HURRICANE-INDUCED SEDIMENT TRANSPORT IN OPEN-SHELF TROPICAL SYSTEMS—AN EXAMPLE FROM ST. CROIX, U.S. VIRGIN ISLANDS[1]

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ABSTRACT: Hurricane Hugo passed directly over St. Croix on 17 September 1989. Sustained winds in excess of 110 knots (gusts to 165 knots) and waves 6–7 m in height accompanied the storm. Along the north coast, wave height was lower (ca. 3–4 m) due to the leeward position of the shelf. In the deeper reefs at Cane Bay and Salt River, damage was confined primarily to the soft-bodied benthic community (e.g., sponges, gorgonians); coral damage was much less severe, largely because of the buffering effects of the water column.

The greatest change observed after the storm was wholesale flushing of sand from shelf-edge areas. **In Salt River submarine canyon, a minimum of 2 million kg of sediment were flushed into deeper water. The transport rate associated with the storm was eleven orders of magnitude above that measured during fair-weather, and the volume of sediment that was removed from the canyon equalled roughly a century of normal sediment accumulation.** At Cane Bay, 336,000 kg of sediment were flushed from a single channel, with similar amounts removed from adjacent breaks in the shelf-edge reef.

A current meter in Salt River submarine canyon provided information on the timing and intensity of the oceanographic processes related to Hurricane Hugo. As the storm approached, waves piled water against the shoreface and in Salt River Bay. As the storm passed over St. Croix, the change in wind direction, followed by a decrease in wave height, triggered a release of water trapped in the bay and along the adjacent shoreline by waves earlier in the storm. For a period of 4–6 hours, net down canyon currents reaching 2 m/s and oscillatory flows up to 4 m/s occurred along the base of the western canyon wall, removing up to 2 m of sand. Similar events were likely responsible for the wholesale removal of sand in eastern Cane Bay. The paradoxical concurrence of wholesale sediment transport and low-level reef damage is related to the protection from waves but not wind afforded by the north coast of St. Croix, facing away from the direction of storm approach.

These observations and measurements provide our first opportunity to relate sediment export in such a high-energy event to the physical processes that were responsible. Calculations based on post-Hugo measurements are in agreement with an earlier sediment budget for Salt River canyon. Sediment export in Cane Bay exceeded the volume similarly predicted.

Because such events are probably common on all exposed carbonate shelf margins, storms like Hurricane Hugo are among the most important factors in the cycling of sediment through exposed, open-marine environments both now and in the geologic past. The patterns of reef damage and sediment transport are much more complicated than previously envisioned, and more thoughtful consideration of their variability and the processes responsible is essential to an understanding of the signature that will be left by major storms.

INTRODUCTION

The literature on major storms has understandably focused on the devastation that such events can have on natural systems. Early works of Stoddart (1962, 1963, 1970) provide some of our better descriptions of hurricane-induced damage to tropical island systems. More-recent studies have extended our observations into offshore marine environments (e.g., Woodley et al. 1981; Rogers et al. 1982).

Post-storm descriptions have tended to focus on dramatic changes within the benthic community in the hardest-hit areas, often leaving us with the impression of total devastation. Careful examination of some accounts (e.g., Woodley et al. 1981; Kjerfve and Dinnel 1983), however, reveal a picture more of patchy damage than of total devastation. This was certainly the case on St. Croix in the wake of Hurricane Hugo (Hubbard et al. 1991).

This paper adds to the observations of these earlier workers by describing the patterns of change that occurred along the leeward (relative to the approaching storm), northwest shelf of St. Croix during Hurricane Hugo in 1989. Specifically, the patterns of reef damage and sediment transport are described, and an attempt is made to show that factors other than the severity of the wave regime must be understood to characterize adequately the possible effects of such major storms.

The ideas proposed in this paper draw heavily on a decade-long program of storm observation at the West Indies Laboratory on St. Croix. Included in the data base are seasonal storms, near misses by Hurricanes Frederick (1979), David (1979), Allen (1981) and Gilbert (1989) and, most recently, Hurricane Hugo. A major focus of the following discussion is the magnitude of hurricane-related sediment transport and its importance relative to fair-weather processes. The data presented in this paper provide the first verification of a model proposed by Hubbard et al. (1974, 1976) to explain patterns of storm-induced sediment export measured along the southern margin of Little Bahama Bank. Hypotheses that major storms remove excess sediment produced by bioerosion of the reef (Hubbard et al. 1981, 1990; Sadd 1984; Hubbard 1986) are similarly supported. This information adds to our understanding of the role and signature of major storms in modern marine systems and, by extension, their ancient counterparts.

Description of the Storm

The eye of Hurricane Hugo passed over St. Croix during the night of September 17, 1989 (Fig. 1). Just east of St.

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Croix, central pressure dipped to 934 mb and the storm slowed to a forward speed of only 7–8 mph. As a result, hurricane-force winds buffeted the island for over 12 hours. Property damage from the storm was the highest in history. Over 85% of the island's buildings were rendered uninhabitable. Less than 10% of the utility poles were left standing; power was not restored for nearly 4 months.

Effects on nearshore environments were highly variable, with areas of near-total devastation occurring in close proximity to those with remarkably little change (Hubbard et al. 1991). In general, the greatest damage was on south-facing shelves oriented directly into the oncoming storm. On southern St. Croix, destruction was less apparent in areas where damage remained from earlier storms, as well as those in which benthic communities were adapted to frequent high-energy disturbance (e.g., shallow algal ridges). On the south side of Buck Island (Fig. 1B), which is normally shielded by St. Croix from near-miss hurricanes, destruction of shallow fore-reef environments was total (Hubbard et al. 1991). More-recent core studies (Hubbard et al. 1992) have identified a long-term signature of these patterns of susceptibility in the internal fabric of St. Croix reefs.

Study Areas

St. Croix is located in the northeastern Caribbean Sea (Fig. 1A). The prevailing Trade Winds result in dominant winds and waves from the east. Wave height in the area is usually 0.30–1.00 m, with periods falling in the 4–6 second range (U.S. Naval Weather Service Command 1970; Hubbard 1989). Tidal range is small (averaging less than 30 cm). Currents are generally weak (ca. 0.05 m/s) and move in a westerly direction along the north shore.

Roughly midway along St. Croix's northern coast, a submarine canyon crosses the narrow shelf near Salt River (Figs. 1B, 2A) and opens onto the steep island face at a depth of about 100 m (Hubbard et al. 1986). The canyon is an extension of Salt River Bay, and its character is probably related to a drainage pattern that developed during lowered sea level. Core investigations have shown, however, that Holocene reef accretion has significantly modified the antecedent topography of the canyon walls (Hubbard et al. 1985, 1986). Currents in the canyon rarely exceed 10 cm/s, and they exhibit both a shorter, oscillatory period related to waves and a longer tidal period of 6–12 hours (Shepard and Dill 1977).

The western canyon margin is a steep, reef-covered wall (Fig. 2B). Coral cover varies from 20 to 25% and is dominated by *Montastrea annularis* and *Agaricia* spp. (Birkeland and Neudecker 1979; Rogers et al. 1984). The eastern margin is a gentler slope with much poorer coral cover (0–15%), a result of the westerly movement of sand along the adjacent shelf (Hubbard 1986). The canyon floor is moderately sorted, medium carbonate sand.

Cane Bay is located 7 km to the west (Fig. 1B). An open and narrow shelf (Fig. 2C), the area provides a dramatic contrast to the more confined environment of Salt River submarine canyon. The bottom slopes gradually from shore to a shelf break that varies in depth from 20 to 80 m. Coral abundance is generally low along the inner third of the shelf, presumably because of the strong influence of terrestrial runoff (Hubbard et al. 1990). Coral cover steadily increases in a seaward direction to a maximum of 50–60% near the shelf break. The dominant corals along the shelf include *M. annularis, Porites* spp. and *Agaricia* spp. (Hubbard 1989; Hubbard et al. 1990). Along the shelf edge, the reef is broken by a regular series of shore-normal channels (Fig. 2C). It has been proposed that these channels serve as short-term repositories of sand produced by bioerosion and act as the primary conduits through which this sediment is exported during the passage of major storms (Hubbard et al. 1981; Sadd 1984; Hubbard et al. 1990).

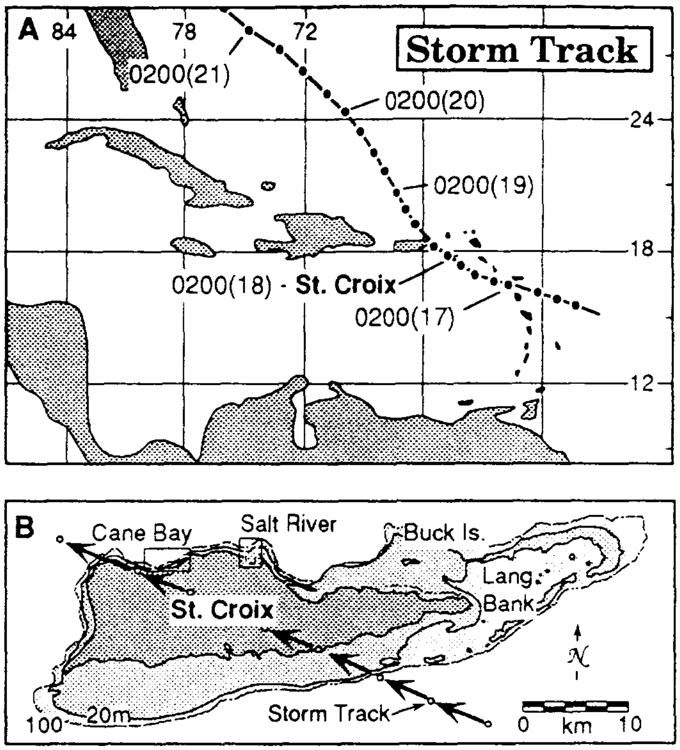


FIG. 1.—A) Storm tract of Hurricane Hugo, 15–20 September, 1989. B) Map showing the locations of the study area, other sites discussed in the text, and the storm tract of Hugo over St. Croix.

An excellent pre-storm data base exists for the ecology and sedimentology of both areas. In Salt River submarine canyon, 12 years of observations and measurements from the research program of the HYDROLAB, and later in AQUARIUS habitats, provide a long-term record of community structure. At Cane Bay, detailed measurements (Sadd 1980; Hubbard et al. 1981; Sadd 1984; Hubbard et al. 1990) provide similar information along three cross-shelf transects (Fig. 2C). The patterns of sediment production and dispersal in both areas are well-documented for low- to moderate-energy conditions (Hubbard et al. 1981, 1982; Hubbard 1986; Sadd 1984). The process data presented here extend our observations to the higher end of the energy spectrum and provide a unique opportunity to test earlier hypotheses regarding the role of major storms in sediment transport along open-shelf margins.

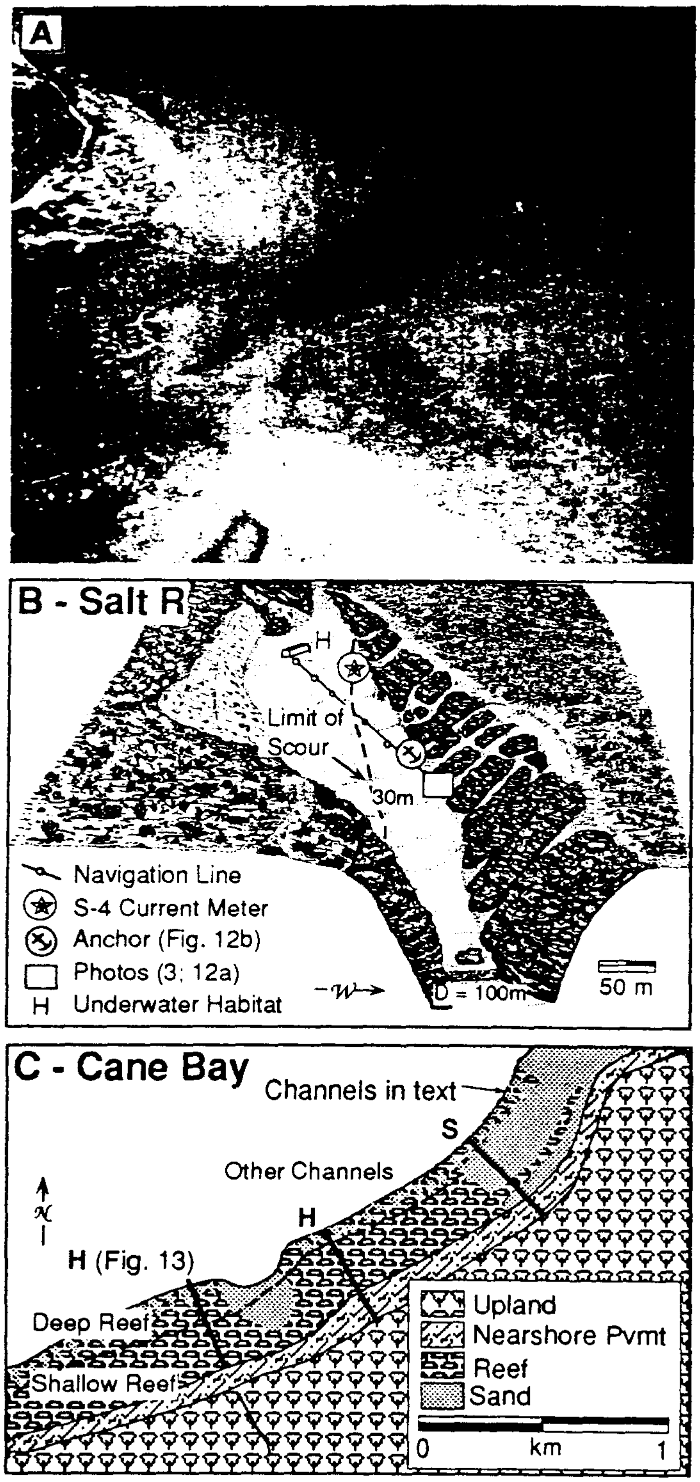


FIG. 2.—A) Aerial view looking northwest across Salt River submarine canyon (dark water at center) and Salt River Bay (lower left). B) Three-dimensional sketch of Salt River canyon. Note the steep western wall and more-gradual eastern slope. The approximate limit of scour along the west wall is indicated by the dashed line. Photo and anchor sites are shown. After Hubbard et al. (1986). C) Map of the shelf at Cane Bay. Channels discussed in text and transects of Sadd (1984—"S") and Hubbard et al. (1990—"H") are shown.

METHODS

Process Measurements

Meteorological and oceanographic data were compiled from aircraft observations made by the National Hurricane Center, observations and measurements made by the author, and the record from a single instrument in Salt River submarine canyon that survived the storm. Hindcasting calculations based on synoptic meteorological data provide supplementary information.

Wind and Wave Hindcasting.—Maximum surface-wind speeds associated with Hurricane Hugo were hindcast using the method of Bretschneider (1952). A similar method was used by Kjerfve and Dinnel (1983) and Kjerfve et al. (1986) to hindcast waves associated with hurricanes Greta and Allen, respectively. The wind speed induced by the barometric-pressure gradient (U_g = geostrophic-wind speed) was determined from a nomogram provided in the "Shore Protection Manual" (U.S. Army 1977, fig. 3.11). The value of U_g from the nomogram was multiplied by a factor of 0.90 to account for wind-speed loss due to isobaric curvature about a low-pressure system in the northern hemisphere (see U.S. Army 1977 for a thorough discussion of this model). The difference between air and sea temperatures associated with Hugo required a further reduction of 40% (U.S. Army 1977) to finally compute the maximum sustained wind speed.

Significant wave height (H_0, in feet) and period (T_s, in seconds) within the hurricane-wind field were computed using the formulae (U.S. Army 1977):

$$H_0 = 16.5e^{R(p_n - p_o)/100} \times \left[1 + (0.208V_f)/(54.81[p_n - p_0]^{1/2} - 0.083\pi[\sin\phi] - 0.5V_f)^{1/2}\right] \quad [1]$$

$$T_S = 8.6e^{R(p_n - p_o)/200} \times \left[1 + (0.104V_f)/(54.81[p_n - p_0]^{1/2} - 0.083\pi[\sin\phi] - 0.5V_f)^{1/2}\right] \quad [2]$$

p_n = normal barometric pressure (29.92 inches of mercury)
p_o = central pressure, in inches of mercury
V_f = forward speed of the storm, in knots
R = radius of maximum winds, in nautical miles
ϕ = the latitude of the storm

The decay of waves as they traveled from the wind field of Hurricane Hugo to St. Croix was determined using the decay curves of Bretschneider (1952), reprinted in the "Shore Protection Manual." Because of the limited shelf fronting both Cane Bay and Salt River, frictional attenuation was ignored. Calculations were made only for times after Hurricane Hugo passed west of the Windward Islands and into the Caribbean.

Instrument Record.—An InterOcean model S-4 electromagnetic current meter recorded process information in Salt River submarine canyon (Fig. 2B) during the passage of the storm. In addition to the speed and direction of currents at 0.5 m above the bed, the meter monitored

FIG. 3.—Underwater photograph near the base of the west wall. Note the abrupt change in color between the darker reef surface and the lighter area of recently exposed substrate (arrow). The steel grating (lower right) previously sat on the sand surface near the intersection of the navigation lines that cross the photo. The *Agaricia* colony to the right of the arrow was not covered by sediment prior to Hugo. The white area near its lower margin is the result of sandblasting by traction load. The bottom drops away to the right of the photo. Depth = 30 m.

mean water level, wave height and wave period throughout the storm using a high-resolution pressure transducer. Measurements were taken for 18 minutes every 2 hours between 4:33 pm on 16 September and 6:33 am on 19 September. During each measurement period, data were taken at one-second intervals. The timing and duration of the measurement sets were based on the available memory of the meter and a time frame felt to likely bracket the passage of the storm.

The meter was deployed at a depth of 18.5 m on the afternoon of 16 September 1989 after it became obvious that Hurricane Hugo would pass close to St. Croix. Because of the anticipated violence of the storm, the base of the meter was tethered to a nearby coral outcrop. Based on earlier observations of wave-generated currents in the canyon, the meter was deployed on the canyon floor near the west wall. The dominant northeasterly wave approach usually forces any downcanyon flow against the western canyon margin. This is reflected in the slightly greater depths on the canyon floor adjacent to the west wall.

The deployment site was not without its drawbacks. During the passage of Hurricane Allen in 1981 and several smaller storms on other occasions, severe turbulence was observed by the author while diving on the site as the storms passed. Strong east-west surge through adjacent channels was observed to confuse the current structure along the base of the wall. Nevertheless, the west-wall site was chosen because of the likelihood that it would be within the field of maximum downcanyon currents.

The current and water-level record was examined using PC-based (MS-DOS) InterOcean software. Wave spectra were computed using a separate InterOcean software package (see Taylor and Trageser 1990 for an initial description and details of computation).

Sediment Transport

After the passage of Hurricane Hugo, reconnaissance dives were made to determine the general magnitude and pattern of sediment scour at both Salt River and Cane Bay. Along the western canyon wall and in the shelf-edge channels at Cane Bay, areas of sediment removal were easily delineated by the difference between the greenish cast of normally exposed reef and the white color of newly uncovered substrate (Fig. 3).

In Salt River canyon, divers measured the vertical displacement of the sediment surface along the west wall at 5-m horizontal intervals. An additional pre-storm reference was provided by one of the tightly strung navigation lines that crossed the canyon floor (Fig. 2B). The

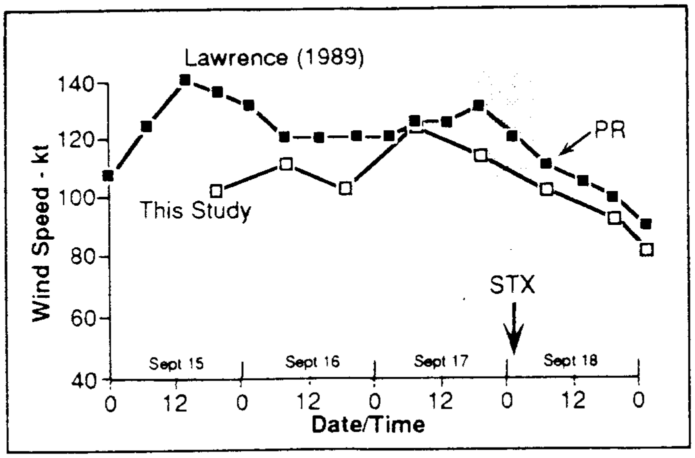


FIG. 4.—Surface-wind speeds (in knots) associated with Hurricane Hugo. Calculations are based on the hindcasting curves of Bretschneider (1952) and a model reported in Lawrence (1989). Shading delineates hurricane winds on St. Croix. Times of the eye over St. Croix and Puerto Rico are also indicated.

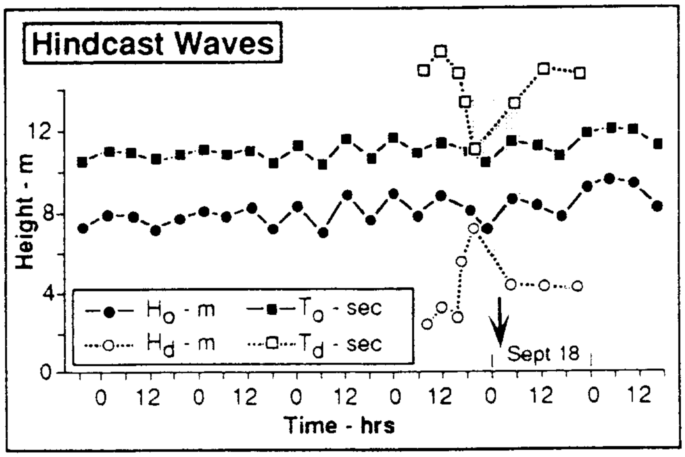


FIG. 5.—Hindcast waves based on synoptic meteorological data, pilot reports, and the model of Bretschneider (1952). Closed symbols refer to waves within the hurricane-wind field (H_o, T_o); open symbols are for decayed waves reaching St. Croix (H_d, T_d). Times for decayed waves have been adjusted to reflect travel time between the storm and St. Croix using a nomogram from the "Shore Protection Manual" (U.S. Army 1977). Shading delineates hurricane winds on St. Croix. The arrow marks passage of the eye.

elevation of the westernmost line above the post-storm canyon floor was measured at 10-m intervals to determine the sediment loss in more central reaches of the canyon. General observations were also made to delineate the extent of the scour elsewhere in the canyon. Mapped landmarks were used for location. Similar measurements of sand loss were made in Cane Bay.

The level of freshly exposed substrate may in part reflect "sandblasting" by sediment moving down the canyon. However, the exhumation of large, attached blocks not seen before the storm, agreement between measurements from the west wall and the navigation line, and scour measurements by a nearby depth sensor (see discussion below) argue against this affecting the calculations or conclusions offered below. If anything, the likelihood that the navigation line, no longer sitting atop the sand, was sagging somewhat at the time of our measurements implies that the scour reported here is a minimum.

RESULTS

Meteorology

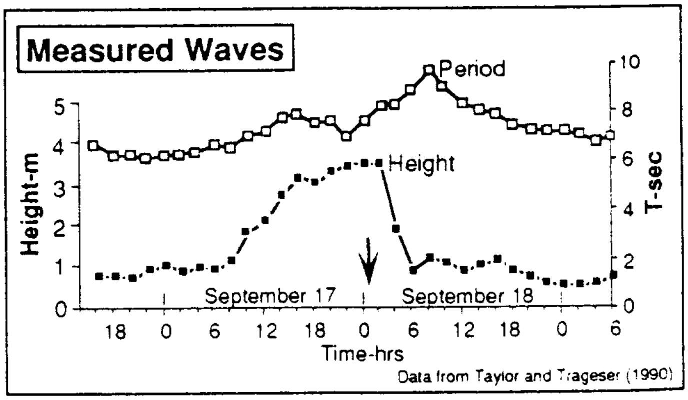
In the months following the storm, personal accounts described possible winds of 130–175 knots. None of these are verifiable, however, as the storm destroyed all recording stations on St. Croix. Nevertheless, available meteorological data do permit a reasonable characterization of the weather conditions that accompanied Hurricane Hugo as it sat over the island.

Figure 4 shows the sustained surface winds hindcast from synoptic meteorological charts. Winds are generally lower than those predicted by a National Weather Service model (Lawrence 1989) and slightly higher (ca. 10–20 knots) than measurements from eastern Puerto Rico (90 knots at 6:00 am on 9/17: Lawrence 1989; Case and Mayfield 1990). Based on our calculations, sustained surface winds on the order of 110–120 knots (125–140 mph), with gusts to 165 knots (ca. 190 mph) occurred on St. Croix.

Oceanography

Waves.—Hindcast wave heights within the wind field of Hurricane Hugo ranged from 7 to 9 m (Fig. 5). Period consistently fell in the 10–11 second range. On St. Croix, very long-period (13–16 second) waves struck the south shore of the island as the storm approached. The 2–3 m heights predicted for decayed waves are consistent with observations made along the south shore. As the storm closed on St. Croix after dark, 7-m high, 6–7 second waves likely pounded the south shore.

On the north coast, waves were smaller, due to the effects of refraction. Seas remained calm (ht ~ 1 m; t ~ 6.5 s) until late in the morning of September 17th (personal observation on eastern St. Croix; measurements to the west: Fig. 6). After that, they gradually built through-



Data from Taylor and Trageser (1990)

FIG. 6.—Wave heights and periods measured in Salt River submarine canyon. The arrow shows the passage of the eye over St. Croix.

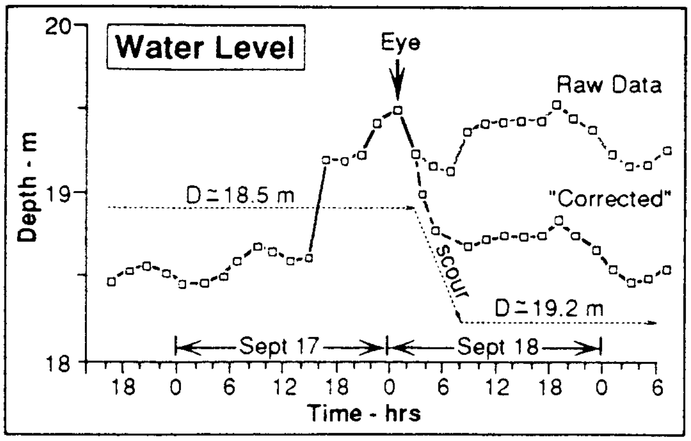


FIG. 7.—Water level measured in Salt River submarine canyon. Each data point is an average of 1080 one-second measurements taken over an 18-minute period. The leveling off of the record between 2:33 and 4:33 am on the 18th, followed by a rise until 8:33 am ("Raw Data"), reflects scour around the meter during the period of maximum current flow. The vertical difference between the "raw data" and the "corrected" record is consistent with scour measurements made near the meter after Hurricane Hugo. The oscillation on the morning of the 19th is a return to normal tidal conditions like those seen in the early part of the record. The arrow marks passage of the eye.

out the day. The largest waves at Salt River (ht = 3.5 m; t = 7–8 s) occurred over a 6-hour period between 8:33 pm on the 17th and 2:33 am on the 18th. The difference between the wave heights measured by the meter (Fig. 6) and those predicted by hindcasting (Fig. 5) is a function of Salt River's leeward position relative to the approaching storm.

Storm Surge.—Because of the narrow shelf and deep water surrounding St. Croix, the potential for storm surge is limited. Based on the locations of backbeach scarps, debris lines, and vessels blown ashore, the storm surge was only 1.0–1.5 m on the north shore and slightly higher on the south shore. The current meter at Salt River measured a nearshore setup of slightly over 1 m between 2:33 pm and roughly midnight on the 17th (Fig. 7).

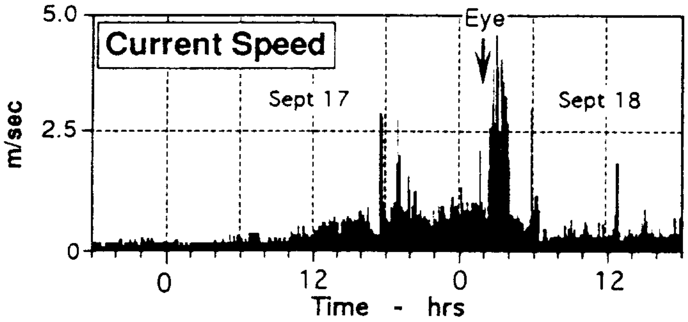


FIG. 8.—Unfiltered record of current speed from 6:33 am on 16 September to 6:33 pm on the 19th. The record is a compilation of one-second measurements made over an 18-minute period every two hours. Directional data are not shown, as the tight nature of the record and frequent oscillations render the graph unreadable. It should be remembered that what appears as a continuous record is actually a composite of 18-min records (i.e., the peak that appears to have occurred between 0233 and 0433 on the 18th really spanned the interval from 0233 to 0251). More detailed records are provided in Figures 9 and 10. The two main spikes in the record occur at 4:30 pm on the 17th and 2:30 am on the 18th. The arrow marks passage of the eye over St. Croix.

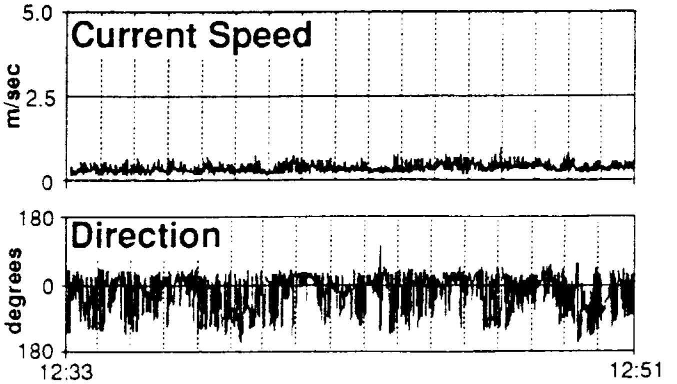


FIG. 9.—Current record from 12:33 to 12:51 on 17 September. Maximum currents exceed 50 cm/s. Currents average 30–35 cm/s and are directed almost solely down canyon. What appear to be oscillations (downward spikes in direction) are an artifact of the way the graph is plotted.

Currents.—An unfiltered record for the entire data interval is given in Figure 8. Until about noon on 17 September, low-velocity (max ~ 10–15 cm/s) oscillatory currents dominated the canyon floor. During the latter part of that interval, pulses of net-downcanyon (290–320°) flows of varying duration started to appear in the record (Fig. 9). Throughout the afternoon, currents gradually increased in intensity as Hugo approached St. Croix.

The most striking feature of the overall record is the interval of current speeds approaching 5 m/s (0.54 m/s = 1 knot) on the morning of 18 September (Fig. 8). Figure 10 illustrates the nature of these currents in more detail. Much of the record is highly oscillatory (Fig. 10). The wild shifts in direction are, in part, normal wave-induced oscillations, but interference by water pumping up and down the channels along the west wall is probably reflected in the record as well. The record also contains minute-long episodes of unidirectional, down-canyon (northerly) flow (Fig. 10). While close examination of the record raises the likelihood that after midnight on the 17th, the directional data (and to some extent, the speed data) were strongly skewed by debris that fouled the meter, the record still provides a sense of the ferocity of storm-induced currents.

Storm Damage

Reconnaissance dives revealed erosion at both Salt River and Cane Bay beyond anything previously documented. The following paragraphs summarize observations made on the first dives in the wake of Hurricane Hugo and relate the patterns of transport to the available process data.

Salt River Canyon.—Most of the the channels along the west wall were swept clear of sand. Much of the soft reef cover (e.g., sponges and, to a lesser extent, gorgonians) had been stripped away by the storm. Debris, including palm fronds, trash and bits and pieces of boats, was common near rocky promontories and other im-

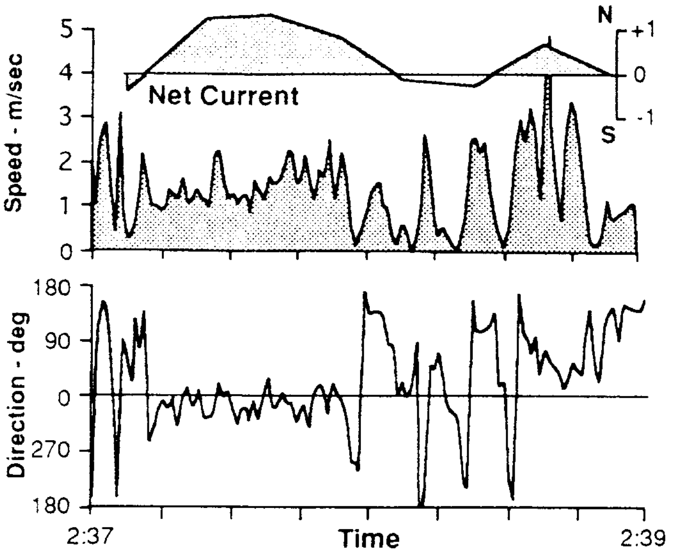


FIG. 10.—Detail of the current record in Figure 8 from 2:37 to 2:39 am on 18 September. The north-south component of the currents is averaged over 15-second intervals ("Net Current"), and shows oscillating flow similar to that seen in Figure 9. Downcanyon flows dominate and exceed 1 m/s. Variations in direction are related to 1) the passage of storm waves overhead, and 2) the pumping of water through the channels running down the west wall. Minute-long intervals of downcanyon (north) flows exceeding 2 m/s can be seen. Comparing these measurements to those shown in Figure 8, it can be deduced that instantaneous-flow velocities of 3–4 m/s were likely generated by storm waves at this time.

mobile features. In general, however, the volume of debris was less than that observed after previous storms, probably a function of stronger and longer-lived currents moving the debris completely off the shelf.

The greatest scour occurred along the base of the west wall from a depth of 15 m to beyond the 30-m contour (Fig. 11A). At a depth of 30 m, roughly a meter of sand had been swept from beneath the concrete base of a way station placed there for divers working from the AQUARIUS underwater habitat (Fig. 3). In some instances, 2 m of sand had been removed (Figs. 11A, 12A). Based on observations along a cross-canyon navigation line at a depth of 30 m, erosion extended to roughly mid-canyon. At a depth of 27 m, an old anchor (Fig. 12B) that had previously been buried by 60–75 cm of sand now stood more than a meter above the sediment surface. Two dead colonies of *Siderastrea* sp. on the anchor yielded uncorrected radiocarbon dates of 101 and 109 YBP ± 0.8% modern, a rough estimate of the last time the anchor had been exposed. A minimum of 1250 m^3 of sand had been removed from the area between the west canyon wall and the limit of scour denoted in Figure 11A. Assuming a bulk density of 1600 kg/m^3, this amounts to at least 2 million kg (2000 metric tons) of sand.

Along much of the eastern canyon floor, many familiar reference points (e.g., sponges, stakes) were still in place. While widespread *net* scour had not occurred on this side of the canyon, there was still evidence of localized erosion and significant throughput of sediment. The AQUARIUS underwater habitat ("H" in Fig. 11B) located near the head of the canyon was listing severely due to scour around its base. Also, shallow channels along the adjacent eastern margin of the canyon were left devoid of any sediment.

Large ripples that covered most of the canyon floor recorded the dominance of wave-induced oscillatory motion during the latter part of the storm. Near the base of the west wall, at depths of 20–25 m, bi-directional ripples (L ~ 75 cm; ht ~ 15–20 cm) remained with their crests roughly parallel to the wall. These were probably caused by strong, E–W surge at the base of the wall. Near the east margin, much larger (l ~ 2.5–3.0 m; ht ~ 40–50 cm) ripples were found at roughly the same depth, with their crests oriented across the canyon. A slight northern asymmetry may reflect some down-canyon flow. The troughs were filled with gorgonians, sea fans and sponges. Across the central canyon axis, ripple orientation and size graded between the two extremes.

Cane Bay.—Damage to the reef was surprisingly low at Cane Bay. While small changes can be seen in pre- and post-storm cover by individual coral species, the reef had changed very little along a cross-shelf transect surveyed before and after the storm (Fig. 13). The resiliency of the reef system at Cane Bay is, in large part, related to the occurrence of the highest coral cover in deeper water (> 10–15 m) near the shelf edge. The shallow-water community, which would have received the brunt of the wave-induced energy, was already depauperate due to the effects of terrestrial runoff (Hubbard et al. 1990) and the often-observed turbid conditions near shore. Closer to the shelf edge, the overlying column of water provided an effective buffer against the effects of storm wind and waves. Also important is Cane Bay's location on the north coast of St. Croix, away from the approaching storm. Despite the extreme winds, the short fetch between St. Croix and the islands to the north limited the severity of wave attack.

Even though damage to the reef was lower than anticipated, significant sediment export still occurred. The shelf-edge channels in the eastern bay were largely devoid of the sediment that had been observed to fill them before the storm. Coral debris, sponges and other material derived from the shelf and adjacent hillsides littered the bottoms of the deepened channels.

In the three easternmost channels, the lowering of the sediment surface averaged nearly 2 m, exposing a system of labyrinths and 5 old anchors that had been hidden below the sand before the storm (Fig. 14A). In the next channel to the west, an additional 4 anchors of similar vintage were discovered (Fig. 14B). These most likely date from the period when sugar cane was actively exported in the later 1700s and the 1800s. Ships servicing the then-flourishing Cane Bay Plantation probably took advantage of the slight shelter of eastern Cane Bay where the anchors were found.

Based on scour measurements and channel dimensions, roughly 325,000 kg (325 metric tons) of sediment were removed from a single channel by Hugo. Similar amounts of sand were removed from at least the adjacent two channels. In Davis Bay, 2 km to the west, sediment export was much lower, despite a greater exposure to storm waves. This pattern is somewhat enigmatic. Also somewhat of

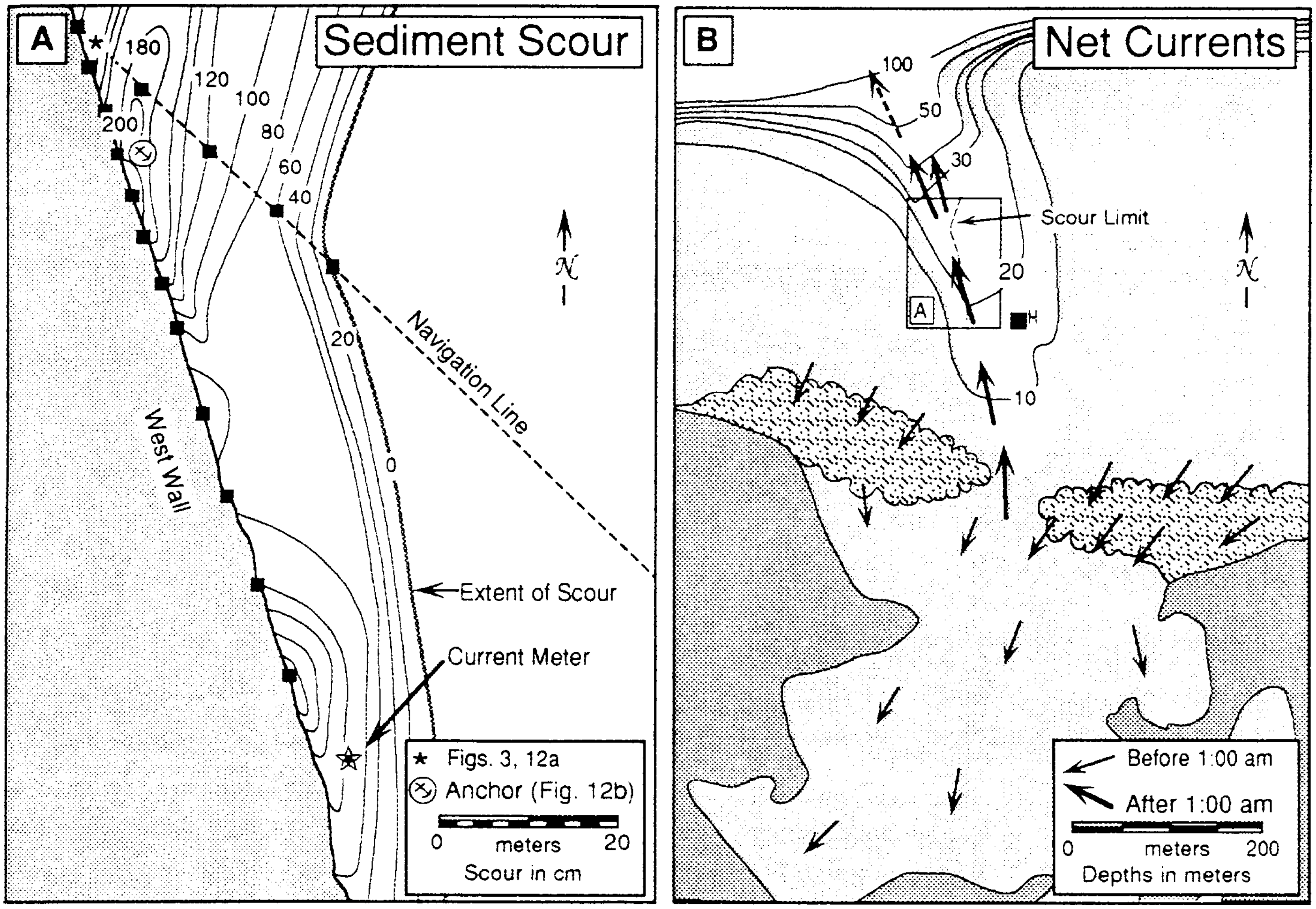


FIG. 11.—A) Map showing the pattern of scour along the west wall of Salt River submarine canyon. Measurement points on which the map is based are shown by closed squares. Contours are also based on spot measurements and observations not shown. The photo location for Figure 12 is shown. **B)** Net-current patterns during the passage of Hurricane Hugo. As the storm approached, building seas piled water up against the face of the reef and into Salt River Bay (small arrows). As the storm moved off to the west, the change in wind direction and the drop in wave intensity released this water, triggering strong downcanyon return flows (large arrows). These currents were largely confined to the west wall of the canyon. The location of the map in A is also shown.

a paradox is the wholesale removal of sand in the face of relatively low levels of reef damage. Both of these problems are discussed in greater detail below.

DISCUSSION

Storm-induced sediment transport such as that seen after Hurricane Hugo has been documented elsewhere (Hubbard et al. 1974; Woodley et al. 1981), but the severity of the scouring at Cane Bay and Salt River is unprecedented in the literature. Also, the oceanographic measurements from Salt River provide valuable insight into possible links between physical processes and sediment removal that could only be inferred until now.

Factors Affecting Scour

Starting around 8:00 am on the 17th, both wave height and period started to increase (Fig. 6). As a result, water was gradually piled up in Salt River Bay and against the shoreface (Figs. 7, 11B). Water level in the nearshore zone continued to rise until midnight, when it reached a maximum elevation 1 m above normal. Surge levels in Salt River Bay were probably greater than those measured in more open water by the meter.

A sudden shift in the wind to an offshore direction after midnight (discussed in greater detail below) is likely responsible for at least the initial release of water from Salt River Bay and the shoreface. Storm surge started to recede (Fig. 7), despite the maintenance of high waves for another two hours (Fig. 6). After midnight (1233) on the 18th, wave height dropped sharply, reinforcing the flushing of Salt River Bay that had already begun (Fig. 7). Timing of the scour is reflected in an apparent flattening of the water-level record at about 0233 on the 18th (Fig. 7). Comparison of the pre- (16 September) and post-storm (19 September) records allowed a "correction" of the data to reflect the magnitude of the erosion (Fig. 7). This agrees closely with scour measurements taken near the meter after the storm.

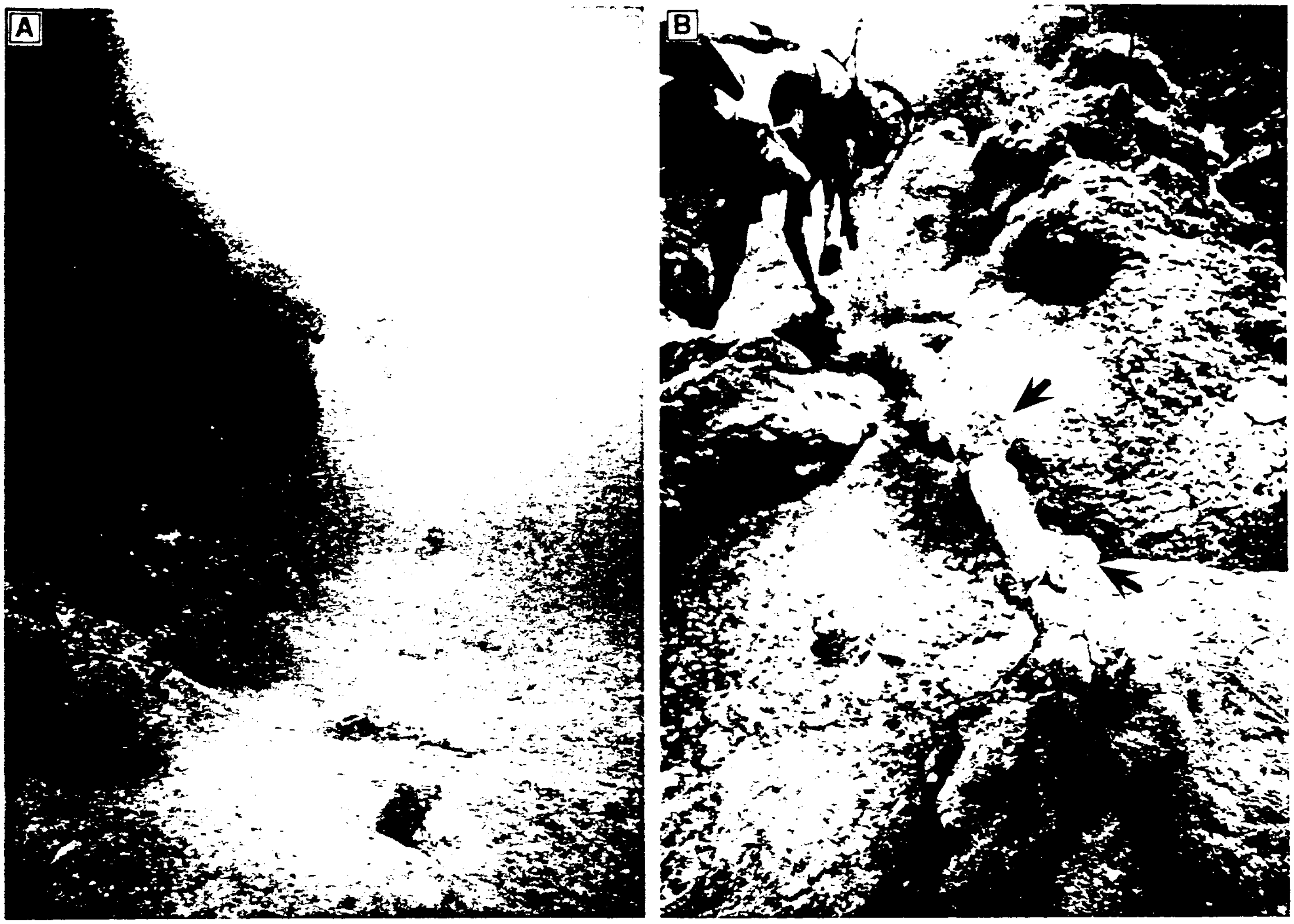


FIG. 12.—**A)** Photograph taken along the west wall of Salt River submarine canyon after Hurricane Hugo. The level of the pre-storm bottom is shown by the dashed line. Note the divers for scale. The photograph is located in Figures 2B and 11A. Depth = 30 m. **B)** Photograph of an anchor exhumed by Hurricane Hugo. The two corals which were radiocarbon dated are shown by arrows. The rock to the right of the anchor was also covered by sand before Hugo. Depth = 27 m.

Based on the scour patterns seen after the hurricane, the zone of maximum flow was confined to the west wall (Fig. 11B). This is consistent with diver observations made during the most severe part of Hurricane David in 1979. During that storm, downcanyon currents reaching 0.50 m/s were measured near the west wall using Fluorescein dye timed over a known distance. Unidirectional currents dropped off significantly away from the wall, presumably similar to what occurred during Hurricane Hugo. In shallower water near the canyon head, currents during these earlier storms were strong enough to induce several meters of scour beneath the base of the HYDROLAB underwater habitat and to move it several meters.

The magnitude of the currents recorded at 2:33 am on the 18th (Figs. 8, 10) and the scour recorded by the depth sensor between midnight and 4:33 am (Fig. 7) clearly reflect strong downcanyon flows throughout this time interval, probably exceeding 1.0–1.5 m/s (ca. 2–3 knots). Currents of this magnitude are consistent with an empirical relationship of Maddock (1969), who determined that in open-channel flow:

$$Q_m = 15.244\ V^3, \qquad [3]$$

where:

Q_m = Sediment transport (siliciclastic), in kg/m-s
V = Current velocity, in m/s

Scour measured in the western canyon compares favorably with predicted sediment-transport rates based on Equation 3 and the assumptions about flow strength and duration summarized in Table 1. Wave-induced oscillation superimposed on the unidirectional flow probably increased transport over the amount predicted by this equation (Hubbard et al. 1977). Also, total transport through the canyon undoubtedly exceeded the net scour that occurred. Based on these observations, it is proposed that the scour observed in Salt River submarine canyon was caused by the sudden release of water held against the shoreface and in Salt River Bay by storm waves and strong onshore winds.

The extent to which this type of return flow is responsible for the scour seen at Cane Bay is difficult to deter-

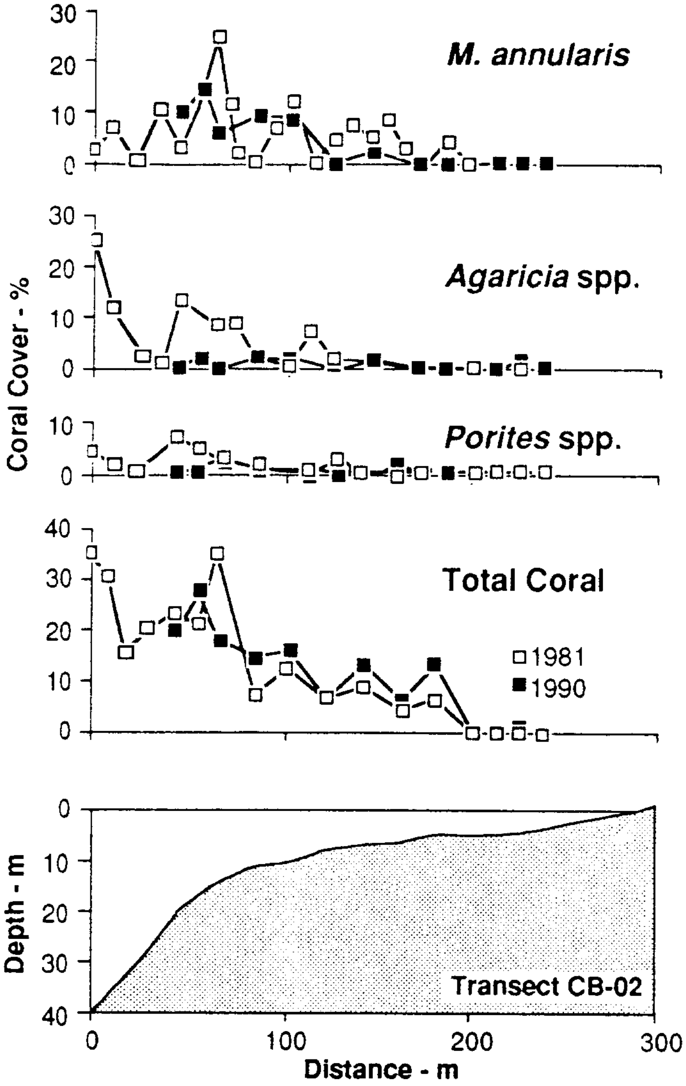


FIG. 13.—Coral cover along a transect in Cane Bay before (open squares) and after (closed squares) Hurricane Hugo (see Fig. 2C for location). Changes in total cover by living coral cover and the abundance of the three most-dominant species were small. Much of the variation can be attributed to the fact that the storm destroyed many of the transect markers, and reoccupation of those sites required measuring from sites that still remained. Based on the natural variability in the reef on a decameter scale, the pre- and post-storm transects showed no significant change. In the deeper portions of the reef (> 15 m) no change could be discerned based on visual estimates.

TABLE 1.—*Computed sediment-transport rates for Salt River submarine canyon. Transport rates are based on equation 3.*

Speed	Assumed Duration	Transport	Total Transport*
0.50 m/s	90 minutes	10,300 kg/m	154,000 kg
1.00 m/s	70 minutes	64,000 kg/m	960,000 kg
1.50 m/s	20 minutes	61,700 kg/m	926,000 kg
Transport for entire storm			2,040,000 kg

* Assumes that the current occurred over the 15-m wide strip adjacent to the canyon wall (i.e., our limit of scour).

mine. Certainly the geometry of Salt River canyon, the location of the reef break near its head and the presence of Salt River Bay behind all served to focus the offshore flow of water to an extent much greater than that possible in Cane Bay. Also, the steep nature of the outer shelf margin in Cane Bay raises the possibility that the scour we saw after the storm had been induced by purely oscillatory currents under the influence of gravitational effects on a steep slope (Hubbard et al. 1981, 1982).

Observations made elsewhere support the possibility that storm-induced wave setup was important in generating seaward-flowing currents and stripping sediment from the deep reefs at Cane Bay. Hubbard et al. (1974) reported 20–25 cm/s off-bank currents in a similar environment along the southern margin of Little Bahama Bank. Because the currents extended only 5–10 m above the reef and did not start until well into the storm, they proposed that water piled up against the shoreface by storm waves had moved offshore along the path of least resistance near the bottom. If this is analogous to the events that occurred in Cane Bay during the passage of Hurricane Hugo, then the slightly embayed nature of the shoreline may have provided an area more susceptible to the entrapment of water in the nearshore zone. This is consistent with the severe scouring seen in eastern Cane Bay while off-shelf transport was much lower in more-exposed areas to the west.

Based on the documented link between storm waves, off-shelf currents and sediment export provided by this study, it is proposed that off-platform sediment transport need not be limited to downdrift margins. It can also occur on shelves facing into the dominant waves and is caused by strong, seaward-flowing currents, whether they are contemporaneous with the high waves that cause them (i.e., the "return flows" of Hubbard et al. 1974, 1976) or closely follow the release of a stored, nearshore hydraulic head as winds shift and waves dissipate (Salt River, this study). As noted by Hubbard et al. (1974, 1976), these mechanisms will be best developed along narrow shelves backed by land or some other barrier.

The Role of Wind versus Waves

Wholesale sediment removal at Cane Bay despite levels of reef damage far below what was expected seems at first paradoxical. This can be resolved, however, by considering the likely wind patterns as Hugo passed over St. Croix (Fig. 15).

As the storm moved toward St. Croix, anticlockwise winds circulating around its 12–15 mile eye approached from the northeast (Fig. 15A). Maximum wave heights occurred in the northeastern quadrant of the storm and reached St. Croix as long-period swell. The impact of these waves would have been confined to the south shore. While the north coast was within the hurricane-wind field for nearly 10 hours before the eye passed overhead, fetch limited the height of hurricane waves. This continued until Hugo neared the south coast (Fig. 15B) and local wind speeds and wave heights increased dramatically.

As the eye of the storm passed over St. Croix (Fig. 15C), winds shifted quickly to an offshore direction. This shift was observed by the author on the eastern end of

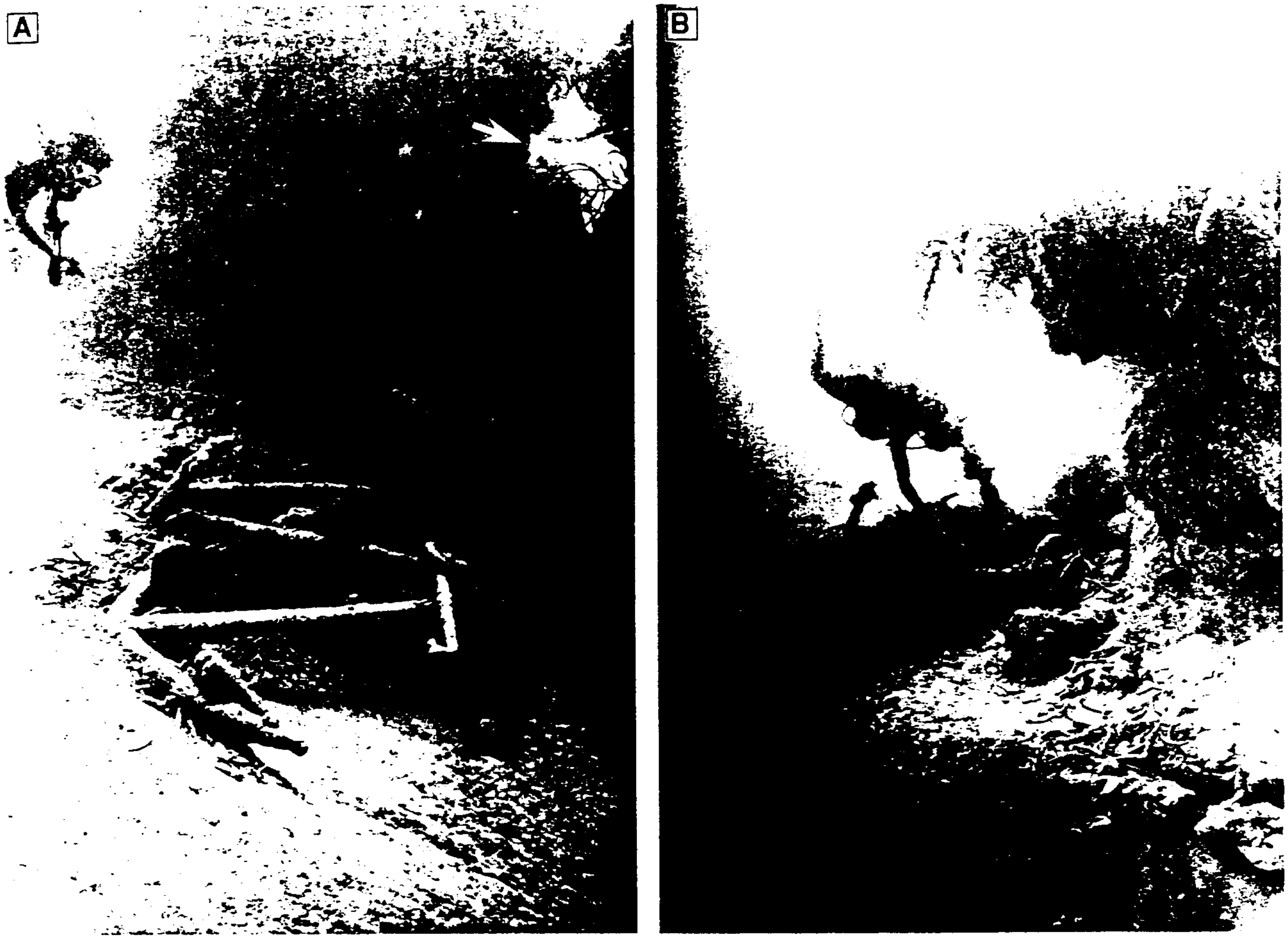


FIG. 14.—A) Underwater photograph from the easternmost channel in Cane Bay. The anchors in the foreground were uncovered by the storm. Note also the caves in the background (arrow) that were in part exposed when sand was flushed from the channel. Depth ~ 25 m. **B)** Underwater photograph from an adjacent channel in eastern Cane Bay. The ledge above the diver marks the level of the sand before the storm. Note the anchors and reef debris littering the channel bottom. Depth ~ 25 m.

the island at about 1:00 am on the 18th as his roof moved rapidly skyward. Based on a forward speed of 10 mph, this wind shift occurred about an hour later at Salt River and Cane Bay.

This directional pattern is consistent with measurements of both wave-height and water-level change at Salt River (Figs. 6, 7). It also explains the apparent paradox of subdued reef damage but high sediment export at Cane Bay. The lower wave heights on the north coast, in combination with the location of the best developed reefs in deeper water, prevented severe damage to the benthic community. The strong onshore winds, however, in combination with 2–3 m high waves, were able to trap water against the shoreface as the storm approached. As Hugo passed over St. Croix, the sudden wind shift, followed by a drop in the waves, triggered intense, offshore-current flow, especially along the embayed eastern shelf where entrapment had probably been greatest. Thus, wind emerges as an important process in controlling both reef damage and sediment transport in this subtidal marine system.

The Role of Storms in Reef Development

Storm versus Fair-Weather Transport.—The measurements made in the wake of Hurricane Hugo provide valuable insight into the magnitude of sediment transport during major storms and the role that such transport plays in the long-term sediment budget of tropical reef systems (Table 2). At Salt River and Cane Bay, only 33 and 64 kg of sediment, respectively, move over the shelf edge on a day-to-day basis (Table 2; see also Hubbard, 1986). During normal periods of heavy weather that occur several times a year, this increases to 440 and 1115 kg/day.

Storm-induced sediment transport far exceeds these values. During a 25-year storm in 1979, 300,000–400,000 kg of sand were removed from the canyon, an amount equal to 5–10 years of sedimentation (Hubbard 1986). At a minimum, Hurricane Hugo removed 2 million kilograms of sand over a 4–6 hour period. At Cane Bay, 336,000 kg of sediment were removed from one 7-m wide channel during the same time period.

While prevailing conditions have likely occurred more than 95% of the time over the past century, they are responsible for only about one third of the total sediment transport in and around Salt River canyon (Table 2). This relationship likely holds at Cane Bay, as well as many other areas. These data underscore the importance of such infrequent, but high-energy events in exposed carbonate settings.

Storms and the Carbonate Budget.—The literature on storm effects has traditionally focused on the tremendous potential for disrupting the benthic community and destroying the physical structure of the reef (Stoddart 1962; 1963, 1970; Connell 1978; Woodley et al. 1981; Rogers et al. 1982; Kjerfve et al. 1986; Mann and Stearn 1986; Hubbard et al. 1991). Some investigators, however, have discussed a more positive role played by storms in flushing excess sediment from the shelf, thereby facilitating reef development. At Cane Bay, Hubbard et al. (1981, 1990) determined that a significant portion of the carbonate produced by reef organisms was ultimately reduced to sediment. Based on limited data from eastern Cane Bay, Sadd (1984) proposed that periodic flushing of the reef by hurricane waves was needed to prevent excess sediment from overwhelming the reef. Based on a broader data base, including cores through the reef system, Hubbard et al. (1990) concluded that while hurricane flushing was perhaps not required to balance sediment production and export at Cane Bay, it had still played a major role in the development of reefs in the area. In Salt River submarine canyon, Hubbard (1986) constructed a detailed sediment budget and found that the sand contained in the canyon today falls far short of the volume that should be there based on the annual sediment-storage rates determined by that study. As a result, major hurricanes were proposed as "a mechanism to periodically flush the canyon axis, and offset the usual imbalance between import and export of sediments".

Based on the measurements reported in Hubbard (1986), 288 million kilograms of sediment should have accumulated in Salt River submarine canyon over the past 6000 years (Table 3). Using sediment-export rates for 25-yr (Hubbard 1986) and 100-yr storms (this study), 206 million kg of sand would have been flushed from the canyon over the same interval. If we add to that number the 61 million kg of sediment remaining in the canyon today, the total of 267 million kg accounts for all but 7% of the total sediment predicted by Hubbard (1986).

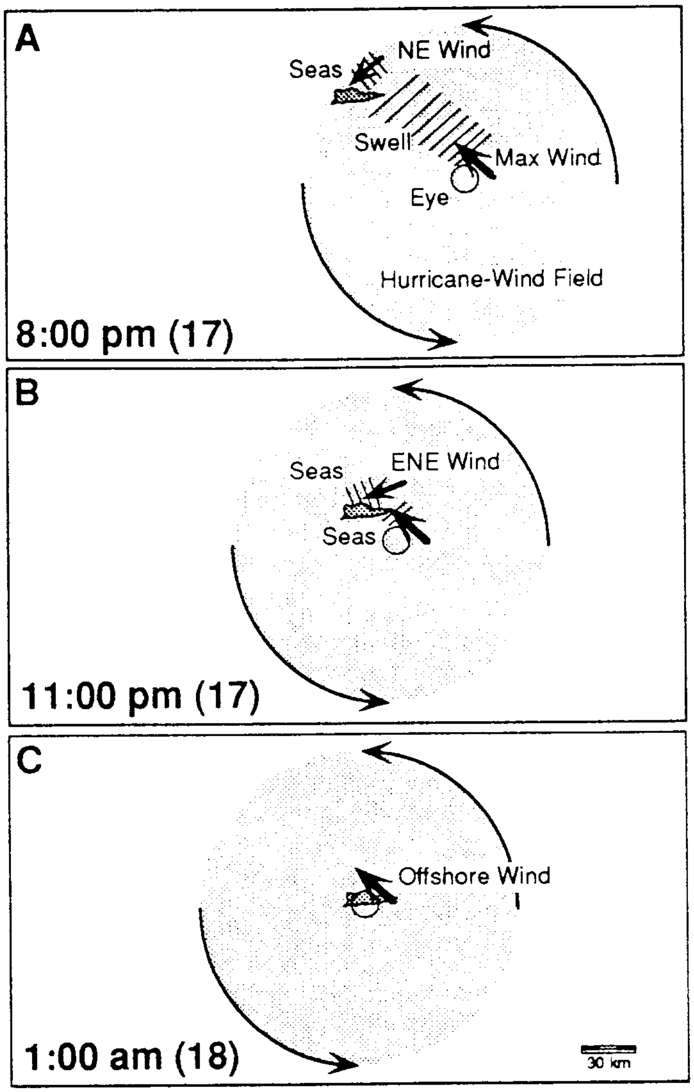


FIG. 15.—Simplified model of wind and wave patterns associated with the passage of Hurricane Hugo. A) As the storm approached from the south, winds on St. Croix were dominantly from the northeast. As the island came within the hurricane-wind field, waves on the north shore started to build. Long-period swell dominated the south shore. **B)** As Hugo neared the island, winds gradually underwent a clockwise shift. Local seas dominated both the north and south shore. **C)** As the eye passed over St. Croix, winds shifted abruptly, resulting in strong offshore winds on the north coast. As a result, water trapped against the shoreface was released (Fig. 7) and wave heights dropped dramatically (Fig. 6).

This discussion relies heavily on a continuity of process over the past 6000 years. However, because of the length of time being considered, variations in the return frequencies of major storms about their long-term average (i.e., a 100-yr storm does not necessarily occur *every* hundred years) can probably be ignored. Given the assumptions necessary in this argument, the agreement is remarkable, and it is felt that whatever errors might exist would not significantly alter the main points of this discussion.

The corals on the anchor found near the west wall lend further support to the assumptions and rates used in these calculations. The fresh nature of the coral surfaces implies that they were buried by the sediment that killed them. Based on the radiocarbon ages of the two corals (100 YBP, 109 YBP), it has been roughly a century since the last time that the anchor on which they sit has been exposed. This corresponds well with the presumed return frequency of Hugo-type storms. The agreement between the volume of canyon fill predicted by the sediment budget of

TABLE 2.—*Sediment-transport rates under various energy regimes at Salt River and Cane Bay*

Location	Condition	Transport (kg/day)	Frequency (days/yr)	Transport per 100 yrs (kg)	Source
Salt River	Fair weather	33	351	1,160,000	Hubbard (1986)
	Small storm	440	14	616,000	Hubbard (1986)
	Subtotal			**1,776,000**	
	25-yr storm	360,000	—	1,440,000*	Hubbard (1986)
	100-yr storm	2,000,000	—	2,000,000*	This study
	Total			**3,444,000**	
Cane Bay	Fair weather	1.23 (65)†	351	44,000	Hubbard et al. (1990)
	Small storm*	22 (1130)†	14	30,800	Hubbard et al. (1990)
	Subtotal			**75,200**	
	25-yr storm	?	—	?	No data available
	100-yr storm*/**	336,000	—	336,000	This study
	Total			**411,200 + 25-year storm** (250 k?)	

† First number is for the 7-m wide eastern channel, based on rates in table 9 (in kg/m-yr) of Hubbard et al. (1990) multiplied by 7. Rate in parentheses is for the entire shelf edge at Cane Bay.

* This occurred over a 4–6 hour period.

** Measured in the easternmost channel in eastern Cane Bay. The actual number for all of Cane Bay cannot be determined, but would be much larger.

Hubbard (1986) and the measurements discussed above lend support both to the calculations presented in this paper and to the earlier budget.

At Cane Bay, 336,000 kg of sediment were removed from the easternmost channel by Hurricane Hugo. According to the budget calculations of Hubbard et al. (1990), approximately 770 kg of sediment produced by the biological breakdown of the reef are added to this channel annually. Sadd (1980, 1984) proposed a slightly lower amount (457 kg/yr). Based on these values, Hurricane Hugo removed a volume of sediment equal to 400–700 yr of sedimentation. Clearly this is inconsistent with the presumed return frequency of Hugo-size storms.

Part of the discrepancy can be explained by the fact that the budget of Hubbard et al. (1990) is based on all of Cane Bay, whereas the scour described in this study occurred only in its eastern part; sediment export was much less to the west. However, the transport data used in the calculations are largely from eastern Cane Bay and therefore are felt to be applicable. Also, the anchors found in the two eastern channels imply that the values reported in Sadd (1980, 1984) and Hubbard et al. (1990) underestimate the the rate of sediment accumulation in eastern Cane Bay. The roles played by bioerosion in producing sediment and by hurricanes in maintaining the dynamic balance between sediment production and sediment export thus appear to be even greater than those envisioned by these authors.

TABLE 3.—*Sediment-budget calculations for Salt River submarine canyon. Data from Hubbard (1986)*

Parameter	Measurement	kg ($\times 10^6$)/ 6 ka
Sediment entering	66,000 kg/yr	396
Sediment exported	18,000 kg/yr	108
Sediment stored (predicted)	48,000 kg/yr	288
25-yr storm	360,000 kg*	86
100-yr storm (Hugo)	2,000,000 kg**	120
Sediment in canyon		61
Sediment stored (computed)		267

* Hubbard (1986) estimated between 240,000 and 480,000 kg; this is an average of the two extremes.

** Data from this study.

CONCLUSIONS

The passing of Hurricane Hugo directly over St. Croix provided a unique opportunity to examine the distribution and magnitude of damage associated with major storms. The long-term data base assembled by local and visiting researchers at the West Indies Laboratory on St. Croix and the National Undersea Research Center (NOAA) at Salt River has allowed a careful comparison of pre- and post-storm environments all around the island. This report has summarized observations and measurements made during and after the storm that add to our understanding of the role of such violent phenomena in the shaping of modern tropical systems. Based on the data presented above, the following conclusions are offered:

1) Sustained wind speeds near 120 knots, with gusts up to 165 knots, likely accompanied the passage of Hurricane Hugo over the island of St. Croix. Wave heights on the northwest coast reached 3.5 m; periods were in the 7–10 second range. Wave heights on the south coast exceeded 6–7 m.
2) Damage to the benthic communities at Salt River and Cane Bay was lower than in many other areas around St. Croix. This was in part because of the location of the sites on a leeward shore. Another important factor was the depth of the water over the reefs.
3) Wind and waves played roughly equal roles in piling up water along the north shore as Hugo approached. The sudden wind shift as the eye passed overhead triggered an initial release of the nearshore head and rapidly knocked down north-shore waves. The im-

portance of wind in controlling subtidal patterns of reef damage and transport needs to be re-evaluated in light of these observations.

4) The seaward-directed flows generated as water trapped near shore was released likely exceeded 2 m/s (ca. 4 knots) in Salt River submarine canyon. Wave-generated oscillatory currents of 3–4 m/s were superimposed on the net downcanyon flow, thereby increasing its erosive potential.
5) Similar processes occurred along the shelf near Cane Bay. The magnitude of the processes cannot be determined quantitatively, but they were likely less intense than those measured at Salt River. A return flow similar in origin but of lesser strength than the one measured at Salt River is likely responsible for the erosion seen in eastern Cane Bay.
6) Roughly 2,000,000 kg of sediment were removed from near the base of the western wall of Salt River submarine canyon. Lesser amounts of scour were observed elsewhere in the canyon. Total transport through the canyon from adjacent environments undoubtedly exceeded this value.
7) Roughly 336,000 kg of sand were swept from the easternmost channel in Cane Bay. Similar rates of erosion were observed in two adjacent channels. Scour was less severe to the west, despite a more open exposure. The confinement of the greatest erosion to the eastern channels where the shoreline is slightly embayed supports the presumption that return flows such as those seen in Salt River were also responsible for the scour seen at Cane Bay.
8) The sediment loss measured in Salt River canyon agrees closely with predicted rates of hurricane-induced export based on a previous sediment budget by Hubbard (1986). Data from Cane Bay imply that hurricane export plays an even greater role than envisioned from earlier studies in maintaining the dynamic balance between sediment production by bioerosion and sediment removal, primarily by physical processes.

ACKNOWLEDGMENTS

West Indies Laboratory sustained severe damage from Hugo. Many offices were destroyed, leaving books, data and other materials buried beneath tons of rubble. Supplies of food, water and fuel were uncertain. The homes of the staff and faculty were severely damaged or totally destroyed.

Despite conditions that are difficult for the reader to imagine, the staff returned to West Indies Laboratory as soon as roads to the east end of the island were cleared. Given the level of devastation and the extent of personal loss during the storm, the commitment of the staff at WIL is nothing short of remarkable. It is to those individuals that my greatest appreciation and admiration is extended.

The staff of the AQUARIUS program at Salt River are also acknowledged for the use of their compressor during the weeks after the storm. In particular, Richard Berey and Glenn Taylor were of great help both in making preparations for storm measurements, and in providing access to the current-meter record. Mike Herko helped deploy the current meter that survived the storm. I wish to also thank Arnold Miller, Karla Parsons, Nan Walker and Heinrich Zankl for their assistance in the field at Salt River and Cane Bay. Karla and Nan also assisted in the data reduction. Henry Tonnemacher is acknowledged for being as foolish as the author and accompanying him on dives in Salt River canyon during earlier storms. Jack Bevens and Miles Lawrence of the National Hurricane Center in Coral Gables, Florida graciously provided synoptic data and pilot information on the storm. Mike DeLuca of NOAA also assisted in obtaining synoptic data. Radiocarbon analyses were run at Beta Analytic, Inc. in Miami. Subsequent discussions of the measurements and observations with valued colleagues have greatly improved the quality of this study. For this, John and Mary Bythell, Elizabeth Gladfelter, Arnold Miller, Karla Parsons, Glenn Taylor, Ivor van Heerden and Heinrich Zankl are all gratefully acknowledged. The manuscript benefited greatly from reviews by Ivan Gill, Arnold Miller, Karla Parsons and an anonymous reviewer. This project was supported by a "Quick Response" grant from the National Science Foundation (No. 9004400).

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