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Hindcasting of hurricane characteristics and observed storm damage on a fringing reef, Jamaica, West Indies

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ABSTRACT

Hurricane Allen is one of the most severe hurricanes on record and caused extensive damage throughout the Caribbean in early August 1980. Coral reefs along the north coast of Jamaica were devastated by the hurricane-induced waves. As in the case of most hurricanes, no wave measurements were made. We have computed the wind field and hindcast the deep water wave characteristics as the storm impacted the fringing reef at Discovery Bay on the north central coast of Jamaica. The deep water waves propagated into shallow water on the forereef and transformed as a result of shoaling and refraction. We found that significant wave height at a given time varied by a factor of 2.6 and that incident wave power for the duration of the storm varied by a factor of 7 along a 3 km section of the Discovery Bay forereef due to variations in local bathymetry. Maximum hindcast breakers reached a height of 11.5 m with a significant wave period of 10.5 s. Observations of the most intense reef damage coincided with areas on the eastern forereef experiencing the highest breakers. We speculate that the degree of reef damage is a function of how much time has elapsed since the previous storm rather than frequency of hurricanes at a locality.

1. Introduction

Water movements are of great importance to corals and coral reefs. The prevailing wave stress regime helps determine community composition and zonation (Goreau, 1959; Porter, 1974; Connell, 1973; Grigg and Maragos, 1974; Geister, 1975, 1977; Rosen, 1975; Porter *et al.,* 1981; Dollar, 1982). It has long been recognized that extreme disturbance by tropical storms and hurricanes/typhoons may drastically affect populations of coral reef organisms, and directly or indirectly affect coral reef structure. But the frequency of exposure to hurricanes differs from place to place and over time. Where severe storms are common, the effects of any one storm are slight (Perkins and Enos, 1968; Randall and Eldredge, 1977; Ogg and Koslow, 1978), because the community has already adjusted to high wave stresses. In regions of lower routine wave stress, or where storms occur rarely compared to coral life spans,

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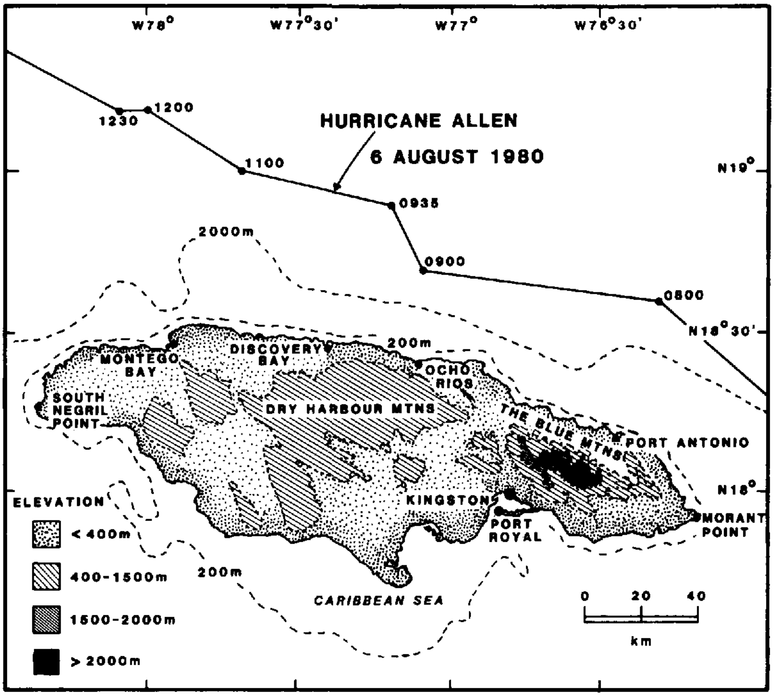

Figure 1. Jamaica map and details of Hurricane Allen storm track.

short-term storm effects are catastrophic (e.g., Stoddart, 1963; Glynn *et al.*, 1964; Ball *et al.*, 1967; Highsmith *et al.*, 1980). In 1980, Hurricane Allen wrought catastrophic damage to coral reefs on the north coast of Jamaica (Woodley, 1980; Woodley *et al.*, 1981; Porter *et al.*, 1981).

The island of Jamaica (Fig. 1) is situated at latitude 18N, well within the NE Trade Wind belt and the Caribbean hurricane zone. Cuba is a geographical barrier located 150 km to the north, which limits the fetch of both trade winds and the occasional winter storms on the north coast of Jamaica. On the average, Jamaica experiences 60 hurricanes or tropical storms per 100 years (Gentry, 1971).

Hurricane Allen had a devastating effect on the coral reefs of the north coast of Jamaica. Details of pre and post Hurricane Allen reef characteristics are particularly well documented along the forereef at Discovery Bay, (Fig. 2), Jamaica (Porter *et al.*, 1981). As in most hurricane situations, however, measurements of the storm waves and the variability in wave power along the reef crest were not made. It is our objective to use available meteorological observations from Hurricane Allen to hindcast wind and wave conditions at Discovery Bay and consider the variability of wave characteristics due to shoaling and refraction on the forereef. We compare the hindcast wave characteristics to observed reef damage. Because hurricane hindcasting techniques are scattered throughout the literature and equations usually expressed in English units,

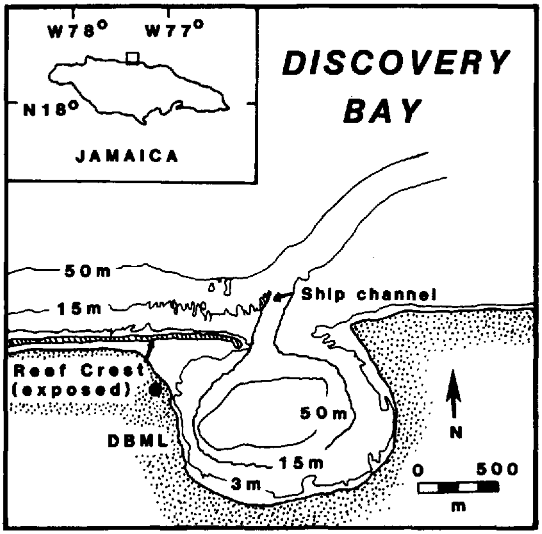

Figure 2. Detailed map of Discovery Bay.

we have chosen to present the computational procedures to allow others to proceed similarly for other hurricane situations. All formulae have been converted to S.I. units. Whereas we focus our analysis on the wave characteristics, we have not included the effect of the storm surge. As the Discovery Bay reef is located at least 45 km to the left of Hurricane Allen's storm track, the storm surge is likely to have been less than 2 m locally, based on Jelesnianski's (1966) analysis. This is collaborated by the calculations by Graus *et al.* (1984) which showed a maximum mean sea level change of only 1 m.

Recent attempts at hurricane wave hindcasting have been made for Greta in 1978 at Carrie Bow Cay, Belize (Kjerfve and Dinnel, 1983) and Allen at Discovery Bay, Jamaica (Graus *et al.*, 1984). Kjerfve and Dinnel (1983) calculated wave conditions in deep water without attempting shallow water modification due to shoaling and refraction. The study by Graus *et al.* (1984) is particularly interesting as we are looking at the same hurricane and location. Whereas we focus on the spatial reef damage in a local area, Graus *et al.* (1984) considered a single reef transect and the geological implications on reef development and did not include effects of refraction.

2. Hurricane Allen

Hurricane Allen originated off the west coast of Africa as a westward propagating tropical wave (Lawrence and Pellissier, 1981), and reached tropical disturbance strength on 29 July 1980. For 10 days, Allen moved steadily west-northwest across the Atlantic at an unusually high speed, 9–13 m/s, due to the strengthening of an Atlantic high-pressure ridge (Wagner, 1980). Allen developed into a tropical storm on 1 August, and reached hurricane strength early on 3 August east of the windward islands.

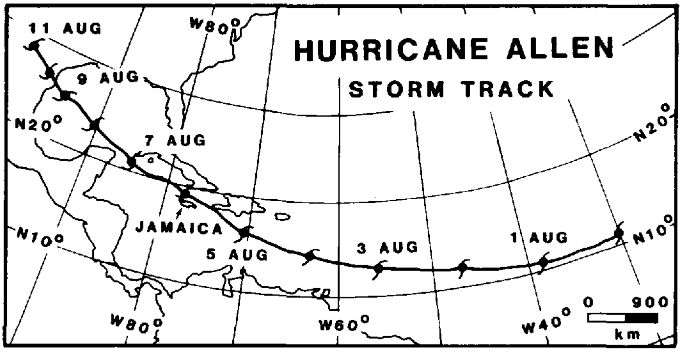

Figure 3. Hurricane Allen storm track.

The general hurricane track (Fig. 3), is based on flight logs from the National Hurricane Center/NOAA. These show that the eye of the hurricane passed north of Barbados, and crossed the southern tip of St. Lucia early on 4 August (Fig. 3). Sustained surface winds were then 46 m/s and central sea level pressure 967 hPa (or mb). As Allen progressed across the eastern Caribbean, the central sea level pressure deepened to 911 hPa, and winds of 77 m/s were recorded east of Jamaica. The hurricane began weakening late on 5 August, and as Allen passed between Jamaica and Cuba early on 6 August (Fig. 4), the central sea level pressure had increased to 955 hPa. Winds and waves generated at this time were the ones affecting the Discovery Bay forereef. Taylor and Staff (1981) re-evaluated the storm track (shown in Fig. 1) in the vicinity of Jamaica. We adopted their track in our hindcasting calculations.

On 7 August, Hurricane Allen intensified for a second time as it passed through the Yucatan Straits. Central sea level pressure dropped to a minimum of 899 hPa (cf. Fig. 5) which represents the second lowest hurricane pressure reading ever for an Atlantic hurricane, and the lowest recorded pressure in this century (Lawrence and Pellissier, 1981). The hurricane reached a maximum 1 min sustained surface wind speed of 85 m/s at this time.

The forward speed of the hurricane slowed to 7–8 m/s while the storm passed through the Gulf of Mexico. The pressure weakened to 945 hPa as the eye of the hurricane made landfall just north of Brownsville, Texas at 0600 GMT on 10 August.

Hurricane Allen was one of the most severe Atlantic hurricanes on record (Wagner, 1980). It exhibited an unusually large variation in intensity, with central sea level pressure fluctuating over a range of 50 hPa. Allen is reported to have caused hundreds of deaths and extensive damage to many Caribbean islands, particularly Barbados, St. Lucia, St. Vincent, Haiti, and Jamaica. Along Jamaica's north coast, Hurricane Allen was responsible for eight deaths and an estimated $100 million in damages (Lawrence and Pellissier, 1981). Waves reached structures at 7 m elevations on land along the north coast of Jamaica. Also, 250–500 mm of rain fell locally along the north coast during the storm passage (Lawrence and Pellissier, 1981).

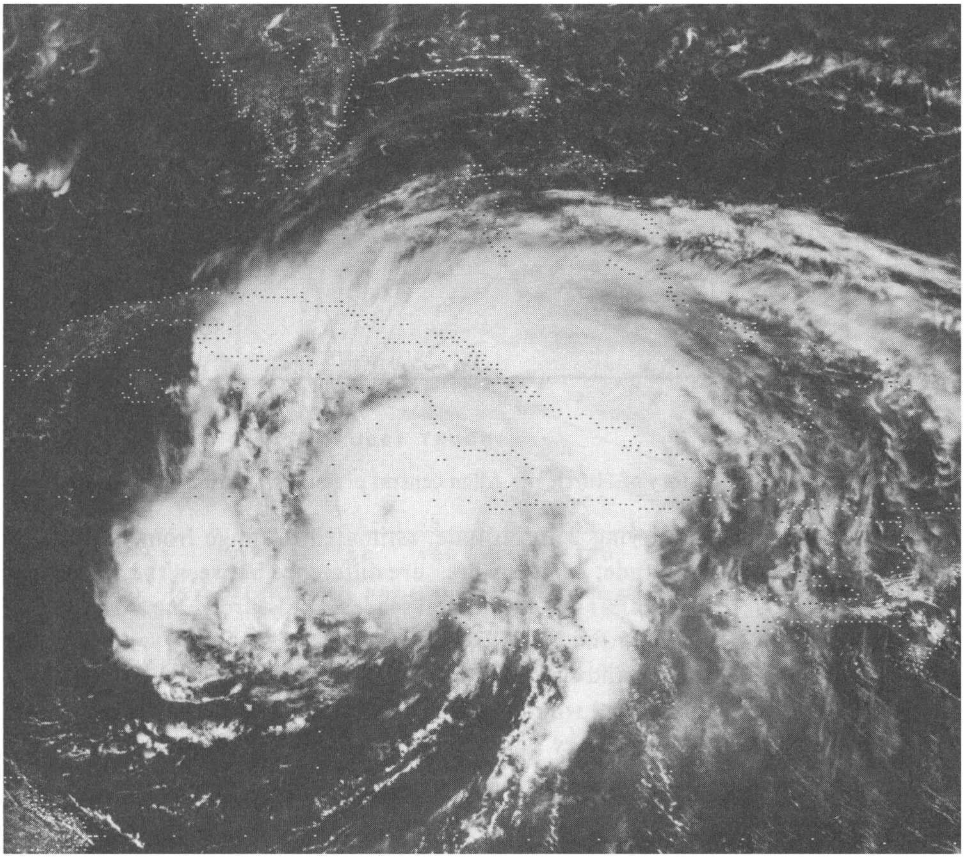

Figure 4. NOAA satellite image of Hurricane Allen on 5 August 1980.

3. Wind hindcasting

The hindcasting of Hurricane Allen wind and wave fields at Discovery Bay, Jamaica, was based on a combination of the techniques of Bretschneider and Tamaye (1976) and Schwerdt *et al.* (1979), and augmented with information from Bretschneider (1966, 1972a, b).

Hurricane measurements were made from aircraft every 6 hrs by National Hurricane Center/NOAA. Measurements included position of storm center, central pressure, and radius of maximum winds (Table 1). We interpolated these data to obtain hourly characteristics of the wind field to be used in subsequent calculations.

Based on a momentum balance of pressure gradient, Coriolis, and centrifugal terms, the 10-min averaged gradient wind speed, U_R, was computed for a stationary hurricane at the radius of maximum winds, R, with

$$U_R = 0.5144\ [k(\Delta P)^{1/2} - fR/2] \qquad (1)$$

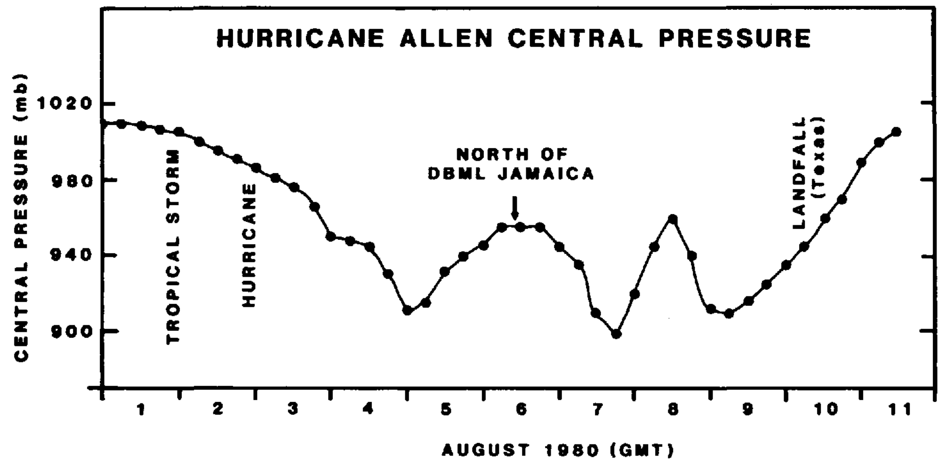

Figure 5. Time history of Hurricane Allen central pressure variation at sea level.

where k is a coefficient varying with latitude, estimated to range from 11.6 at 18N latitude to 10.8 at 45N latitude; ΔP is the pressure difference between the ambient sea level pressure ($P_N = 1013.2$ hPa) and the central sea level pressure of the storm P_c, such that $\Delta P = P_N - P_c$; and f is the Coriolis parameter, $f = 2\omega \sin(\phi)$, where ω is the angular velocity of the earth and ϕ is latitude.

The 10 min averaged gradient wind speed for a stationary storm at a distance r from the center of the storm to Discovery Bay is denoted U_r, and was computed from

$$U_r = U_R \{\delta + ([R/r][1 - 2R\delta/r] \exp [1 - R/r] + \delta^2)^{1/2}\} \tag{2}$$

where $\delta = -fr/2U_R$ (Bretschneider and Tamaye, 1976).

The 10-min averaged surface wind speeds for a stationary storm at a 10 m reference level, and distances R and r from the storm center, are denoted U_{RS} and U_{rs}, respectively, where

$$U_{RS} = k^* U_R \tag{3}$$

$$U_{rs} = k^* U_r . \tag{4}$$

Table 1. Hurricane Allen meteorological input data used in the hindcasting. Source: Taylor *et al.* (1981) and the National Hurricane Center reconnaissance fix log from flight measurements.

Date	Time (GMT)	Measured position Lat/Long.	Central pressure (hPa)	Radius of maximum winds (R) (km)
6 Aug 1980	0600	18.3/75.9	955	24.0
6 Aug 1980	0800	18.6/76.3	955	—
6 Aug 1980	0900	18.7/77.1	955	23.1
6 Aug 1980	1100	19.0/77.7	955	23.1
6 Aug 1980	1200	19.2/78.0	955	—

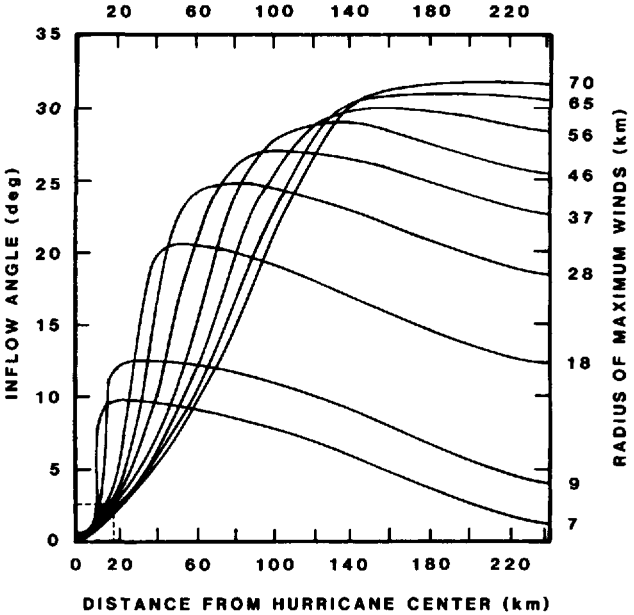

Figure 6. Nomogram to determine the hurricane wind inflow angle as a function of distance from hurricane center and radius of maximum winds (adopted from Schwerdt *et al.*, 1979).

The constant, k^*, expresses the decrease of the wind speed as a function of height above the surface, and depends on latitude. We chose $k^* = 0.90$ for the Hurricane Allen computations near Jamaica (Schwerdt *et al.*, 1979).

Wind directions at Discovery Bay were estimated hourly. We drew a circle around the center of the hurricane with Discovery Bay on the perimeter. The local wind direction was taken to coincide with the tangent to the circle, with winds blowing in a cyclonic sense. However, due to frictional effects, there is an incurvature of the wind vector toward the hurricane center. We determined a corrected wind direction for each hour of storm passage as a function of distance from the storm center to Discovery Bay and radius of maximum winds (Fig. 6) (Schwerdt *et al.*, 1979).

Because of the forward motion of Hurricane Allen, it is necessary to compute hourly wind speed corrections for a slowly moving storm (Bretschneider and Tamaye, 1976). Surface wind speeds in a moving hurricane are denoted U_{RS^*} and U_{rs^*}, at the radius of maximum winds and at a distance r from the storm center, respectively, where according to Schwerdt *et al.* (1979)

$$U_{RS^*} = U_{RS} + 1.17(V_F^{0.63}) \cos(\theta) \tag{5}$$

$$U_{rs^*} = U_{rs} + 1.17(V_F^{0.63}) \cos(\theta) . \tag{6}$$

The forward speed of the storm, V_F, varied from 6–25 m/s while Hurricane Allen was positioned north of Jamaica. The angle θ is an angle measured counterclockwise

Table 2. Results of hindcasting of wind and deep water wave characteristics for seven hours with Hurricane Allen in the vicinity of Discovery Bay, Jamaica.

Time (GMT)	Interpolated position Lat./Long.	R (km)	r (km)	ΔP (hPa)	V_F (m/s)	Corrected wind direction (from)	θ (°)	U_{RS^*} (m/s)	U_{rs^*} (m/s)	H_{RV} (m)	H_{rv} (m)	T_s (s)
0600	18.3/75.9	24.0	160	58.2	8.3	332	135	37.7	18.2	7.9	4.6	10.0
0700	18.4/76.1	23.7	140	58.2	8.3	328	133	37.7	20.0	8.0	5.2	10.1
0800	18.6/76.3	23.4	120	58.2	16.7	324	134	36.0	20.0	7.2	4.8	9.5
0900	18.7/77.1	23.1	45	58.2	18.0	296	187	33.6	29.5	6.2	6.1	8.8
1000	18.9/77.4	23.1	55	58.2	11.0	244	219	36.7	30.5	7.4	7.1	9.7
1100	19.0/77.7	23.1	70	58.2	11.0	230	252	39.2	30.1	8.5	7.8	10.4
1200	19.2/78.0	23.1	105	58.2	8.3	221	259	40.0	25.6	8.8	7.2	10.5

from the direction in which the hurricane was moving to the direction of the corrected wind at Discovery Bay (Schwerdt *et al.*, 1979). Hindcast wind parameters are given in Table 2.

4. Deep water wave hindcasting

The significant wave height is the common engineering measure of wave height and is defined as the average wave height of the one third highest waves. The significant wave height at the radius of maximum winds for a stationary storm is denoted H_R, where

$$H_R = K'(R\Delta P)^{1/2} . \tag{7}$$

The coefficient K' is an empirical function of fR/U_R, varying from 0.009 for fR/U_R equal to 0 to 0.004 for fR/U_R equal to 0.4 (Bretschneider and Tamaye, 1976). By regression of K' on fR/U_R, the relationship may be approximated as

$$K' = 0.0352(fR/U_R)^2 - 0.0247(fR/U_R) + 0.0083 . \tag{8}$$

Based on the computations of H_R, the significant wave height, H_r, a distance r from the hurricane center was determined from digitization of a lookup table (Fig. 8) (Bretschneider and Tamaye, 1976). H_r is a function of fR/U_R and r/R, and incorporates the effects of changing wind speeds on wave generation.

The significant wave heights, H_R and H_r, respectively, must also be corrected to account for the forward motion of the hurricane. The corrected wave heights, H_{RV} and H_{rv}, are

$$H_{RV} = H_R\,[1 + 1.17(V_F^{0.63}) \cos(\theta)/U_{RS}]^2 \tag{9}$$

$$H_{rv} = H_r\,[1 + 1.17(V_F^{0.63}) \cos(\theta)/U_{rs}]^2 \tag{10}$$

(Schwerdt *et al.*, 1979).

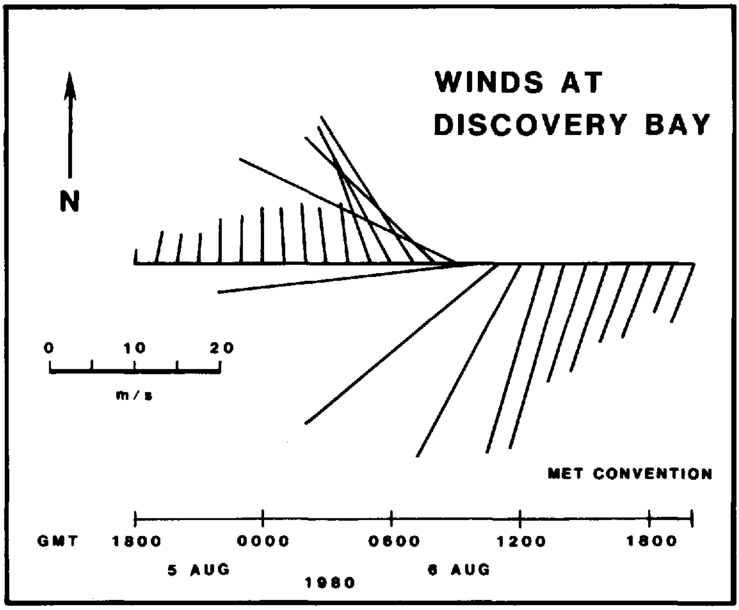

Figure 7. Time history of hindcast 10 m sustained wind speed at Discovery Bay.

The significant wave period, T_s, is related empirically to T_o, the period of maximum energy density of the hurricane wave spectrum. According to Bretschneider and Tamaye (1976),

$$T_o = 0.78\, U_{RS^*} \tanh\, [\ln(X_1/X_2)^{0.5}]^{0.6} \tag{11}$$

where

$$X_1 = 1 + 34.9\, H_{RV}/U^2_{RS^*} \tag{12}$$

$$X_2 = 1 - 34.9\, H_{rv}/U^2_{rs^*}\,. \tag{13}$$

From values of T_o, significant wave periods were computed hourly from Bretschneider and Tamaye (1976)

$$T_s = 0.946\, T_o\,. \tag{14}$$

The wave hindcasting results for 7 hours of storm passage are also given in Table 2.

5. Wave refraction and shoaling on the forereef

As waves propagate shoreward into shallow water, they change due to shoaling and refraction. In general, wavelength, wave steepness, and celerity decrease drastically, whereas wave height increases slightly. Waves generated more than 18 hours prior to the passage of Hurricane Allen did not reach Discovery Bay because of the storm track

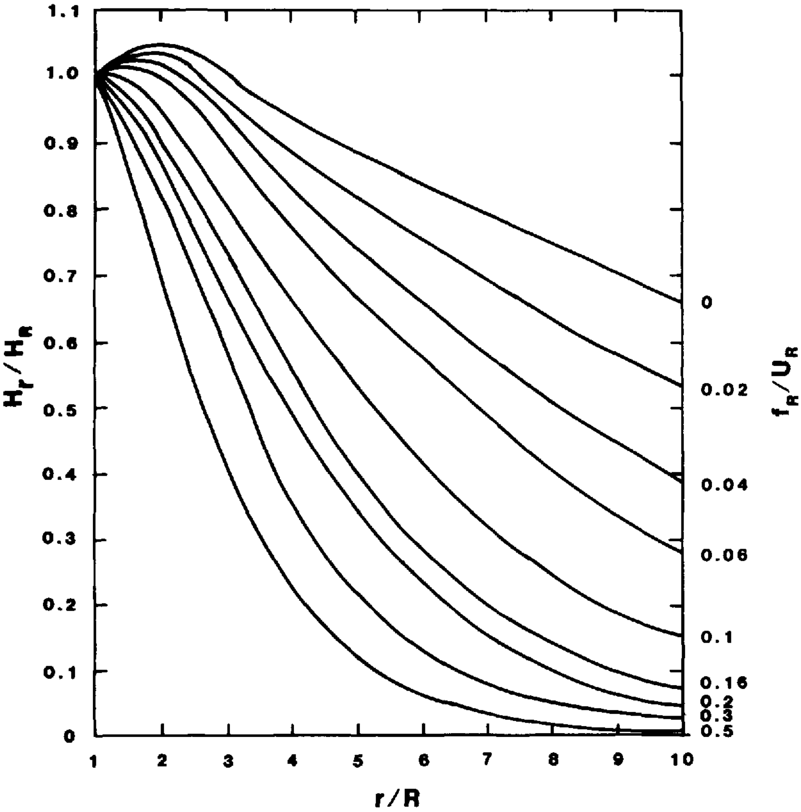

Figure 8. Nomogram to determine the significant wave height H_r compared to H_R as a function of fR/U_R and r/R.

relative to the shape of Jamaica. We have chosen to construct refraction diagrams of the Discovery Bay forereef hourly from 0600 to 1200 GMT on 6 August 1980. The eye of the hurricane was directly north of Discovery Bay at 1000 GMT.

Refraction diagrams for the storm-induced significant waves were constructed according to the orthogonal method (CERC, 1977), beginning when the local water depth equalled half the deep water wavelength. The direction of wave approach was taken to be along a tangent drawn between Discovery Bay and a circle with a radius equal to the radius of maximum winds, centered in the hurricane eye, on the side of the circle where winds blow toward the hindcast site. In shallow water, waves refract according to Snell's Law

$$\sin \alpha_j = (C_j/C_i) \sin \alpha_i \qquad (15)$$

where α_i is the incident angle between the wave crest and the local isobath; α_j is a similar angle as the wave crest passes the next isobath; and C_i and C_j are the wave celerities at the two isobaths, respectively. We drew smoothed depth contours for 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, and 100 m in front of the fringing reef at Discovery Bay. We ignored abrupt depth variations due to spur and groove features. Wave orthogonals were constructed 100 m apart in deep water and projected toward Discovery Bay and the breaking point.

We calculated local celerities from

$$C = (gT_s/2\pi) \tanh (2\pi h/L) \tag{16}$$

$$L = CT_s \tag{17}$$

where h is the local water depth and L the local wavelength. It was necessary to solve for L in Eq. (16) iteratively. Knowing the incident angle α_i, α_j could then be calculated and assumed to be the new incident angle between wave crest and bottom contours at the half-way distance to the next isobath.

Coefficients of refraction, K_r, were computed from the refraction diagrams, where

$$K_r = (b_o/b)^{1/2} \tag{18}$$

and b_o and b are the distances between adjacent orthogonals in deep water (b_o = 100 m) and within the shoaling region, respectively.

Assuming solitary waves (CERC, 1977; Dean and Eagleson, 1966; and Komar, 1976), we computed the breaker wave height (H_b) and local depth (h), requiring iterative computations. The coefficient of refraction was initially determined for points along the reef where the waves were most likely to break. According to McCowan (1894), this happens when horizontal water velocity at the wave crest equals the celerity, which occurs when

$$(H_b/h) = 0.78\ . \tag{19}$$

The next step was to calculate a new, unrefracted deep water wave height, H'_o, from

$$H'_o = H_o K_r \tag{20}$$

for each wave orthogonal. The breaking wave height, H_b, was then computed along the reef from

$$H_b = H'_o [3.3(H'_o/L_o)^{1/3}]^{-1} \tag{21}$$

which incorporates both refraction and shoaling (CERC, 1977). The deep water wavelength corresponding to the significant waves is

$$L_o = gT_s^2/2\pi\ . \tag{22}$$

The best estimate of the breaker depth, d_b, is not expressed by Eq. (19) but rather by

$$d_b = H_b[a_1 - a_2 H_b/gT_s^2]^{-1} \tag{23}$$

(CERC, 1977), which incorporates the effect of changing bottom slope, β. The constants, a_1 and a_2, are related to the bottom slope

$$a_1 = 1.56[1 - \exp(-19.5\,\beta)]^{-1} \tag{24}$$

$$a_2 = 43.75[1 - \exp(-19.5\,\beta)]^{-1}. \tag{25}$$

We verified that the initial coefficients of refraction were compatible with the calculated breaker depth. If this were not the case, K_r was adjusted and the computation repeated iteratively until the coefficient of refraction was consistent with the computed breaker depth (CERC, 1977). In carrying out our calculations, we ignored bottom friction, percolation, and wave energy reflection, assuming that these effects are secondary compared to shoaling and refraction.

6. Bottom water velocities and wave power

After completion of the refraction diagrams, we computed horizontal water wave velocities to compare to the observed reef damage along the Discovery Bay forereef. In doing so, we applied solitary wave theory (Dean and Eagleson, 1966) for the breaking conditions. The shoaling solitary wave predictions are good approximations at the breaking point (Svendsen and Hansen, 1976) and are a good choice for extreme waves (Naheer, 1978).

The celerity for a shoaling wave is closely approximated by

$$C = [g(H + h)]^{1/2} \tag{26}$$

(Dean, 1966) where g is gravity, H is the local wave height and h is the local water depth. Below the wave crest, water particles are moving horizontally with a maximum velocity in the direction of wave propagation.

The maximum horizontal velocity will occur below the crest (McCowan, 1894; Munk, 1949) and may be expressed as

$$U_{\max} = cN/[1 + \cos(M + Mz/h)] \tag{27}$$

where z is the vertical distance below the still water level, and M and N are parameters, which depend on the ratio H/h (Munk, 1949). Although we have previously used a H/h breaking ratio which depends on bottom steepness (CERC, 1977) as suggested by Ippen and Kulin (1954), it is here convenient to assume the validity of Eq. (19). This is justifiable as the critical H/h breaking ratio only deviates slightly from 0.78, and usually ranges from 0.78–0.90. According to Munk (1949), acceptance of Eq. (19) yields $N = 0.64$ and $M = 0.98$.

At the bottom, where $z = -h$, and below the wave crest, Eq. (26) reduces to

$$U_{\max(\mathrm{bot})} = cN/2 \simeq 1.514 \times H^{1/2} \tag{28}$$

which we have used to calculate the horizontal maximum bottom velocity at the breaker point along the entire forereef. However, seaward of the breakers we used linear theory to calculate bottom velocities, where

$$U_{\max(\mathrm{bot})} = \pi H/[T_s \sinh(2\pi h/L)] \tag{29}$$

which is a reasonable approximation for $H/h < 0.4$ and h/L sufficiently large (Komar, 1976).

The total energy for a solitary wave is given by

$$E_T = [(8/(27)^{1/2}]\, \rho g H^{3/2}\, h^{3/2} \tag{30}$$

(Dean and Eagleson, 1966). In shallow water, the energy travels with the speed of the celerity (Kinsman, 1965). A solitary wave has an infinite period. However, it is convenient to assume that the effective period equals T_s. If so, each wave is performing work per unit length of wave crest given by Eq. (30) every effective wave period. It is then reasonable to define an equivalent wave power for the hurricane breaker as

$$P \triangleq E_T/T_s \tag{31}$$

or by invoking Eq. (19)

$$P \cong 22{,}363\; H_b^3/T_s \tag{32}$$

in units of W/m of crest length at the point of breaking.

7. Hindcasting results

We chose to carry out the hindcasting for a 7-hour period with the hurricane center within a distance of 160 km from Discovery Bay. The necessary input parameters are (1) latitude and longitude of the storm center (cf. Fig. 1); (2) central hurricane surface pressure (cf. Fig. 5); and (3) radius of maximum winds (as obtained from National Hurricane Center flight logs). The input data are summarized in Table 1.

The hindcasting procedure yielded the wind and deep water wave characteristics presented in Table 2. The maximum deep water wave height was 7.8 m with a significant period of 10.4 s. As the storm waves progressed across the forereef slope, they shoaled and refracted. The associated wave transformations are hindcast in Figures 9a–g, and show considerable variation in wave breaker height along a 3 km section of forereef at Discovery Bay. Peak breakers 11.5 m high struck the eastern forereef at 1100 GMT (Fig. 9f), or 0700 local summertime, on 6 August according to these calculations. This coincides closely in time and height with the observed peak waves of 12 m photographed on the eastern forereef and reported by Woodley *et al.* (1981).

In general, throughout the storm passage, the breaker heights (Fig. 9a–g) on the eastern forereef were significantly higher as compared to the waves on the western forereef. This was due to the refraction patterns caused by the local topography, which focused the waves onto the eastern forereef and caused a build-up of wave height. According to the calculations, only briefly at 1000 GMT (Fig. 9e) did the breakers on

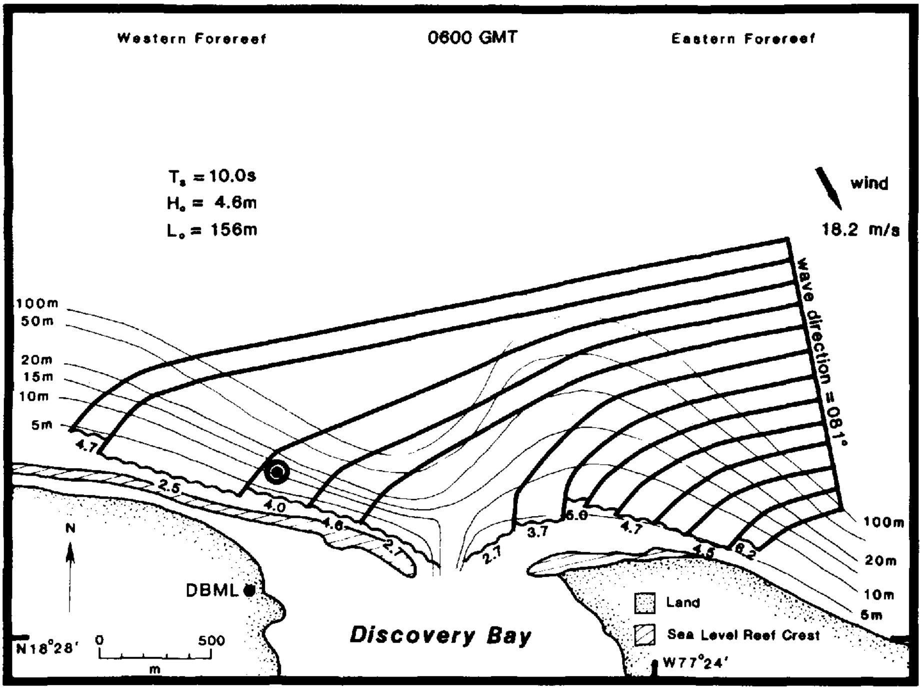

Figure 9a. Hindcast significant wave characteristics on the Discovery Bay forereef at 0600 GMT on 5 August 1980. The marked spot on the western forereef indicates the location of Monitor Reef Photostation VI. Location of the Discovery Bay Marine Laboratory (DBML) is also shown.

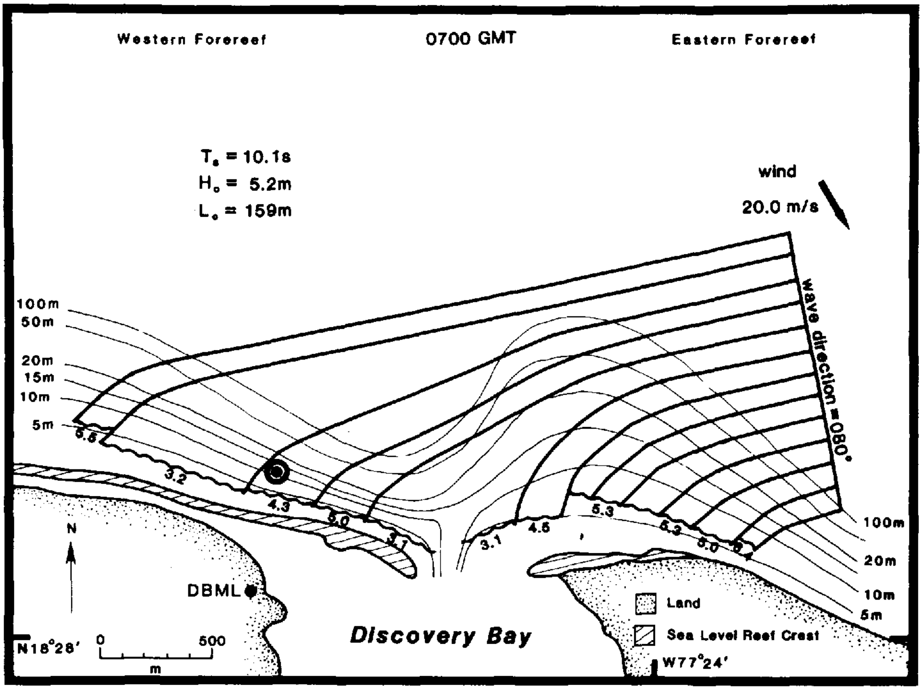

Figure 9b. Hindcast significant wave characteristics on the Discovery Bay forereef at 0700 GMT on 5 August 1980.

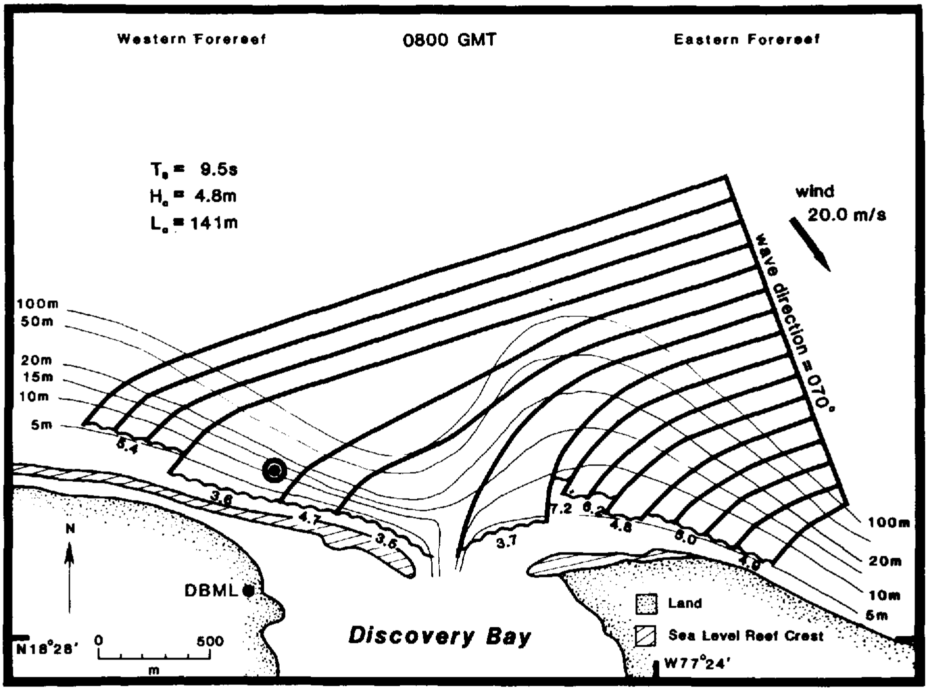

Figure 9c. Hindcast significant wave characteristics on the Discovery Bay forereef at 0800 GMT on 5 August 1980.

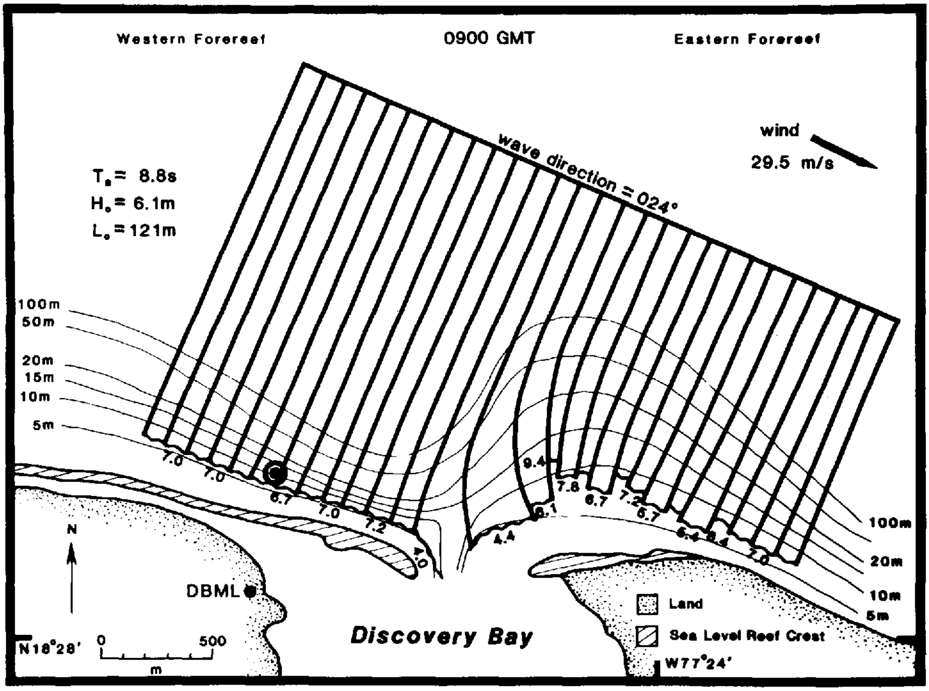

Figure 9d. Hindcast significant wave characteristics on the Discovery Bay forereef at 0900 GMT on 5 August 1980.

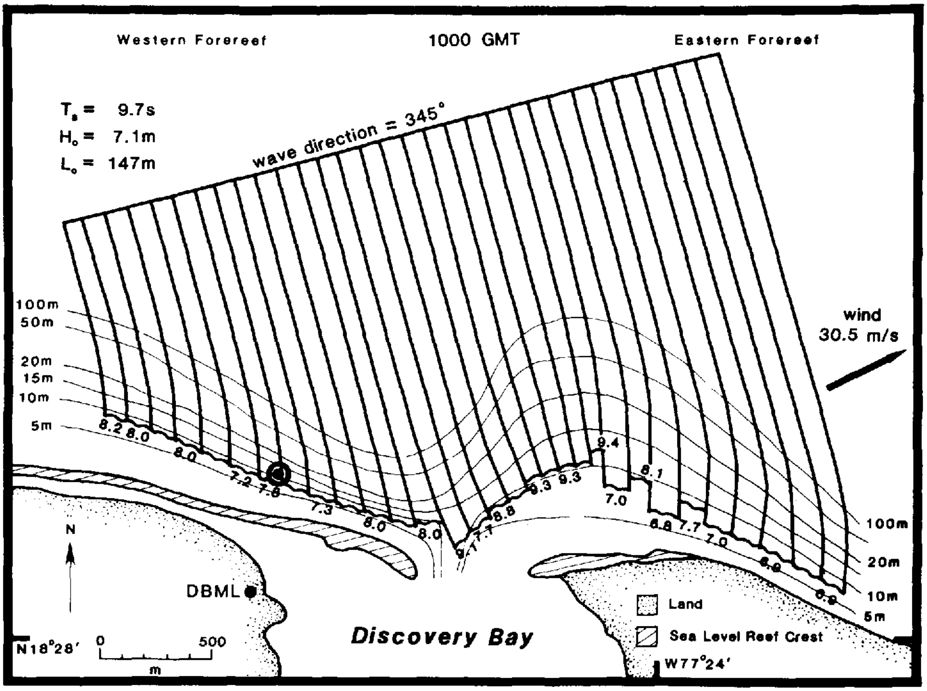

Figure 9e. Hindcast significant wave characteristics on the Discovery Bay forereef at 1000 GMT on 5 August 1980.

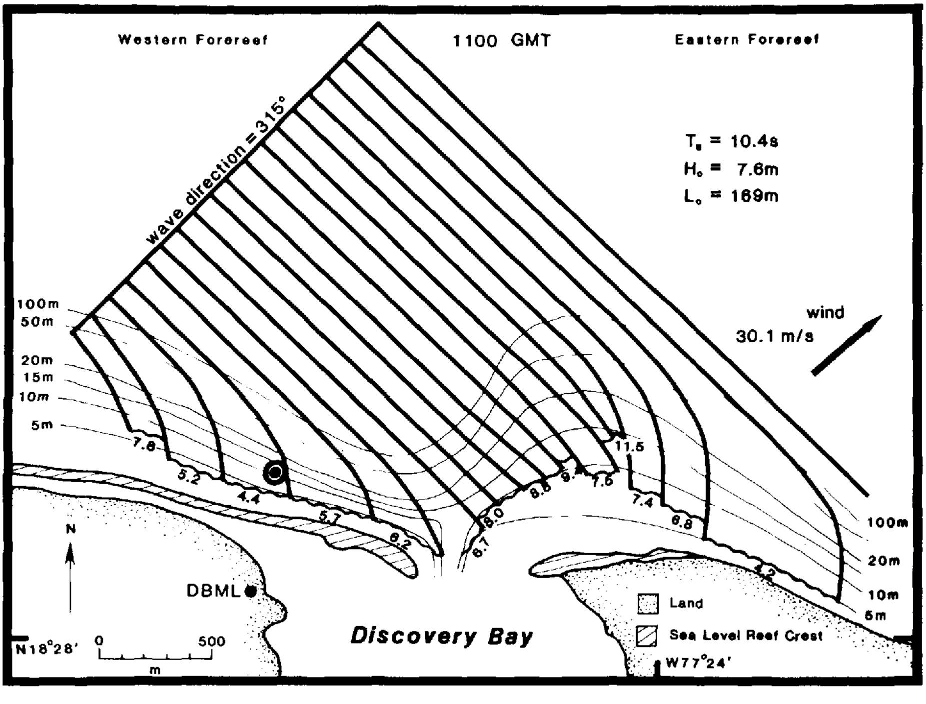

Figure 9f. Hindcast significant wave characterisitcs on the Discovery Bay forereef at 1100 GMT on 5 August 1980.

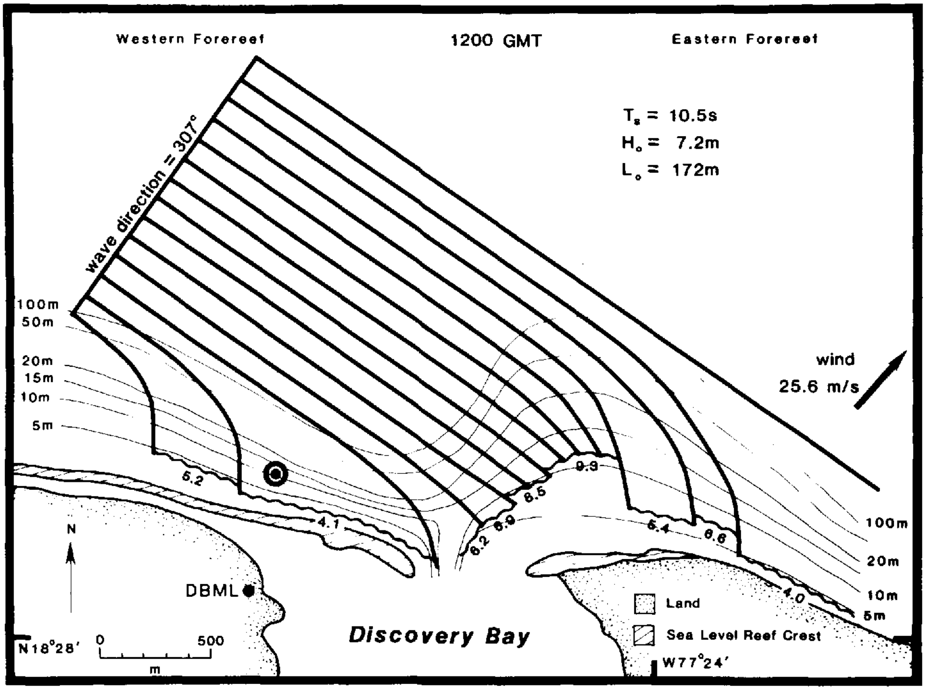

Figure 9g. Hindcast significant wave characteristics on the Discovery Bay forereef at 1200 GMT on 5 August 1980.

the western forereef reach a height of 8 m, when Hurricane Allen was 55 km from Discovery Bay (Fig. 1). The theory utilized in our calculations may exaggerate the deep water wave height for a moving hurricane within approximately 2*R* of the storm center (0900 and 1000 GMT) (Ijima *et al.*, 1968), because of the dominance of hurricane wind waves rather than completely developed swells near the storm center.

Because of wave refraction, the calculated breaker heights varied by as much as a factor of 2.6 along the 3 km stretch of Discovery Bay forereef at any one time. Similarly, the calculated wave power and the maximum bottom velocity at the breaking point showed significant variation along the forereef and in time as the hurricane passed by (Fig. 10). The eastern forereef experienced a maximum bottom velocity of 5.1 m/s and breaker wave power of 551 × 10^6 W/m of wave crest. In contrast, the western forereef experienced a maximum 4.3 m/s bottom velocity briefly and no breaker wave power in excess of 169 × 10^6 W/m of wave crest. Throughout the 7 hours of hindcast storm passage, the maximum bottom velocity at the breaker point exceeded 2.4 m/s everywhere. The water depth at the breaker point varied from approximately 4 to 15 m.

Our hindcasting results differ somewhat from those reported by Graus *et al.* (1984). Our breaker heights are greater than those implied by Graus *et al.* (1984). The

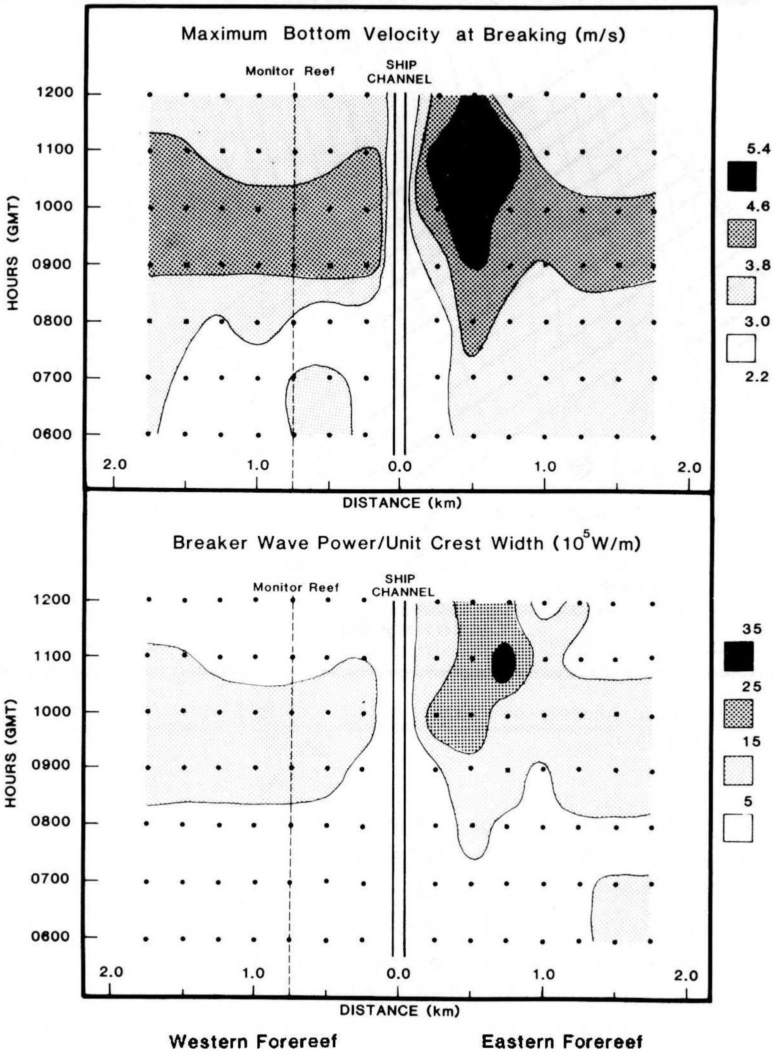

Figure 10. Schematic representation of maximum bottom velocity (m/s) at the breaking point and an equivalent breaker wave power (W/m of wave crest) as a function of position along the reef crest and time.

significant difference is that we focused on effects due to shallow water refraction, a process they chose to ignore. Graus *et al.* (1984) selected to compute the shallow water wave-induced changes from a single generalized depth profile on the western forereef. We, on the other hand, want to emphasize spatial differences over a small distance, which can only be explained by including refraction. The importance of refraction is seen by a difference in breaker heights of a factor of 2.6 between highest and lowest breaker heights at 1100 GMT (Fig. 9f). More important, the maximum wave power incident on the 3 km Discovery Bay forereef for the duration of the storm varied by a factor of 7 (cf. Fig. 10) from the eastern forereef to the ship channel.

Our calculations of deep water wave heights and periods show some differences as compared to calculations by Graus *et al.* (1984) and are less easy to explain. Our deep water significant wave height estimates at Discovery Bay for 0600-0800 GMT exceed those of Graus *et al.* (1984) by 1–2 m. Similarly, our significant wave periods for 0600–0800 GMT exceed those of Graus *et al.* (1984) by approximately 1–2 s. On the other hand, our calculations for 0900 and 1000 GMT compare closely. Graus *et al.* (1984) elected not to perform hindcasting at 1100 and 1200 GMT, whereas we found the largest breakers occurring at 1100 GMT in agreement with observations (Woodley *et al.*, 1981). The discrepancy is presumably due to slightly different choices of hindcasting input parameters (position, central pressure, and radius of maximum winds). The conclusions with respect to effects on the reef zones are not affected by this discrepancy.

8. Discussion

The described hurricane wave model utilizes several simplifying assumptions, as is necessary in hindcasting procedures. These assumptions include an idealized storm track determined from intermittent remote sensing rather than continuous monitoring, and no interaction between ocean surface winds and the land mass of Jamaica. Ground observations following sunrise (0930 GMT) on August 6, 1980 (Woodley *et al.*, 1981) suggest that the model matches actual wave conditions fairly well. Although the direction of wind predicted from the model coincides with directions determined from photographs taken at the time, the predicted intensification of wind, from 18.2 m/s at 0600 GMT to 30.1 m/s at 1100 GMT contrasts with observer recollection of falling winds during that interval. The wind speeds generated by the model therefore probably better reflect offshore conditions than onshore conditions. This discrepancy is likely to be due to interference and sheltering of the wind by the local island topography with winds from the south of west, which occurred after approximately 0800 GMT (Table 2).

The model correctly hindcasts the observed rotation in wave direction from easterly to northwesterly throughout the morning. At no time during the most severe pounding of the shoreline did the winds reinforce the waves. In fact, Allen's hurricane force winds in the vicinity of Discovery Bay generally blew in opposition to its storm-generated waves, perhaps mitigating to some extent the destructive force of the waves.

Wave heights generated by the model are difficult to compare against wave heights generated by the storm since no pertinent wave measurements were made at the time. Maximum breaker heights predicted from the model are in qualitative agreement with a few shoreline observations (Woodley *et al.*, 1981). The diminution in maximum breaker height predicted by the model after 1100 GMT is also in agreement with subjective impressions of the storm's lessening intensity throughout the day. The increase in breaker height until 1000 GMT (shortly after daybreak) on the western forereef is contrary to visual impression, but as the waves began to arrive from a more northerly direction, perpendicular to the reef crest, the accuracy of shorebased observations might have diminished.

The strength of the hindcast model is in generating a realistic set of wave rays and projecting them onto the reef surface so that bottom velocities and wave power can be determined. The absolute timing of this stress in any one 24 hour period is not critical, considering the geological time scale on which the impact of this event must be measured. Ecological processes of reef growth and development that operate on the scale of centuries were interrupted for geologically an instant in time.

Woodley *et al.* (1981) saw much larger waves breaking on the eastern forereef than on the western forereef, and stated that damage was more severe in the eastern locality. Liddell and Ohlhorst (1981), who compared reef morphology and community composition on the eastern and western forereef terraces, suggested that some of the differences they observed were due to differing wave-energy regimes. They suggested that the eastern forereef was more susceptible to storm damage because of its greater seaward extension and its location in relation to storms blowing from the east. This is confirmed by our calculations (Fig. 9a–g), but it is also clear that the topography of the eastern forereef focuses waves from any direction. In Hurricane Allen, this resulted in higher breakers, culminating in the formations of localized breaker heights exceeding 10 m between 1000 and 1100 GMT (Fig. 9e and f).

The most conspicuous effect on the reefs at Discovery Bay of the waves generated by Hurricane Allen was the breaking of many corals, especially branched forms. Prior to the storm, the branched corals *Acropora palmata* and *A. cervicornis* dominated on the western forereef terrace, the former in shallow water down to −6 m, the latter to −20 and −25 m. During the storm, virtually every colony was broken, and afterwards the populations had been reduced to 4–15% of their former areal cover (Woodley *et al.*, 1981). Some of this breakage must have been brought about by the impact of water-borne fragments. Pieces of *A. palmata* skeletons, in particular, were transported shoreward to form a new boulder rampart and a series of islands on the reef flat. But at least initially, destruction was probably achieved by the drag forces due to water movement alone.

The susceptibility of Caribbean acroporid corals to damage by storm waves is well known (e.g. Stoddart, 1963; Glynn *et al.*, 1964; Ball *et al.*, 1967; and others). Although they break readily, they grow quickly and will soon regenerate (Gilmore and Hall, 1976; Tunnicliffe, 1981). Their strategy in competition for space on a reef seems to be rapid overgrowth, balanced against the risk of damage from occasional storms. Porter *et al.* (1981) showed that the *Acropora* spp. at Discovery Bay, already dominant, were increasing their areal dominance by overgrowth between 1976 and 1978. However, they lost it altogether after Hurricane Allen, which was better endured by more compact and slower-growing species. A lightly damaged acroporid reef will regenerate in a few years (Shinn, 1976). However, Caribbean acroporid corals recruit slowly (Rylaarsdam, 1983) and a population that has been nearly or totally eliminated by a severe storm may not be restored until decades have elapsed (Stoddart, 1974; Pearson, 1981). The effect of Hurricane Allen on acroporid corals at Discovery Bay was catastrophic (Woodley *et al.*, 1981). This was partly due to the subsequent effects of predation and disease (Knowlton *et al.*, 1981). Populations were reduced to a 2% fraction of their former levels. As Stoddart (1974) pointed out, there are differences in strength between hurricanes, and the incidence of particularly severe hurricanes may be an important factor influencing the abundance of acroporid corals at localities in the Caribbean.

The hindcast maximum water velocities generated by Hurricane Allen just above the forereef surface at Discovery Bay are shown in Figure 11. The computed results are only shown for the wave breaking point and represent the maximum horizontal component of a largely horizontal orbit. Local reef topography would have deflected the flow into other directions (Vosburgh, 1977). This is an important point, because the large flattened branches of *A. palmata,* generally oriented normal to prevailing wave surge, will be much more likely to break when stressed in unaccustomed directions. Our model suggests that the entire *A. palmata* zone experienced violent turbulent wave-induced flow below the breakers and near the bottom in excess of 5 m/s on the eastern forereef to a depth of −15 m, and in excess of 4 m/s on the western forereef at a depth of −10 m. The water velocities sufficient to break coral have been explored only for *A. reticulata* (Vosburgh, 1977) and *A. cervicornis* (Tunnicliffe, 1982), and partially for *A. palmata* (Hernandez-Avila *et al.*, 1977). Highsmith (1981) presented the detailed calculations for three massive corals. *A. reticulata* is a table shaped Pacific form. Using one colony about 0.5 m high and 0.8 m long, Vosburgh (1977) estimated the breaking forces and equivalent velocities of water movement over the colony in three different directions. They were 828 N by a horizontal flow of 5.2 m/s, 480 N by a vertical flow of 4.1 m/s, and 415 N by a 3.8 m/s flow perpendicular to the blade.

Hernandez-Avila *et al.* (1977), in field experiments on ten specimens of *A. palmata,* 0.5–1.5 m in height, found that horizontal forces of only about 230–350 N were sufficient to break their stems. Unfortunately, they did not relate these values to water flow over the entire colony. However, they also worked on colony fragments and calculated that forces up to 179 N could be exerted on horizontal units 30 cm long by water flowing at 4 m/s, and forces nearly twice as great if the flow were perpendicular to a flat branch. If an average colony in the 0.5–1.5 m size range presents a profile equivalent to five 30 cm fragments, a horizontal flow of 4 m/s could develop forces as large as 895 N to 1600 N, depending on the flow direction. The horizontal flow rate necessary to generate the breaking forces observed by Hernandez-Avila *et al.* (1977), would then be about 2–2.5 m/s if a simple square-power relationship is assumed. In Vosburgh's (1977) specimen of *A. reticulata,* similar forces would be developed by

Figure 11a. Pre-Hurricane Allen close-up of Photostation VI, located at a depth of 11 m on the Monitor Reef fore-reef slope, straight north of Discovery Bay Marine Laboratory (DBML) (cf. Figs. 2, 9a–g). The photo was made on 25 September 1976, and shows an 0.5 × 0.5 m area. Photo by J. W. Porter.

horizontal flows of 2.7–3.4 m/s. In the larger and multifoliate colonies of *A. palmata,* these forces would be developed by even lower velocities, such as those just estimated. Thus, we can suggest that the breaking velocity of horizontal flow for the *A. palmata* specimens studied by Hernandez-Avila *et al.* (1977) would have been roughly 2–2.5 m/s.

However, all ten of the *A. palmata* tested by Hernandez-Avila *et al.* (1977) (at Cayo Turromote, Puerto Rico) had their stems weakened by bioerosion. A single colony with a healthy stem (size not specified) resisted a horizontal force of 500 N. Thus the strength of a healthy specimen is not known; neither is the prevalence of boring in the

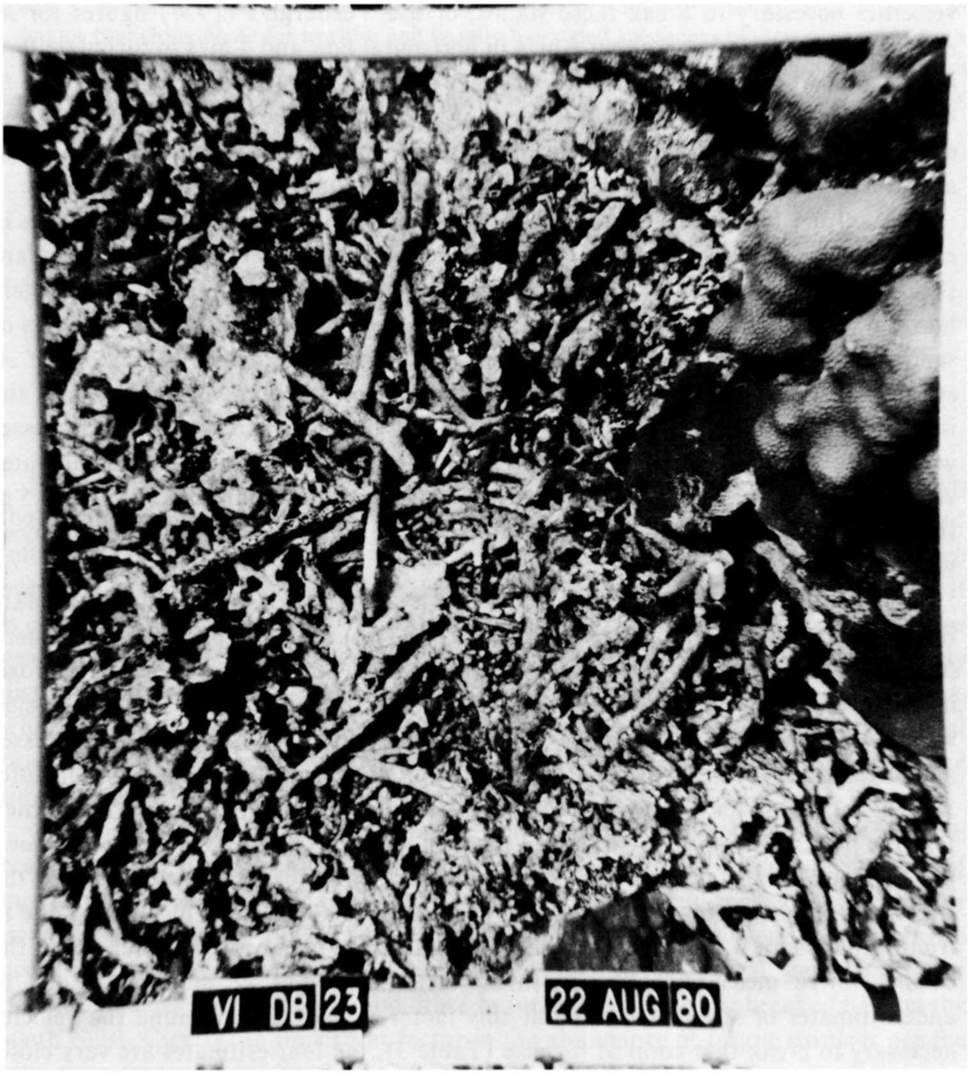

Figure 11b. Post-Hurricane Allen close-up of Photostation VI, the identical location of the close-up in Figure 11b. This photo was made on 22 August 1980 and shows the removal and disruption of the branching *Acropora cervicornis* thicket but survival of *Montastrea annularis* head coral colonies. Photo by J. W. Porter.

A. palmata at Discovery Bay prior to Hurricane Allen. Tunnicliffe (1980) reported burrows in the fracture surface of a stem broken by a severe storm. If the corals were similar to those in Puerto Rico, horizontal water velocities in excess of 2.5 m/s would have toppled most of the stands. Even lower turbulent flows would have achieved the same result. *A. palmata* colonies at Discovery Bay may have been healthier, as they certainly were larger, exceeding 2 m in height. In that case, we can only guess at velocities necessary to break these stands, or use Vosburgh's (1977) figures for *A. reticulata.* Our estimate is about 5 m/s in horizontal flow and 4 m/s in turbulent flow at the point where the waves break. We have calculated that turbulent flows of up to 4.3 m/s were developed on the western forereef, where the *A. palmata* stand was almost totally reduced to rubble. Clearly, the damage was compounded by the high additional forces imparted by sharp blows inflicted in tumbling or flying fragments.

At 1000 and 1100 GMT during the hurricane passage, breaker-induced velocities in excess of 5 m/s extended down into the zones where *A. cervicornis* was abundant (below −5 to −8 m). Most of the *A. cervicornis* zone, however, experienced largely horizontal, pre-breaker flows parallel to the forereef slope, resulting in linear scars of sand scour (Woodley *et al.,* 1981). Prior to the storm, the growth directions of *A. cervicornis* (staghorn coral) showed little or no orientation with respect to the incidence of prevailing waves (Tunnicliffe, 1983). Thus, even purely horizontal stresses would have been as destructive as any others. Hindcast maximum horizontal water velocities over the range of occurrence of *A. cervicornis* ranged from 5.1 m/s at −5 m (breaker-induced velocities) (Fig. 11) to 2.4 m/s at −25 m (calculated from linear wave theory [Wiegel, 1964]).

Interpretation of our results with respect to *A. cervicornis* is made easier by the fact that Tunnicliffe (1979, 1980, 1981, 1982, and 1983) studied this species on the western forereef at Discovery Bay. She measured the breaking stress in the skeleton (approximately 300 Nm^{-2}) and pointed out the prevalence (about 75%) of basal bioerosion which weakened stems considerably (Tunnicliffe, 1979). She also measured stresses and water speeds *in situ,* at various depths, under waves up to 1.2 m high (Tunnicliffe, 1980 and 1982). This was technically very difficult and for only one coral (specimen D) were pairs of values recorded over a range of velocities (Table 3). Inspection shows that measured stress varies by less than the square power of water speed. In fact, the stress is proportional to the speed raised to a power of about 1.3. This may be due to frictional losses of water velocity closer to the substrate than near the outer end of the colony, where measurements were made. Also, it might be an artifact due to underestimates of strain. However, if this factor is used to determine the velocity necessary to break that coral at its base (Table 3), the four estimates are very close, about 1.6 ms^{-1}. Our calculations suggest that flows of this magnitude occurred, during Hurricane Allen, briefly to depths of −26 m on the western forereef, and to −27 m on the eastern forereef, based on linear wave theory (Wiegel, 1964). Tunnicliffe's eroded specimen (Table 3) would have snapped and toppled at a flow of 0.35 ms^{-1}, if we use the same expression. Such flows were exceeded everywhere this species was common on both the eastern and western forereefs.

In fact, *A. cervicornis* colonies were toppled below −20 m and shattered to depths of about −18 m on the western forereef (Tunnicliffe, pers. comm.). Even at about −14 m, the median branching order (Tunnicliffe, 1983) was reduced from 5 to 2 (Tunnicliffe, 1980; Woodley *et al.,* 1981), indicating an average of at least two non-basal (therefore in healthy skeleton) breaks per colony.

Table 3. Breaking stress (τ_c), *in situ* stress (τ) and near-bottom water velocity (U_{max}) normal to major branching plane for healthy and basally bioeroded specimens of *Acropora cervicornis* about 0.5 m high (data from Tunnicliffe, 1980, 1982). The water velocity necessary to break those specimens, U_c, as derived from Tunnicliffe's (1980, 1982) data is $U_c = (\tau_c/\tau)\ 0.77 \times U_{max}$.

Specimen	Breaking stress τ_c (Nm^{-2})	*In situ* stress τ(Nm^{-2})	Water velocity U_{max}(ms^{-1})	Velocity causing breakage (U_c) (ms^{-1})
D (healthy)	271×10^5	10×10^5	0.12	1.52
		45×10^5	0.40	1.59
		60×10^5	0.50	1.59
		120×10^5	0.85	1.59
C (eroded)	35×10^5	17×10^5	0.20	0.35

It is obvious from the size and abundance of *Acropora* spp. prior to Hurricane Allen that many years, at least a few decades, had elapsed since any comparable storm had influenced Discovery Bay. An analysis of hurricane impact on the reefs of Jamaica over the last hundred years is not yet complete (Kjerfve and Woodley, in prep.). But it is clear that the north coast was influenced by six hurricanes (of which at least three were severe) in the first two decades of this century (1903–1917), but was not seriously disturbed again until 1944, and again not until 1980 (Neumann *et al.*, 1981). Thus, while hurricane frequency at Discovery Bay may have been uniform on a geological time scale, it has been highly irregular on a time scale of decades, comparable to the time necessary for growth to full size of acroporid corals.

Goreau (1959) ascribed differences between the reefs at Ocho Rios on the north coast and Port Royal on the south coast (Fig. 1) to differences in the occurrence of hurricanes between the two areas. He studied these reefs a few years after a hurricane had hit Port Royal in 1951 (the first direct hit since 1916) and found (a) extensive areas of dead corals in the *Acropora palmata* zone at Port Royal, and (b) a lower population density of acroporid and other branching corals in the breaker zone on the south coast. Clearly, an important factor in the abundance of fragile corals is not the long-term frequency of hurricane impact, but the time elapsed since the last major disturbance. We suggest that the reefs of the north and south coasts would have appeared more similar, in the abundance of dead and living *Acropora,* in 1918 (both reefs smashed) or in 1940 (both reefs recovering) than they did in the late 1950's (south coast reefs smashed) or do today (north coast reefs smashed).

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APPENDIX

Definition of variables

Parameter	Units	Description
a_1, a_2	(−)	Bottom slope constants used to calculate the ratio H_b/d_b.
b	(m)	Distance between orthogonals within shoaling region.
b_o	(m)	Distance between orthogonals in deep water.
C, C_i, C_j	(m/s)	Wave celerity.
d_b	(m)	Breaking depth of waves.
E_T	(J/m)	Total solitary wave energy.
f	(s^{-1})	Coriolis parameter equal to $2\omega \sin \phi$.
g	(m/s^2)	Gravity equal to 9.81 m/s^2.
h	(m)	Local water depth.
H	(m)	Local shallow water wave height.
H_b	(m)	Wave height at breaking point.
H_o	(m)	Deepwater wave height; equals H_{rv}.
H'_o	(m)	Unrefracted deepwater wave height.
H_R	(m)	Significant deepwater wave height at a distance R from the center of a stationary hurricane.
H_r	(m)	Significant deepwater wave height at a distance r from the center of a stationary hurricane.
H_{RV}	(m)	Significant deepwater wave height at a distance R from the center of a moving hurricane.
H_{rv}	(m)	Significant deepwater wave height at a distance r from the center of a moving hurricane; equals H_o.
k	(−)	Latitude coefficient used to calculate U_R.
k^*	(−)	Coefficient expressing decrease of wind speed as a function of height above surface and used to calculate U_{RS} and U_{rs}.
K'	(−)	Coefficient which is a function of fR/U_R and used to calculate H_R.
K_r	(−)	Coefficient of refraction.
L	(m)	Local wavelength.
L_o	(m)	Deepwater wavelength.
M	(−)	Empirical solitary wave constant equal to 0.98.
N	(−)	Empirical solitary wave constant equal to 0.64.
P	(W/m)	Equivalent wave power per unit length of wave crest at breaking point.
P_c	(hPa)	Central sea level pressure of hurricane.
P_N	(hPa)	Ambient sea level pressure, assumed equal to 1,013.2 mb.
R	(m)	Radius of maximum winds.
r	(m)	Distance from hurricane center to arbitrary location within influence of the hurricane, where $r > R$.
T_o	(m)	Period of maximum energy density.
T_s	(s)	Significant wave period.
U_c	(m/s)	Near bottom velocity necessary to break a particular coral colony.
$U_{\max}$	(m/s)	Maximum horizontal wave velocity below crest.
$U_{\max(\mathrm{bot})}$	(m/s)	Maximum horizontal bottom wave velocity below crest at breaking point.

APPENDIX (Continued)

Definition of variables

Parameter	Units	Description
U_R	(m/s)	10 min averaged gradient wind speed at a distance R from the center of a stationary hurricane.
U_r	(m/s)	10 min averaged gradient wind speed at a distance r from the center of a stationary hurricane.
U_{RS}	(m/s)	10 min averaged surface wind speed at a distance R from the center and at 10 m reference level for a stationary hurricane.
U_{rs}	(m/s)	10 min averaged surface wind speed at a distance r from the center and at the 10 m reference level for a stationary hurricane.
U_{RS^*}	(m/s)	10 m averaged surface wind speed at a distance R from the center of a moving hurricane.
U_{rs^*}	(m/s)	10 m averaged surface wind speed at a distance r from the center of a moving hurricane.
V_F	(m/s)	Forward speed of hurricane.
z	(m)	Distance below still water level, measured negative down.
α_i, α_j	(°)	Angle between wave crest and local isobath.
β	(rad)	Bottom slope of the forereef.
δ	(–)	Parameter equal to $-\mathrm{fr}/2\mathrm{U}_\mathrm{R}$.
ω	(s^{-1})	Angular velocity of earth equal to $7.29 \times 10^{-5}\ s^{-1}$.
ϕ	(°)	Latitude.
θ	(°)	Angle measured counterclockwise from vector indicating forward movement of storm to corrected wind direction at Discovery Bay.
ΔP	(hPa)	Difference between ambient sea level pressure and central sea level pressure.
ρ	(kg/m^3)	Water density equal to 1,030 kg/m^3.
τ	(Nm^{-2})	*In situ* stress on coral.
τ_c	(Nm^{-2})	Stress required to break a coral colony.

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