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Pollution by Mud of Great Barrier Reef Coastal Waters

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ABSTRACT

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Oceanographic data from the coastal waters of the Great Barrier Reef near Cairns were obtained for two months in the 1997 dry season when river runoff was negligible. A muddy coastal zone was found with suspended sediment concentration reaching 1000 mg/L during trade winds. These high turbidity events are very stressful conditions for coral reefs and were caused by resuspension of sediment by wind waves. In calm weather a nepheloid layer prevailed, extending about 30 km offshore and carrying coastal mud toward offshore coral reefs. In this layer, muddy marine snow with flocs exceeding 1000 μm in diameter was found inshore, while only small flocs < 100 μm were found offshore. Near-surface visibility may have decreased by 50% in the last 70 years. High turbidity appears to be due to man and ultimately threatens the main body of the Great Barrier Reef.

ADDITIONAL INDEX WORDS: *Mud, turbidity, siltation, resuspension, nepheloid layer, Great Barrier Reef.*

INTRODUCTION

Most of our knowledge of the historical, physical properties of the waters of the Great Barrier reef (GBR) is derived from the 1928–1929 British Museum Expedition. This pioneering study was mostly carried out near Low Isles (16°23′S, 145°34′E; see Figure 1 for a location map). MOORHOUSE (1933) and ORR (1933 a and b) reported clear water (mean visibility ≈11 m) during the South East trade wind season from about April to October. Human impacts at that time were negligible. Since that time most of the forest and natural vegetation that covered the land have been cleared and much of it is now intensively farmed with usually no protective cover against soil erosion. This resulted in a large increase in mud discharged by rivers on the coast of the Great Barrier Reef (ANON, 1993; WOLANSKI, 1994, LARCOMBE *et al.*, 1996, WACHENFELD *et al.*, 1997). Historical photographs and navigation maps of the Cairns waterfront (see location in Figure 1) suggest that what was largely a sandy coast is now buried under 1.5 m of mud (WOLANSKI and DUKE, 2000). The increased muddiness of the coast has been reported also at other locations along the coast of the Great Barrier Reef following European settlement. For instance, WOLANSKI (1994) reported an invasion by mud of a sandy beach flat at Townsville (19.3°S). Large areas of mangrove forests that acted as efficient sediment traps (FURUKAWA *et al.*, 1997), have also been removed by farming. Many estuaries essentially have become drains bringing all the eroded, fine sediment directly to the sea. In view of this man-made increased muddiness of coastal waters, oceanographic data were collected to assess the offshore extent of the dispersion of the mud and the potential threat it poses to the Great Barrier Reef.

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METHODS

For six weeks, in August and September 1997, six oceanographic moorings were maintained in a cross-shore transect at sites 1–6 shown in Figure 1 in depth varying from 3 m inshore to 23 m offshore. Water depth and equipment deployed are summarised in Table 1. At sites 1–5 the moorings included Inter-Ocean model S4 current meters at about half-depth, a Dataflow salinometer and a total of 19 nephelometers spread across the water column, the lowest one being located 0.5 m from the bottom. The units averaged data over 1 min and recorded these data at 5 min intervals.

At site 6 near Pixie Reef an Inter-Ocean model S4 current meter was deployed 6m from the bottom, and a Dataflow salinometer at 17 m off the bottom in 25 m depth. During mooring deployment and recovery, and also in December 1997 when dry weather conditions prevailed, vertical profiles of salinity, temperature and suspended solid concentration (SSC) were obtained using a CTD equipped with an Analite backscatterance nephelometer. The nephelometers were calibrated *in-situ* for suspended solid concentration. *In-situ* photographs of the suspended matter were obtained using the method of AYUKAI and WOLANSKI (1997).

Suspended solids were collected at 2.5 m from the bottom every 2 days at site 5 using a McLane automated suspended sediment trap and the samples were was analyzed in the laboratory following the techniques described by WOLANSKI *et al.* (1999).

Wind and rainfall data were obtained from meteorological stations at Green Island and Cairns.

RESULTS

Southeast trade winds peaking at 15 m s^{-1} prevailed throughout the study period, occasionally interrupted by short periods of calm weather (Figure 2). The tides were

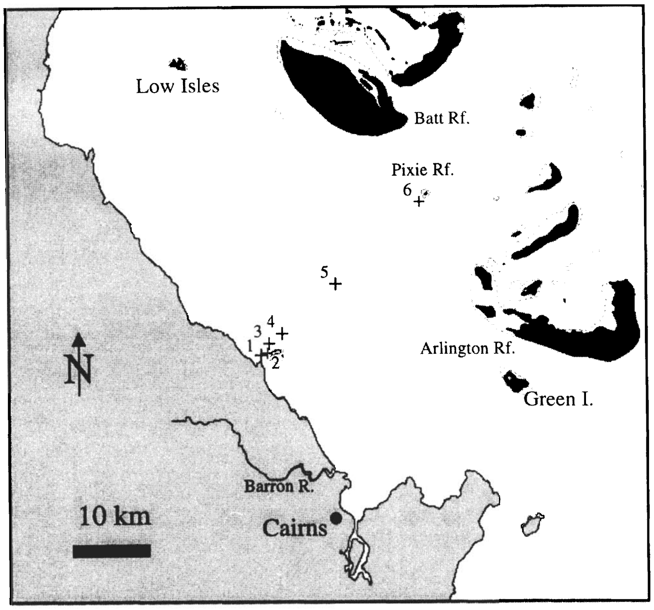

Figure 1. General location map showing the mooring sites.

mostly semi-diurnal with a strong diurnal inequality, peaking at about 3 m peak-to-trough at spring tides and 0.5 m at neap tides (Figure 2). Freshwater runoff and associated riverine sediment inflow was negligible during the study because it was carried out in the dry season.

The currents were mostly alongshore, alternating northward and southward at periods of several days, the tidal variations were small and the low-frequency currents were dominant (Figure 2). The currents were southward with speed of about 0.2 m s^{-1} during calm weather and northward with a speed of about 0.4 m s^{-1} during strong trade winds and fluctuated very little with the tides.

The suspended solid concentration (SSC) fluctuated widely in coastal waters (Figure 2). Maximum SSC was about 1,000 mg l^{-1}, at which time the visibility as reported by divers at site 1 was zero (it was pitch black at 2 m depth and the divers could not see their hand against the face mask). The SSC was smaller further offshore. The SSC did not vary with the tides. Inshore, high SSC occurred frequently, but only during strong wind; at these times SSC was uniform throughout the water column. Offshore, high SSC events (>50 mg l^{-1} peaking in one event at 200 mg l^{-1}) occurred occasionally. At these times the high SSC events were limited to near the bottom (Figure 3a). During strong winds, suspended solids consisted of fine terrigenous mud forming flocs typically 30–60 μm in diameter (not shown).

In calm weather a near-bottom nepheloid layer was observed apparently cascading down the slope (Figure 3b). At that time in coastal water SSC reached 50 mg l^{-1}. Offshore SSC values in the nepheloid layer peaked at about 10 mg l^{-1}. Inshore, the suspended matter consisted of muddy marine snow, *i.e.* small mud flocs (typically 30–80 μm in diameter) attached to sticky marine snow flocs typically 200–1000 μm in diameter (Figure 3c). The marine snow was observed to be made of mucus, plankton detritus as well as other biological detritus. Offshore the suspended solids were present as inorganic mud flocs < 60 μm in diameter.

Table 1. *Mooring details.*

Site number	Water depth (m)	Depth of current meter (m)	Depth of nephelometer (m)
1	2	N/A	0.25, 1
2	4	2.5	1, 2, 3, 3.5
3	6	4.5	3, 4, 5, 5.5
4	11	6	6, 8, 10, 10.5
5	18	12	14, 17, 17.5
6	25	19	N/A

The spectrum of sea level (not shown) revealed that the semi-diurnal tides contained most of the energy. On the other hand the alongshore currents and wind showed negligible energy at diurnal and semi-diurnal tidal frequencies; most of the energy was contained at low-frequencies with period > 3 days with no apparent peak in the spectra. The wind showed a weak peak at diurnal frequency, an indication of a sea-breeze effect. The spectra of SSC at stations 1 and 2 were weakly energetic at the diurnal frequency, possibly an effect of the sea-breeze, but not at all at the dominant tidal semi-diurnal frequency. Highest energy in the spectra was at about 10 days period. This period is the same for the peak in the wind and current spectra, it is also the maximum period for which the spectrum can be reliably calculated from this time series.

Alongshore wind offshore (at Green Island) and currents were significantly correlated with a lag increasing with distance offshore, the wind preceding the current ($R = 0.8$ at 2 h lag at site 2; $R = 0.6$ at 8 h lag for site 3 and $R \approx 0.8$ at 16 h lag at sites 5 and 6).

The alongshore currents and the SSC were also significantly correlated, the current preceding SSC, R = 0,.7 at 2 hr lag at site 2, $R = 0.45$ at 6 hr lag at site 3, $R = 0.5$ at 13 h lag at site 4. A negative and significant correlation between wind and current occurred at site 5 located further offshore, $R = -0.5$ at zero lag. No correlation ($|R| < 0.2$) between currents and SSC prevailed at site 5.

For sites 1 and 2 a significant correlation also existed between alongshore wind velocity and SSC; at site 1 $R = 0.7$ at zero lag and 0.9 at 14 h lag; at site 2 $R = 0.7$ at 2 h lag. For site 3, no strong correlation was apparent ($R < 0.4$). At site 4 the correlation was negative and significant, $R = -0.45$ at zero lag. At site 5 no correlation was found between the wind velocity and the SSC ($|R| < 0.2$).

The SSC fluctuated coherently with distance offshore between sites 1–4. Between sites 1 and 2, $R = 0.75$ at 0.4 h lag; between sites 1 and 3, $R = 0.73$ at 2.3 h lag and between sites 1 and 4, $R = 0.65$ at 7.3 h lag. The correlation however became negative but was still significant for sites further offshore, *e.g.* between sites 1 and 5 $R = -0.5$ at 16 h lag.

The suspended solids collected every 2 days at site 5 in a McLane sediment trap were largely inorganic. TOC varied from sample to sample between 1.4 and 3.7%, TIC between 1.0 and 3.7%, Ca between 6.6 and 8.5%, Si between 16.3 and

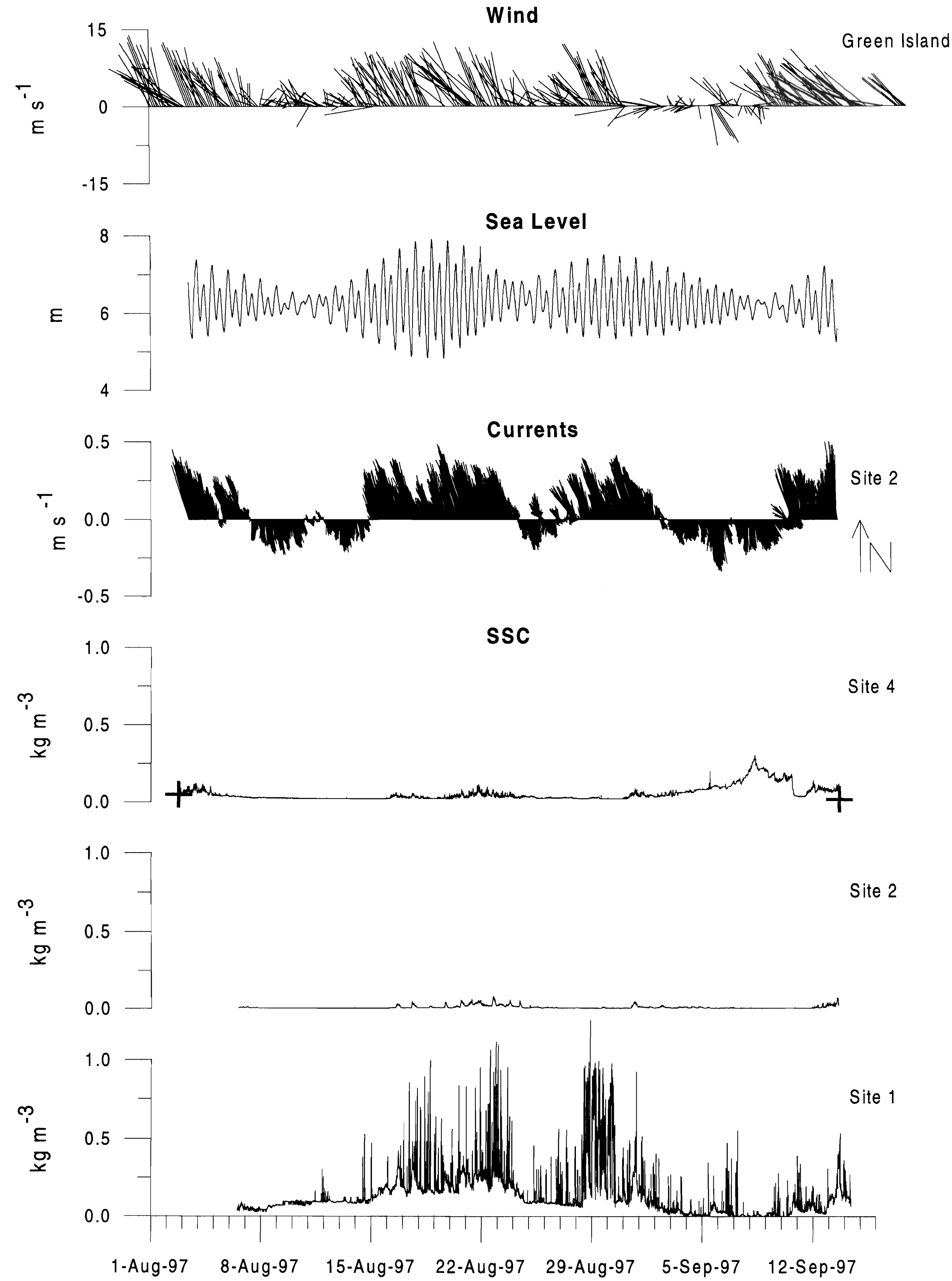

Figure 2. Time series plot of the wind vectors (shown using the oceanographic convention), sea level, currents, and examples of the measured near-bottom suspended solid concentration.

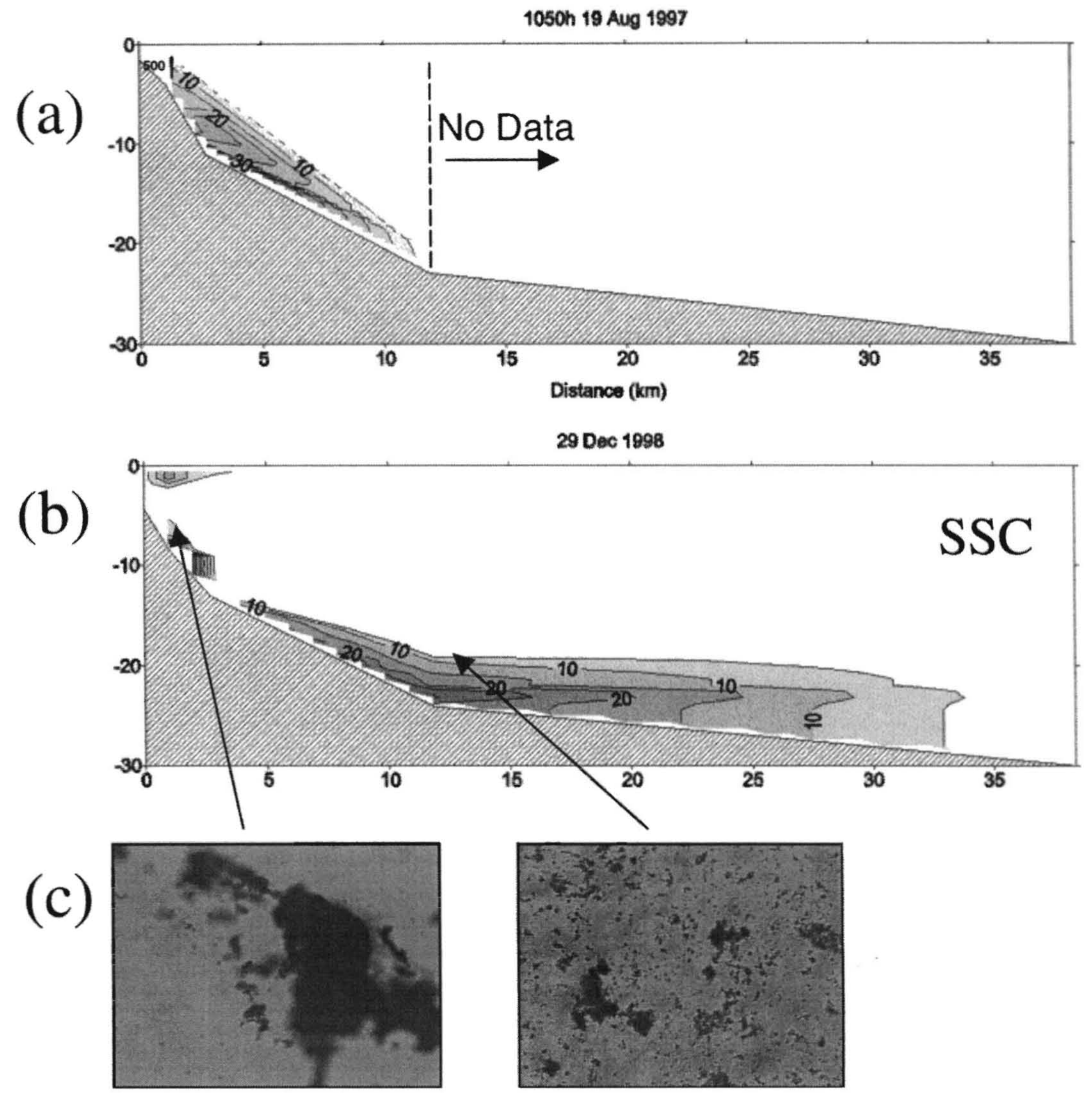

Figure 3. (a) shows the cross-shore distribution of SSC during strong winds at 1050 h on August 19, 1998, as measured by the nephelometers on the moorings. At that time only small flocs (diameter < 60 mg l^{-1}) were present at all sites. (b) shows the cross-shore distribution on December 29, 1998, still in the dry season, in calm weather conditions. Note the near-bottom nepheloid layer. (c) Micro-photographs spanning 250 μm in width, also taken on December 29, 1998, showing the presence of muddy marine snow in inshore waters, and of small flocs of diameter < 60 μm in offshore waters.

20.1 and Al between 7.5 and 8.3. The suspended sediment was thus mainly terrigenous mud.

DISCUSSION

The water circulation in this area of the Great Barrier Reef was similar to that previously reported by WOLANSKI (1994). In particular the macro-tides (up to 3 m peak-to-trough) propagated perpendicular to the coast, generating weak tidal currents in coastal waters. The dominant current in calm weather was alongshore southward, driven by the southward flowing East Australian Current on the continental slope of the Great Barrier Reef. Strong southeasterly trade winds reversed the current from southward to northward, with the lag between wind and currents increasing with water depth or distance offshore.

What is new is the finding of high values (up to 1,000 mg l^{-1}) of suspended solid concentration (SSC) in coastal waters. Also new is the finding of a nepheloid layer with fine sediment apparently cascading from inshore to offshore in calm weather. The high SSC occurred only during strong winds and in inshore waters. It was made visible by a band of muddy water a few km wide parallel to the coast and extending northward and southward as far as one could see from the ship. Visual observations at sea under strong winds revealed patches of muddy coastal waters moving offshore several km from the coast. Riverine sediment inflow was negligible during that period, the dry season. The material making the waters turbid in coastal waters was terrigenous mud resuspended by waves during strong winds, during strong winds no marine flow formed and the flocs remained small.

On the outer edge of the coastal band, site 4, there was a negative correlation between wind and SSC. This finding suggests that the wind waves during the study period did not resuspend sediment at that depth, and that the nepheloid layer formed consistently in calm weather. Hence the coastal mud is locally stirred by wind and currents inshore and propagates offshore in calm weather only.

In calm weather muddy marine snow formed inshore. It was similar to that described by AYUKAI and WOLANSKI (1997) and WOLANSKI *et al.* (1999) for nutrient-rich, muddy tropical coastal waters elsewhere along the muddy tropical coast of the Great Barrier Reef.

During the ship-born study of this process, calm weather prevailed. The nepheloid layer extended offshore past site 5. The currents at the time were southward with speed < 0.2 m s^{-1}. This speed was too small to entrain the bottom mud but sufficient to generate near-bottom turbulence inhibiting the settling on the bottom of suspended mud. WOLANSKI *et al.* (1992) reported a similar example of dredged mud dumped at sea, settling toward the bottom, prevented by near-bottom turbulence to reach the bottom and, instead, forming a nepheloid layer. Thus, we suggest the nepheloid layer was generated inshore and propagated offshore. Bottom turbulence associated with the prevailing current was sufficiently large to maintain the near-bottom nepheloid layer in suspension and too small to entrain the sediment upward throughout the water column. This hypothesis is consistent with the finding of a decrease in SSC in the nepheloid layer with distance offshore. It is also consistent with the negative correlation between currents and SSC at site 4, while the correlation was positive at the inshore sites 1–3.

There exists a strong negative correlation ($R^2 = 0.8$) between visibility (measured by a secci disk) and SSC (WOLANSKI *et al.*, 1981). Accordingly it was possible to compare the near-surface visibility along the transect with that measured by ORR (1933a) at Low Isles in 1927 also in the dry season. (Figure 4). Low Isles is situated North of the transect at the same distance from the shore as site 5. In 1927 human impacts on the Great Barrier Reef were probably smaller than at present because farming was less extensive though indiscriminate deforestation was underway (RATCLIFFE, 1947). The wind direction and speed during August–September were similar in 1927 and 1997, comprising periods several days to several weeks in duration of strong southeasterly trade winds, separated by periods of calm weather. Furthermore there is negligible runoff during the dry season. Thus it appears justified to compare visibility in the dry seasons of 1927 (at Low Isles) and 1997 (at site 5).

If the water visibility near Low Isles in 1927 was typical of historical conditions for this region of the Great Barrier Reef, we can only conclude that human activities already have halved the visibility. If true, this is an alarming result because it is a clear indication of a serious pollution of the Great Barrier Reef by mud following land clearing, intensive farming, dredging, removal of mangroves and other human activities increasing the discharge of mud in coastal waters.

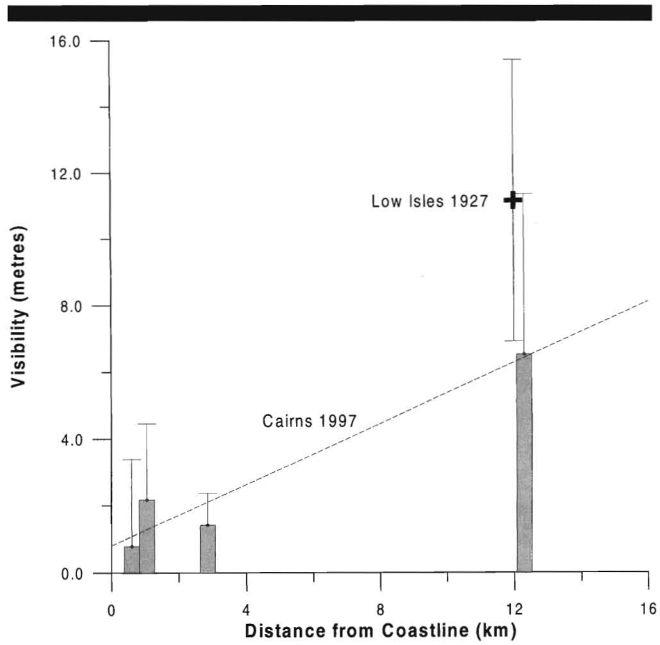

Figure 4. Mean water visibility near the surface and its standard deviation shown as error bars, at the mooring sites in August–September 1997. Note the increasing visibility with distance offshore. In 1997 at site 5 located 12 km from the coast the mean visibility near the surface was half that measured in 1927 by ORR (1933a) at Low Isles (see Figure 1 for a location map).

Intense tropical rain in the wet season (December–March) generates severe erosion of cleared in this area (WOLANSKI, 1994). Increased muddiness of coastal water results. This is apparent along the Cairns waterfront which, as historical photographs and navigation charts revealed, is now a 1.5 m thick mud layer covering what was a sandy beach 100 years ago (WOLANSKI and DUKE, 2000). Presumably mud and nutrients from land runoff may be responsible for the acute deterioration of coral reefs at Double Island (near site 2) where our underwater observations revealed that most (probably >90%) hard corals on the west side were dead, a few still had a thin coating of mud in grooves, most were completely covered by algae, and soft corals were growing over hard corals at the remaining places. At Low Isles, BELL and ELMETRI (1995) reported a shift from a predominance of hard corals in 1927 to a predominance of soft corals at present. Similar changes (ROGERS, 1983 and 1990; YAMAZATO, 1987; BELL, 1992; MCCLANAHAN and OBURA, 1997) have been observed in other places where coral reefs have been subject to increased pulses of both nutrients and mud. The mud contains most of the nutrients and these are only released into the water column during wind stirring (WALKER and O'DONNELL, 1981). The reaction of a pristine coral reef to pulses of both nutrients and mud from land runoff is presumably always negative, that is environmental degradation; recovery, if any, can vary spatially and temporally as a result of varying ecological processes (MCCOOK, 1994). The scientific problem of separating natural from human impacts on coral reefs is difficult in the presence of tropical cyclones that can occur in the wet season and may cause major geomorphologic changes to reefs (DONE, 1990). Low Isles coral reefs for instance were damaged by tropical cyclones in 1934 and 1950. However, only for the 1950 cyclone, when presumably more mud was available for resuspension as a result of erosion from cleared land, was mud explicitly mentioned as having killed corals (HILL, 1985 a and b).

If human-derived turbidity is already a problem in the dry season, it certainly is an even more serious problem during the wet season and during tropical cyclones, for which no data are available.

The finding of mud cascading from inshore to offshore in a nepheloid layer in calm weather suggests that pulses of fine terrigenous mud may also ultimately reach the main body of the Great Barrier Reef in calm weather. It would then be brought to the surface during strong trade winds. There it is diluted by the fine calcareous sediment continuously produced by pelagic forams and borers on the coral (WOLANSKI *et al.,* 1999). Present estimates of the threat to the Great Barrier Reef from terrigenous mud rely mainly on analysis of the carbonaceous content of surface sediment. This assumption assumes a quasi-steady state situation and it neglects the pulse-like intrusion of terrigenous mud. Except when the system is overwhelmed by terrigenous mud, at which time it may be too late for remedial actions, the analysis of grab samples is thus an inappropriate method.

CONCLUSION

We suspect that environmental degradation of the Great Barrier Reef will continue unabated, indeed will worsen, as land clearing continues and farming activities intensify, simply because, in practice, little is done to prevent pollution by mud notwithstanding the World Heritage status of the Great Barrier Reef. The problem is not only social and economical, it is also political because integrated coastal management is still not routinely practiced and because different agencies, indeed different governments, are responsible for managing the land on the one hand and the Great Barrier Reef on the other hand.

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