Chapter 52

STORM CONDITIONS AND VEGETATION IN EQUILIBRIUM OF REEF ISLANDS

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The study of reef islands on the British Honduras coast before and after a major hurricane in 1961 demonstrated the critical significance of vegetation in determining whether storm action is mainly erosional or aggradational. Man-induced vegetation change in this area has led to major storms becoming primarily destructive, and this change can be related to the recent history of the islands. Instability resulting from continued interference with natural vegetation will have serious consequences for the economic use and even future existence of the islands; such use will best be regulated by allowing natural regeneration of vegetation in shelter belts along the most exposed shores of islands.

NATURE OF REEF ISLANDS

Detrital reef islands are of two major types: sand cays and sand-shingle cays. Sand cays consist of coral grit, algal, shell and other organic sediments in the size range 0-2 ϕ, accumulated on a reef flat under the action of refracted waves. The point of accumulation is a function of wave approach and characteristics, and of reef geometry and depth. On small patch reefs and at gaps in linear reefs, sand cays normally develop on the leeward side of the reef flat. Sand-shingle cays develop primarily because of the lodgment on reef flats, of coral and mollusc shingle in the size range -5 to -10 ϕ, median -8 ϕ, with subsequent accumulation of sand-size sediments to leeward. Lodgment may take place either under the action of refracted waves on patch reefs or at reef gaps, or on exposed linear reefs as unrefracted waves dissipate energy when crossing the reef flat. The point of sedimentation will again depend on local wave characteristics and reef morphology.

Islands of these types have been investigated off the coast of British Honduras, Central America, where a 130-mile long barrier reef and three atolls give widely varying conditions of reef island formation. The reefs are aligned north-south, transverse to the dominant Northeast Trades and wave trains, and tides are negligible (less than 2 ft.). With essentially unidirectional waves and no tidal complications, the nature of above-water sedimentation is essentially a function of (a) local exposure to waves, largely a matter of protection by windward reefs; and (b) local reef morphology, in particular width and depth of the reef flat. Under these conditions, initially formed sand and sand-shingle islands may rise to a height of 3 ft. above still water level under the action of wave run-up. Such islands may then be colonised by vegetation, and the sediments subject to local diagenesis, either by cay sandstone formation above high water level, or by intertidal beachrock formation.

Detailed mapping of islands on the British Honduras reefs in 1959-61 showed considerable areal variations in island topography and sediment composition. On the exposed eastern reefs, sand-shingle cays reach a maximum height of 10 ft. above sea level on Lighthouse and Glover's Reefs. On more protected reefs (Turneffe Islands, southern barrier reef), islands do not exceed 5 ft. in maximum elevation, with less coarse seaward shingle ridges. Along the central barrier reef, protected by the atolls to windward, islands lack shingle and are less than 5 ft. in height. On protected shoal areas within the barrier and Turneffe lagoons, colonisation by Rhizophora mangle and Avicennia germinans has led to island formation and the entrapment in more exposed areas of sand on their windward sides.

EFFECT OF HURRICANE HATTIE

Mapping of these islands was completed in August 1961. On October 30-31 1961 Hurricane Hattie crossed diagonally over the centre of the reef area (figure 1), with a minimum recorded pressure of 27.4 inches, winds gusting to over 200 m.p.h., and a storm surge extending on the mainland coast to about 30 miles north and 15 miles south of the storm centre, with a maximum amplitude of 15 ft. Wave action associated with the hurricane was greatest to the north of the storm track: initial easterly swell was followed late on 30 October by wind-driven northerly then easterly seas, travelling directly across the Caribbean towards the transverse atoll and barrier reefs. South of the storm track, initial easterly swells were followed by southeast, south and southwest seas with the passage of the storm. In the reef area these were generated in shallow water with restricted fetch, in areas where the storm surge was less significant: hence they were much less destructive than seas to the north of the storm track. Distinction must be made between sea and wave action, therefore, which varied in intensity on each side of the storm, and wind action, which was more symmetrically zoned in intensity north and south of the storm track. As a result, damage in the reef area varied both with dominant process and location:

(a) submarine changes and damage to living reef by waves was catastrophic to the north of the storm track for a distance of 30 miles from the centre, but much less important to the south.

(b) wave action on reef islands was greatest to the north of the storm track, but much less to the south, decreasing with distance from the storm centre.

(c) wind action on reef islands was greatest near the storm

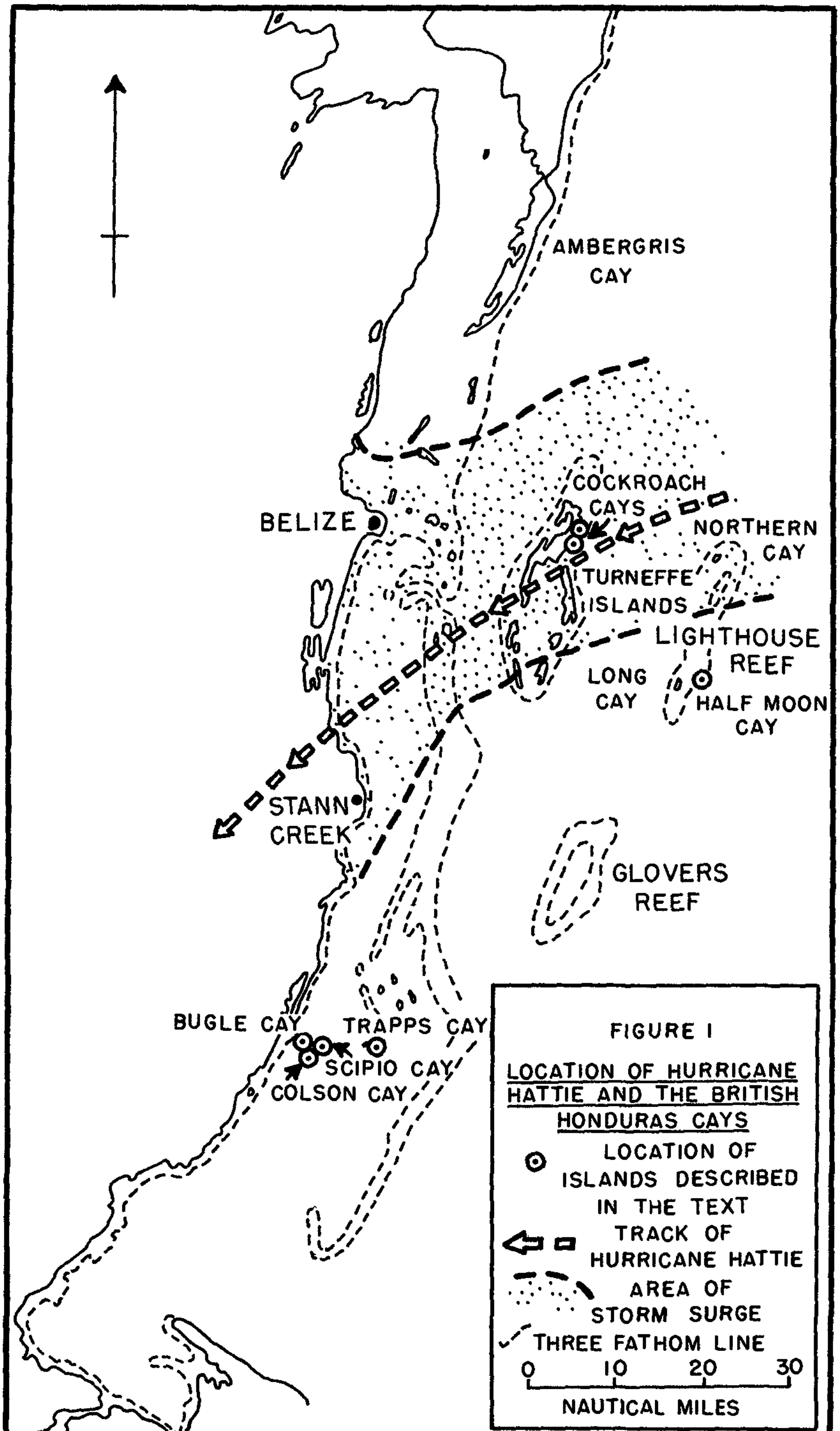

AMBERGRIS CAY
COCKROACH CAYS
BELIZE
NORTHERN CAY
TURNEFFE ISLANDS
LIGHTHOUSE REEF
LONG CAY
HALF MOON CAY
STANN CREEK
GLOVERS REEF
BUGLE CAY
TRAPPS CAY
SCIPIO CAY
COLSON CAY
FIGURE I
LOCATION OF HURRICANE HATTIE AND THE BRITISH HONDURAS CAYS
LOCATION OF ISLANDS DESCRIBED IN THE TEXT
TRACK OF HURRICANE HATTIE
AREA OF STORM SURGE
THREE FATHOM LINE
0 10 20 30
NAUTICAL MILES

TABLE I

ROLE OF VEGETATION COVER IN HURRICANE EFFECTS ON REEF ISLANDS DURING HURRICANE HATTIE, 1961

VEGETATION TYPE / HURRICANE EFFECT	(A) NATURAL VEGETATION	(B) COCONUTS WITH REGENERATED THICKET	(C) COCONUTS WITH LOW UNDERGROWTH	(D) COCONUTS WITH NO UNDERGROWTH	(E) SMALL ISLAND WITH SMALL VEGETATION THICKET	(F) UNVEGETATED
DISAPPEARANCE	-	-	-	2	10	7
MAJOR SURFACE SAND-STRIPPING & CHANNEL-CUTTING	-	2	3	17	-	-
MAJOR BEACH RETREAT	-	3	-	10	-	-
MARGINAL AGGRADATION	15	9	-	-	-	-

NUMBERS REFER TO INDIVIDUAL ISLANDS IN EACH VEGETATION & DAMAGE CLASS centre, decreasing symmetrically both to north and south.

Because of the extreme conditions, no quantitative data are available on wave conditions during the passage of the storm: all available data has been collated elsewhere (Stoddart, 1963).

Within this framework of storm conditions, changes on detrital reef islands varied greatly, but remapping of all damaged islands in 1962 demonstrated regularities. Reef islands vary in size, shape, height, composition, and vegetation cover. Erosional effects due to waves were of two main types: first, peripheral backwearing of shorelines, both on sand and shingle beaches, leading to undermining and removal of surface vegetation, and in some cases followed by deposition of fresh sediment on the eroded shore; and second, surface stripping of sand and scouring of channels and holes by overtopping water, with attendant vegetation damage. Within 40 miles of the storm centre, the first type, peripheral beach erosion, was universal, and to some extent is only a more extreme case of the annual shoreline readjustments following winter storms of "northers". The incidence of surficial erosion was much more limited, and was restricted to islands where overtopping by the sea gave wave action access to island interiors. Clearly, this occurred most often on low islands; on islands narrow transverse to the direction of water movement; and on islands exposed to most intense sea conditions, particularly those within the high storm surge zone, where smaller cays were overtopped by up to 10 ft. of water. Hence, on the larger islands, such as Ambergris Cay, Long Cay (Lighthouse Reef), and Northern Cay (Lighthouse Reef), in spite of shoreline readjustments of up to 50 yards, gross topographic changes were minor, and damage in the interiors was restricted to felling of trees by wind. Conversely, on small islands, easily overtopped, erosion could be catastrophic over the whole cay surface, and in several cases led to the complete disappearance of the cay.

VEGETATION AND HURRICANE CHANGES

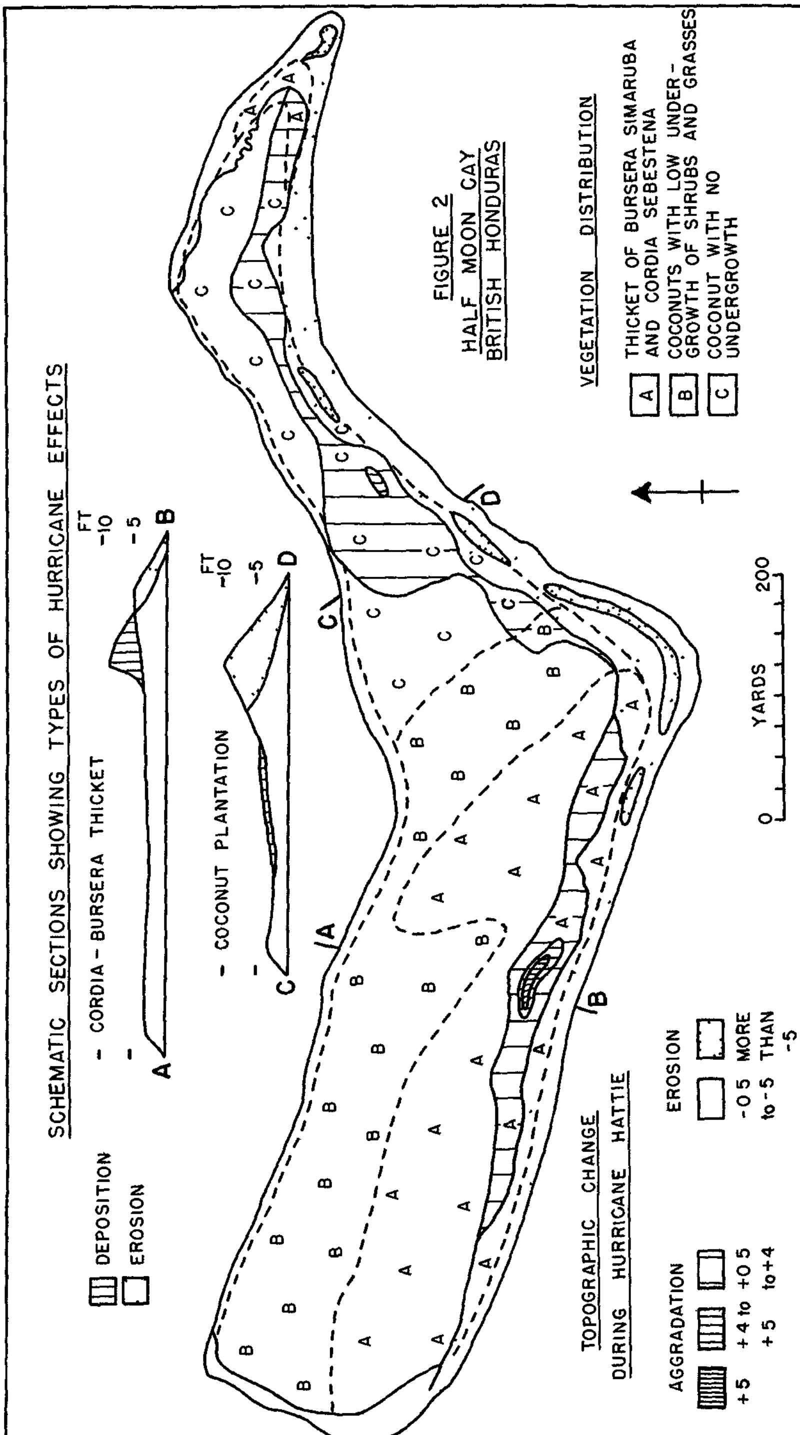
Mapping disclosed, however, one further critical variable limiting hurricane effects, which is best demonstrated by reference to examples.

In the southern barrier reef lagoon , off Placencia, 30 miles south of the storm centre, there are numerous small sand cays on individual patch reefs. Most of these islands consist of peripheral sand beach ridges with interior Avicennia marsh. Vegetation on the beach ridges consists of a dense thicket of Thrinax, Cordia and coconuts. The pattern of damage at Scipio, Colson, Owen, Trapp's and Cary Cays was similar: beach retreat and minor cliffing, with local destruction of vegetation, on the weather side, followed by deposition of fresh shingle both on the old beach ridge crest and as a low carpet to seaward of the eroded cliff. The fresh crest shingle was banked against and partly buried the palm thicket and ground vegetation, had a maximum thickness of about 3 feet, and presented a steep slope to landward. On neighbouring Bugle Cay, however, in other respects topographically similar, the original vegetation had been cleared for a lighthouse station and coconut plantation, with no undergrowth. In spite of distance from the storm centre the sea overtopped the island and wave action took place across the whole cay surface. Shore retreat averaged 10-20 yards, much more than on vegetated islands, surface sand was stripped and trees disappeared, and all houses were destroyed. Sediment deposition was restricted to shoal water on the leeward side of the island, and no fresh shingle accumulated along the seaward beach ridge.

Similar, if more spectacular effects, were seen at Half Moon Cay, 20 miles south of the storm centre, on the exposed eastern reef of Lighthouse Reef atoll. Half Moon Cay (Figure 2) is a sand-shingle island 1100 yards long, with shingle ridges along its south and northeast shores, reaching a maximum height of 10 ft. above sea level. Comparison of contour maps made in 1961 and 1962 gives a detailed picture of hurricane changes. Vegetation distribution is again significant. The western half of the island in 1961 was covered with a thicket of Cordia sebestena, Bursera simaruba, Ficus, Neea and coconuts; the eastern half had been cleared of natural vegetation, mostly since 1927, and in 1961 carried tall coconuts, largely without ground vegetation. Before the hurricane the thicket-covered west end of the cay consisted of a seaward shingle ridge, declining in height from 9 ft. to 3 ft. above sea level from east to west, with attendant decrease in shingle calibre; Cordia formed a dense hedge along the ridge crest. Lagoonward of the crest the surface was flat, built of coarse coral grit and rotten shingle, and covered with dense vegetation. The eastern half of the cay, under coconuts, was almost entirely sand, the seaward beach crest rising mostly to more than 8 ft., and locally to 10 ft. above sea level. During the hurricane, in addition to considerable wind damage to vegetation, changes resulting from south to southwest seas took the following forms:

(a) on the sand area under coconuts: the seaward beach retreated up to 20 yards, and the crest elevations were lowered at least 3 ft. and in places up to 7 ft. The area back of the crest suffered surface sand stripping, with some channelling on the narrower part of the cay.

(b) on the western vegetated sector, the seaward ridge crest was pushed about 25 yards landward and nearshore vegetation was uprooted and destroyed. The dense vegetation thicket, however, acting as a baffle against the waves, served as a massive sediment trap for coral blocks, shingle and sand. In place of the former graded sediment distribution and decline in crest height from east to west, fresh sediment has been piled against the vegetation barrier to a height


SCHEMATIC SECTIONS SHOWING TYPES OF HURRICANE EFFECTS
DEPOSITION
EROSION
A - CORDIA - BURSERA THICKET - B
FT
-10
-5
C - COCONUT PLANTATION - D
FT
-10
-5
FIGURE 2
HALF MOON CAY
BRITISH HONDURAS
VEGETATION DISTRIBUTION
A THICKET OF BURSERA SIMARUBA AND CORDIA SEBESTENA
B COCONUTS WITH LOW UNDERGROWTH OF SHRUBS AND GRASSES
C COCONUT WITH NO UNDERGROWTH
YARDS
0
200
TOPOGRAPHIC CHANGE DURING HURRICANE HATTIE
AGGRADATION
+5
+4 to +5
+0 5 to +4
EROSION
-0 5 to -5
MORE THAN -5

of 8 ft. above sea level for most of its length, and in one place to 10 ft. The inner edge of the fresh sediment is marked by a sharp break of slope.

Thus, where the natural vegetation had been replaced by coconuts before the storm, erosion and beach retreat led to net vertical decreases in height of 3-7 ft.; whereas where natural vegetation remained, banking of storm sediments against the vegetation hedge led to net vertical increases in height of 1-5 ft.

The Half Moon Cay case is best documented, but throughout the reef area affected by the hurricane the same pattern is seen. For example, north of the hurricane track, on the east-facing reef of Turneffe Islands, one island in the Cockroach Group (Cockroach Cay) had been cleared for coconuts. During the hurricane all the vegetation disappeared, and surface sediments were scoured out over the whole island surface to depths of 1-2 ft., with no corresponding above-water deposition. Smaller, lower islands a few yards away, which retained their natural vegetation of Bursera, Cordia and Thrinax, suffered slight marginal erosion but massive deposition of fresh shingle against the vegetation hedge (as at Pelican Cay). Comparative pre- and post-hurricane maps for most of the storm-affected islands have been published elsewhere (Stoddart, 1963), and provide further evidence on the significance of vegetation cover in affecting the nature of hurricane effects.

SUMMARY OF CHANGES

From these data we conclude that:

(1) on islands with natural littoral thicket, or with coconut thicket with dense naturally regenerated undergrowth, both within and outside the surge zone, debris-laden storm waves are incompetent to destroy more than an outer fringe of vegetation, and massive deposition of sand and shingle from storm waves occurs at the margins of the thicket.

(2) on islands planted to coconuts, especially with no undergrowth, and particularly within the storm surge zone, trees are readily removed, either by direct wind and wave action, or by erosion of the substrate by waves. Destruction of the vegetation removes any obstacle to storm waves, which may cause general beach retreat, surface sand stripping and channel-cutting, and in extreme cases total erosion of the island.

(3) on mangrove islands the mangrove was defoliated during the storm but not uprooted. Since these islands are located in sheltered areas remote from zones of active sediment production, however, little aggradation followed. These islands are not further considered here.

On islands in the first category, it is immaterial whether vegetation mortality is immediate or delayed: the major point is that vegetation retained its root-hold and remained in the position of growth, and this prevented the passage of sediment-laden storm water. Table 1 summarises types of physiographic change for all islands studied, in terms of six categories of vegetation cover, and clearly demonstrates the importance of vegetation type in controlling the pattern of storm effects.

A MODEL OF REEF ISLAND FORMATION

These data have important implications for the morphology, structure, history and equilibrium conditions of reef islands generally. A model of island evolution suggested by the British Honduras cases will be briefly stated, and then related to known history of the islands and to outstanding problems of island morphology.

The conditions necessary for the accumulation of detrital reef sediments have already been stated in outline as functions of wave characteristics, reef depth and geometry, and source and nature of sediment supply. A full statement would also include effects of tides and tide and wind-induced currents. Such conditions are clearly competent to account for the formation of embryonic "sand-bores" or small unvegetated detrital islands of reef areas, which are typically of variable topography, location and size, and often of intermittent life. Such patches are stabilised by vegetation growth through a series of successional stages to climax, and secondarily by diagenesis of loose clastic sediments. Sandbores, however, rarely if ever exceed 3 ft. in height, whereas cays, depending on exposure, may reach 10 ft. It is suggested here that the climax vegetation of reef islands, by its dense structure and root system, forms a natural protection against storm waves, and that further, once such vegetation is established, it acts during violent storms as a sediment trap, leading to net increase in height of the land surface. In 1961 storm sediments were thus built to a height of 10 ft. above sea level at Half Moon Cay, a height equal to that of any other island on the reefs before the storm. In the reef island ecosystem, therefore, vegetation and sediment accumulation are complexly interlocked: without the sediment-trapping function of the natural vegetation, islands could not be built to heights of more than 3-5 ft. above sea level without relative shifts of sea level. High-standing islands are thus in complex equilibrium with marine processes, with vegetation as a critical control during major storms. If the vegetation is removed from any island, this equilibrium is disturbed. Sediment is no longer trapped from storm waters, which cause considerable marginal and surficial erosion leading to net decrease in surface height and even to disappearance or fragmentation of the island. When natural vegetation is removed, it is normally replaced by coconut plantations, which (a) have an open structure easily penetrated by seawater; (b) frequently have no ground vegetation, exposing the surface to stripping and channelling; and

(c) have a dense but shallow (12-18 inches) root mat easily undermined by marginal sand sapping. Hence, in any given area subject to catastrophic storms, islands with natural vegetation will tend to increase in height during storm action and thus become progressively less subject to catastrophic damage, while those under coconuts will tend to be eroded and destroyed.

IMPLICATIONS OF THE GENERAL MODEL

Some implications of this model may now be explored. First, the change from aggradation to erosion must date from the replacement of natural vegetation by coconuts. In British Honduras coconuts are a post-Columbian introduction. They were first noted by Uring in 1720, but according to a sketch of Half Moon Cay in 1829 were still few in number. They apparently increased during the eighteenth century (Speer, 1765; Jefferys, 1775), but chiefly with the growth of the coconut export industry in the period 1850-1930. At Half Moon Cay most of the trees date from the 1920's. The vegetation change, therefore, has largely taken place within the last century. Apart from maps by Speer and Jefferys, the first detailed charts of the reefs date from the Admiralty surveys in the 1830's, since which time approximately twenty islands have disappeared on these reefs (Figure 3). Many others have undergone erosion, especially on their seaward shores. Almost all islands described in 1760-1830 as being covered with bushes or thicket are now planted with coconuts, and those within the storm area suffered severe damage in 1961. There is no evidence of islands becoming established as vegetated cays during this same period. Concurrently with the widespread replacement of natural vegetation by coconuts, therefore, there has been a large scale disappearance of formerly vegetated islands, in a period when (since 1787) there have been 21 recorded hurricanes, 14 of them since 1900.

The proposed model also provides a simple explanation for the height of reef islands. As shown elsewhere (Stoddart, 1962a) there is no evidence in the area of raised reefs, raised beachrock, or raised beaches indicating Holocene high stands of sea level, said to be widespread in the Indo-Pacific reef province. No such high stands have been found in detailed studies in the Gulf Coast area of the U.S.A. (Shepard, 1961), and it would therefore be unwise to call upon postulated high stands of the sea to explain anomalously high sediment accumulation on reef islands. The 1961 hurricane data indicate clearly that such high accumulation can take place during storms under certain vegetation conditions, to heights equal to those so far recorded on the reefs.

Island accumulation by this mechanism will result in distinctive island structures, characterised by a succession of soil and root horizons dipping seaward and overlain by thick but narrow and variable bands of fresh sediment, generally coarse and poorly sorted.

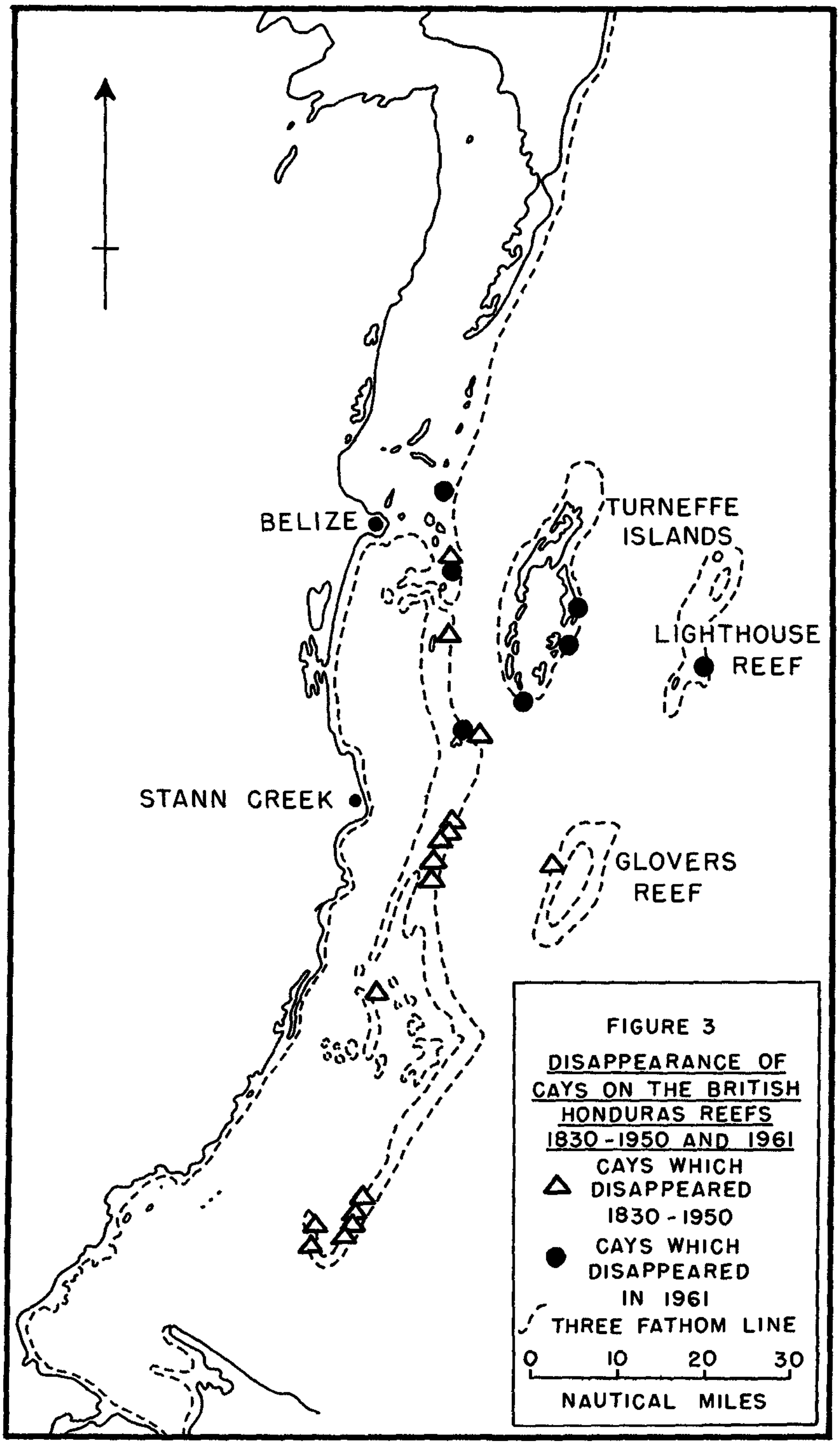


FIGURE 3

DISAPPEARANCE OF CAYS ON THE BRITISH HONDURAS REEFS 1830-1950 AND 1961

Such structures could easily be demonstrated on cay margins following the 1961 hurricane, but was not further verified by trenching. However, trenching on Jaluit Atoll, Marshall Islands, following Typhoon Ophelia in 1958 revealed sequences of soil horizons buried by later sediments (McKee, 1959; Blumenstock, 1961), and similar structures are reported from Ifaluk Atoll, Caroline Islands (Tracey, Abbott and Arnow, 1961). Acceptance of the present model involves two further structural implications:

(1) that island structures will differ (a) in islands still covered by dense natural vegetation, (b) in those where natural vegetation has been recently replaced, and (c) in those where coconuts have been established for many centuries. In the Caribbean the vegetation change has been relatively recent, whereas reef islands in the Indo-Pacific may have been planted to coconuts for a very long time. The history of the origin and spread of the coconut is significant here.

(2) that island structure and topography will differ on islands exposed to tropical storms from those in areas where such storms do not occur. Information on reef islands, however, is at present rather sparse: a useful location to test this suggestion would be the atolls of the Maldive and Laccadive groups, the southern parts of which are not affected by tropical storms, while the northern parts are (Oldham, 1895; Sewell, 1935).

IMMEDIATE PROSPECT

Apart from the general applicability of the model relating storm conditions, vegetation type and sedimentation, there is the question of the long-term stability of the British Honduras cays. The evidence indicates quite clearly that conversion to coconuts has disturbed the reef island equilibrium, often with catastrophic results. There are two major motives in removing natural vegetation on these cays: first, the economic return from the coconut plantations, which has been most important up to 1960; and second, the provision of tourist amenities in developing the islands as holiday and fishing resorts, which is likely to become more important in the future. In this context natural vegetation has no scenic attraction and harbours rats, iguanas and insects. With the increasing frequency of major storms on this coast since 1945 it is unlikely that capital will again be available for coconut replanting and clearing on any large scale on the reef islands; indeed, there is a distinct possibility that in some cases natural vegetation will return and the old equilibrium be re-established. On the other hand the attraction of tourists is a Government policy which has few other outlets apart from the coastal reefs and islands: mechanised vegetation clearance has already taken place on one of the larger islands near Belize. If this continues in such a drastic form, involving clearance more complete than that in the transition from natural vegetation to coconut plantation, the instability of reef islands under storm conditions will be accentuated. With present hurricane frequency and magnitude, unrestrained clearing will inevitably lead to catastrophic erosion and disappearance of reef islands, and to major damage to any capital installations. Both tourist development programmes and new coconut plantations could safeguard island stability by a shelter belt policy of allowing natural regeneration of vegetation along the exposed and windward sides of cays. It is, of course, impossible to safeguard against wind effects on buildings and trees during hurricanes, but such marginal shelter belts would at least give protection against erosion by overtopping storm waves at times of high surge. Further work would be required on resistance to uprooting of local trees, but indications are that the dominants of natural littoral thicket are well adapted to resist storm action. Unless such measures are adopted, capital investment on reef islands is likely to be unrewarding.

From the physiographic point of view, reef islands present a useful indication of the limitations of frequency-magnitude studies of process, in the interpretation of topographic forms, and of the role of vegetation in effecting equilibrium between material and process. The conclusions reached here are those demonstrated by the changes during the 1961 hurricane in British Honduras, and subsequent work may indicate whether they are of more than local application.

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