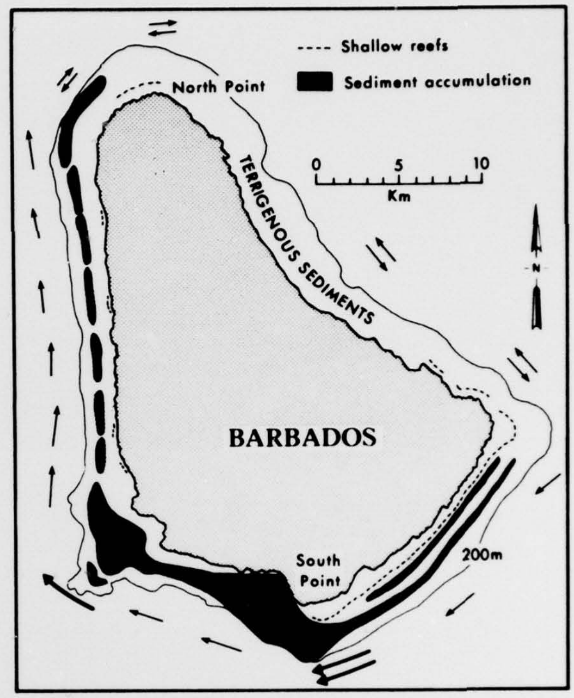


Figure 7. Distribution of accumulations of sediment and shallow reef growth around Barbados and generalized current pattern.

by the tide in a mean drift that which only occasionally can overpower the tidal currents and push the drogues northwesterly. This is apparently the situation depicted in Fig. 3.

Patterns of Sediment Accumulation

Barbados

The extensive areas of sediment accumulation that occur on the southwestern shelf of Barbados (Fig. 7) appear to be well correlated with the distribution of currents summarized in the model (Fig.6). These sediments are dominantly skeletal carbonates derived from both shallow- and intermediate-depth coral-algal reefs growing along the southeastern-facing facet of the island. At South Point, in particular, a broad apron of these sediments has spread across the shelf and over the shelf margin. A large-scale depositional feature ~24 m in vertical dimension has developed at the shallow-shelf abrupt break in slope (Fig. 8). Reconnaissance dives demonstrated that the feature resulted from draping of Recent carbonate sediments over the shelf edge into an adjacent basin. No remnants of the original shelf platform were visible through the Recent sediment cover. Extensive siltation problems along the adjacent shoreline near Cotton House Bay (Fig. 1) illustrate that these sediments are being swept not

Figure 8. (A) Aerial view (looking roughly west) of the large sediment accumulation area in the lee of South Point, Barbados (asterisk notes the position where underwater picture 8 (B) was taken.

Figure 8. (B) Divers sitting on the seaward face of the large sediment accumulation form which has a vertical dimension of ~24 m.

only across the shelf into deeper water but also along shore to the northwest.

This immense prism of sediment observed to be accumulating near South Point appears to be carried into the area by the strong currents predicted by the model. The rapid deceleration of current speed and loss of sediment-carrying capacity away from the Point contribute toward the piling up of sediment at this location. As expected, and as shown on Fig. 7, the occurrence of reefs on the unstable bottoms of these sediment-rich areas is minimal. Other areas of abundant sediment shown in this figure are in the form of mid-shelf bands caught between old, submerged reef ridges (11) along the western and

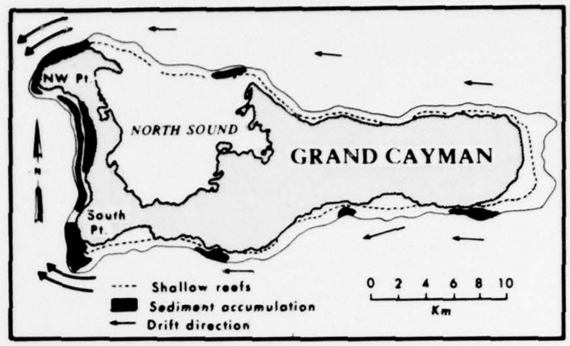


Figure 9. Distribution of accumulations of sediment and shallow reef growth around Grand Cayman and generalized current pattern.

southeastern facets of the island. The area around North Point, where the model predicts weak currents, displays numerous shallow reefs and mid-shelf sediment accumulations. The sediment flux around this Point must be minimal compared to that at South Point in order to provide the stable substrate necessary for reef formation.

Grand Cayman

The pattern of sediment accumulation on Grand Cayman (Fig. 9) also correlates with the current pattern but more closely resembles the flow-without-circulation model shown in Fig. 4. Reefs are much more common and better developed here than on Barbados because there are no significant accumulations of highly mobile sediment along the extensive northern and southern flanks (Fig. 9) of the island. At the northwestern and southwestern corners of the island, however, both in situ field measurements (4) and nautical charts indicate the presence of intense current rips much like those depicted in Fig. 4. The rapid deceleration of the current in the lee of these points leads to deposition and accumulation of large amounts of sediment on the shelf (Fig. 9). As on Barbados, reef growth is poor at these locations inasmuch as this process excludes reef development on many hard shelf substrates because they are drowned in sediment. On both islands long carbonate beaches form on the lee sides and reefs are confined to small patch reef varieties as well as discontinuous deep shelf margin reefs.

Summary

Current meter and drogue observations, theoretical analysis of the flow around islands, and air photo and diver inspection of bottom conditions lead to the following conclusions relating the strength and location of currents to the degree of sediment accumulation and reef growth.

1. Observations of drogues drifting with the current, combined with current meter data, have delineated zones of high current speed (jets or

rips, 50-80 cm/sec) along the shores of both Barbados and Grand Cayman Islands. Zones of weak, intermittent, and disorganized flow (stagnation zones, 2-10 cm/sec) are also systemically located around these islands.

2. Theoretical models of the flow around islands predict the existence and correct locations of these jets and stagnation zones. Grand Cayman appears to be a type with two jets on its flanks and two stagnation zones (nose and tail), predicted by a model with no net circulation, around the island. Barbados, on the other hand, represents a type with a finite net circulation around its circumference. In this latter case an intense jet forms on the southwestern flank and a single large stagnation zone occupies the northern end.

3. Extensive areas of sediment accumulation occur to the lee of these high-speed current zones. As the carrying capacity of currents in the accelerated flow zone decreases toward the island lee, sediments are deposited and then gradually worked onshore and along shore by wave action as well as other currents.

4. The accumulation and shifting of sediments on the lee sides of islands restrict suitable substrate areas for coral colonization and subsequent reef growth. Where shallow reefs appear, they are generally patch-like in design and not extensive. Deep shelf reefs generally occur at the shelf margin and have frequent breaks in the reef trend to allow mass movement of sediment off the shelf.

5. The interplay between "around-the-island" circulation and sediment transport appears to play a significant role in producing favored sites of sediment accumulation, thereby restricting substrate areas where reefs can develop. These processes are of primary importance in the exclusion of well-formed reefs on the lee sides of islands.

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