Appendix C

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The importance of wave-induced bed fluidisation in the fine sediment budget of Cleveland Bay, Great Barrier Reef

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Abstract

Data from a three-year long field study of fine sediment dynamics in Cleveland Bay show that the sediment was not resuspended during calm weather conditions, that wave-induced fluidisation of the fine sediment on the seafloor in shallow water was the main process causing bed erosion in shallow water under small waves during tradewinds, and that shear-induced erosion prevailed during cyclonic conditions. These data were used to verify a model of fine sediment dynamics that calculates sediment resuspension by both excess shear stress and wave-induced fluidisation of the bed. The riverine fine sediment discharge into the bay is short-lived and, for present land-use conditions, may exceed by 50-75% the sediment export. Sediment is thus accumulating in the bay on an annual basis, which in turn may degrade the fringing coral reefs. For those years when a tropical cyclone impacted the bay there may be a net sediment outflow from the bay. During the dry, tradewind season, fine sediment was progressively minnowed out of shallow, reefal waters.

Keywords: fine sediment, waves, erosion, deposition, model, coral, Great Barrier Reef

1. INTRODUCTION

Nutrients, fine sediments (mud), and agrochemicals from human activities on land degrade coastal coral reefs worldwide, including those of the Great Barrier Reef of Australia (Hughes and Connell, 1999; Brodie et al., 2001; Wilkinson, 2004; Pandolfi et al., 2005). The mechanisms responsible for this degradation are many, including shading and smothering benthic organisms by the mud, bio-eroders whose density is also controlled by the mud, and algal mats that grow over the coral, retain the mud and prevent the recruitment of coral larvae (Fabricius, 2005; Stamski and Field, 2006; Richmond et al., 2007; Cooper et al., 2008). The resulting degradation depends on coral species, sedimentation rates, the residence time of this mud on the corals, and the presence of transparent exopolymer particles (TEP; Fabricius et al., 2003; Philipp and Fabricius, 2003; Fabricius, 2005). Thus the fate of corals depends on the fate of the riverine mud and the latter is poorly known. Indeed, there remains much uncertainty about how much of the riverine mud reaches coral reefs (Kingsford and Wolanski, 2008; Wolanski et al., 2008) and how long in time does the mud remain near coral reefs, being available for resuspension by waves and thus causing degradation of coral reefs long after having been discharged in reefal waters by river floods (Fulton and Bellwood, 2005; Richmond et al., 2007). Thus a key parameter controlling reef degradation by riverine mud is the residence time of the mud in GBR reefal waters within reach of wave-driven resuspension events.

An estimate of this residence time is unavailable because of the paucity of data and because of difficulties in quantifying the resuspension and deposition rates of mud in tropical coastal waters. The settling velocity w_s of the suspended mud in tropical coastal waters is greatly enhanced by the biology, principally the presence of

TEP, that generates large, muddy marine snow flocs (Ayukai and Wolanski, 1997; Wolanski et al., 1998, Lumborg et al., 2006; Wolanski, 2007; Maerz and Wirtz, 2009; Pejrup and Mikkelsen, 2010). However this parameter w_s can be measured from settling experiments in the field or calculated using data from a string of turbidity meters deployed along the vertical, though not in the laboratory where the biology is absent. The settling rate, D, of the mud in suspension is then calculated following Einstein and Krone (1962)

$$D = \{C\, w_f\, (1 - (u_b/u_d)^2), \text{ if } u<u_d;\ 0, \text{ if } u>u_d) \qquad (1)$$

where C is the suspended sediment concentration (SSC), w_f is the settling velocity, u_b is the near-bottom velocity, and u_d is the threshold velocity for settling.

By contrast the erosion rate E of mud cannot be measured in the laboratory because it strongly depends on, firstly, the wave dynamics that laboratory experiments at reduced scales cannot reproduce adequately, and, secondly, on the biology, that laboratory experiments cannot reproduce either. The main biological processes determining the value of F are the competing influences of algae that make the mud less erodible and of bioturbation that makes the mud more erodible (Wolanski, 2007; Maerz and Wirtz, 2009; Andersen et al., 2010).

Commonly in the engineering literature (Partheniades, 1965 and 1986; Dyer, 1986),

$$E = \{M_e\, ((u_b/u_c)^n - 1), \text{ if } u > u_c;\ 0, \text{ if } u > u_c\ \} \qquad (2)$$

where M_e is an erosion rate that chacterises the bottom sediment properties including the effect of the biology on its erodibility, u_c is the threshold velocity for erosion, and n is a constant. Laboratory studies suggest $n = 2 - 4$, while field experiments suggest that n = 4 -6 (Johansen et al., 1997; Wolanski et al., 1995; Wolanski and Spagnol, 2003).

In the presence of waves, it is unclear how to apply Eq. (2) because waves enhance mud erosion both by increasing the bottom shear stress and by fluidising the bottom mud by generating excess pore pressure in the substrate; the fluidised mud is then brought up in suspension by tidal currents (Maa and Mehta, 1987; Aldridge and Rees, 1997). In engineering models for E, excess pore-pressure effects are commonly neglected, so that bed erosion is assumed to result from shear stresses only; thus M_e is assumed to be a constant and u_b is calculated from the combined shear stresses of the currents and the wave orbital velocity (Sheng and Lick, 1979; Soulsby et al., 1993). However bed fluidisation and the resulting bed erosion occur even if the waves are small, and these models perform poorly when tested against observations with small wave orbital velocities; indeed Maa and Mehta (1987) presented observations where fluidisation occurred for $u \ll u_c$.

Thus Eq. (2) should be modified to parameterise wave-induced fluidisation. Eq. (2) could theoretically be modified by assuming smaller values of u_c in the presence of waves. However this would over-simplify the problem because waves and erosion waves also influence M_e,

$$M_e \propto H_s^3 \tag{3}$$

or

$$M_e \propto \{(H_s - h_0), \text{ if } H_s > h_0; 0, \text{ if } H_s < h_0) \tag{4}$$

or

$$M_e \propto \{H_s - h_0)^3 \text{ if } H_s > h_0; 0, \text{ if } H_s < h_0\} \tag{5}$$

where H_s is the significant wave height and h_0 is a critical wave height whose value increases with increasing water depth (Wolanski et al., 1995; Rodriguez and Mehta, 2000; Foda and Huang, 2001; Wolanski and Spagnol, 2003). No published study has quantified how to modify both u_c and M_e to include wave-induced fluidization in Eq. (2).

This paper addresses this question in order to be able to estimate the residence time of riverine mud in reefal, coastal waters of the Great Barrier Reef. Rates of sediment transport and sedimentation in these waters are not well documented, though a wind-driven northward drift has been inferred from longshore variation of sediment composition and texture along the 10 m isobath (Lambeck and Woolfe, 2000). The study site was Cleveland Bay, Townsville (Fig. 1a). The bay is impacted by the discharge of two seasonal rivers, namely the Ross River and Alligator Creek with a catchment area of 998 km^2 and 265 km^2, respectively. Both catchments, particularly the catchment of the Ross River, are heavily impacted by human developments. Published studies of sediment dynamics in this bay were focused in the central and eastern area, far from the corals fringing Magnetic Island; this is the area with the deepest waters and where mud dredged to enable navigation was dumped for the last fifty years over a sandy mud substrate; these studies revealed that the bottom mud was stable, being resuspended only under rare swell and storm events (Wolanski et al., 1992; Lou and Ridd, 1997). There have been no published studies of mud dynamics in the shallower, reefal waters around Magnetic Island although there has been significant and recent degradation by mud of the corals fringing Magnetic Island; indeed the intertidal area between Hawkings Point and West Point was covered by sand and coral patches in 1937 and was covered by mud and muddy sand with no corals from the 1980s onwards (Wolanski, 1994).

This paper is divided in several sections. Firstly, the results of a three years long field study of mud dynamics in Cleveland Bay, are described; they show no resuspension during calm weather conditions, resuspension under small waves and small tidal currents in shallow waters during the tradewinds, and a larger, but moderate, resuspension under cyclonic conditions. Secondly, their dynamics are modelled; it is shown that Eqts. (1-5) are unable to explain the observations; these equations were modified to parameterise the wave-induced pore pressure build-up in the substrate, yielding a new, semi-empirical mud erosion law by both excess shear stresses and excess wave-induced pore pressure. Thirdly, a net fine sediment budget is derived for Cleveland bay that suggests that land-use in the adjoining river catchment results in the accumulation of riverine mud in reefal waters, which in turn may degrade the fringing coral reefs.

2. METHODS

Field studies

An Analite nephelometer was deployed on September 16, 2005, at site 1 near Magnetic Island (Fig. 1 and Table 1). Two other Analite nephelometers were deployed at sites 2 and 3 on 13th September 2007. Data were obtained at 10 min interval until the end of January 2009. Field trips were conducted on a 3- to 6-weekly basis to download data and service the instruments (Table 1). The turbidity readings were converted to suspended sediment concentration (SSC) using a calibration curve for each instrument derived using local mud from these sites.

Occasional vertical profiles of salinity, temperature, and SSC were obtained using a SeaBird CTD cum OBS.

Wind speed and direction data at 30 min intervals at site 4 were obtained from the Australian Institute of Marine Science. Significant wave height and period data at 30 min interval at 5 were obtained from the Queensland government Department of Environment and Resource Management. Current meter data were available at sites 6-8 from Wolanski et al. (1992). Tide data from the port of Townsville at 10 min interval were obtained from Maritime Safety Queensland. Data on the timing and location of dredging operations along the shipping channel were provided by the Townsville Port authority.

Ross River discharge data were obtained from the Commonwealth Bureau of Meteorology. Ross River SSC data during river floods were also provided by Z. Bainbridge (pers. comm.). Surface salinity and SSC data in Cleveland Bay during the February 2007 Ross River plume were provided by Z. Bainbridge (pers. comm.).

In-situ microphotographs of sediment flocs in suspension were obtained in January 2007.

**** MODIS data method to add here********

Numerical modelling

For the oceanography sub-model of Cleveland Bay, the non-structured grid SLIM model was used (Lambrechts et al., 2008). The near-field grid is shown in Fig. 1b; the horizontal resolution varies between 100 m near the Port of Townsville and 2 km far offshore. The model domain (not shown) covers the whole 1600 km long Great

Barrier Reef (Lybrand, 2006). The model forcings were the East Australian Current, the wind, the tides, and, during the wet season, the Ross River discharge. This oceanographic model was used to drive a fine sediment dynamics model that relied initially on Eqts. (1-5) for calculating settling and resuspension; these equations were modified to calculate bed erosion under both excess shear stresses and excess wave-induced pore pressure in the substrate, and this is explained below in the results.

3. RESULTS

Fine sediment dynamics in the dry season

This is also called the tradewind season and typically it lasts from April to November. The SSC data at Middle Reef (and at the other two sites, not shown) show (Fig. 2a) that tidal currents were too small by themselves to resuspend the bottom sediment. In a 0D model, the predicted SSC was calculated using Eq. (5) assuming $h_0 = 0.2$ m. The encouraging comparison between predicted and observed SSC (Fig. 2a), suggests that resuspension occurred only in the presence of waves. Thus resuspension occurred in a series of events controlled by waves. A few of events at the end of the dry season, labelled A, B, and C, were overpredicted by the 0D model (Fig. 2a). As is shown in Fig. 2b, during each event the mud was resuspended during periods of maximum significant wave height and wave period, and also varying with the tides. The 0D model overpredicted the duration of the resuspension events.

Water leaving radiance in MODIS images were used to visualise the near-surface SSC distribution during the tradewind season. These images show (Fig. 3) a near-surface SSC that was maximum inshore and decreased seaward, forming a turbid coastal boundary layer; within this layer the SSC distribution was however patchy, with highest values near headlands.

Fine sediment dynamics in cyclonic conditions

Data were collected during January 2009 under cyclone Hamish. The SSC values generally decreased seaward, varied weakly with the tides, and showed a long period of weakly-varying, quasi steady, SSC during, and for about one day after, the storm (Figure 4a).

Fine sediment dynamics during river floods

The February 2007 Ross River flood plume waters moved longshore northward past Middle Reef but not reaching Magnetic Island. Ship-born observations (not shown) revealed near-surface SSC in the plume decreasing with distance from the mouth at a faster rate than that predicted by salinity, being at 10 mg l^{-1} at Middle Reef while the salinity was about 25. At the Middle Reef mooring site the average SSC at 4.4 m depth during the peak of the flood was about 14 mg l^{-1}, with instantaneous peak values of 24 mg l^{-1}.

Modelling

The oceanography model reproduced well (not shown) the current meter observations at the sites 6-8. During calm weather conditions the flood tidal currents enter Cleveland Bay both east and west of Magnetic Island at peak speeds of ~ 0.2 m s^{-1}. In calm weather the flood tidal currents converge towards a stagnation line in West

Channel (see Fig. 1a). The tidal currents diverge from that line at ebb tides. During strong wind events in the tradewind season, this stagnation line is shifted westward to West Point. During cyclone Hamish the currents in West Channel did not reverse sign with the tides and were longshore northward at velocity peaking at 0.7 m s^{-1} (not shown).

These data were also used to calibrate the fine sediment dynamics model for wave-dominated muddy, shallow waters. Because the suspended sediment was in the flocculation-enhanced settling range and because the flocs were of similar size and shape as in the tropical Fly River estuary and King Sound (not shown), the dependence of w_f (m s^{-1}) on C (kg m^{-3}) was assumed to be the same (Wolanski et al., 1995; Wolanski and Spagnol, 2003),

$$w_f = \min(0.01\ C, 0.003) \qquad (6)$$

Using Eqts. (2)-(5) the model was unable to reproduce all the observations, i.e. during calm weather, during tradewinds, and during cyclonic conditions. In Cleveland Bay, u_c ~0.3 m s^{-1} (Wolanski et al., 1992; Lou and Ridd, 1997). During tradewinds, the largest waves had H_s ~ 0.8 m and T_s ~ 4 s (Fig. 2b); assuming linear wave theory, these waves thus generated a small additional shear stress which, using Eq. (2) is unable to account for the observed bed erosion except if u_c decreases by 45% by wave-induced bed fluidisation. If this decrease is proportional to H_s, the resulting model predicted unrealistically large (by a factor of 10 to 100) the observed SSC values during cyclone Hamish (not shown).

Eq. (2) was thus unable to reproduce the observations under tradewinds and cyclonic conditions. A new method was thus necessary to calculate bed erosion due to shear stresses and wave-induced excess pore pressure. Accordingly, the resuspension model was modified to explicitly parameterise wave-induced pore water pressure build-up. Accordingly, the erosion (E) was modeled as

$$E = E_1 + E_2 \qquad (7)$$

where E_1 is the erosion due to wave-induced pore pressure build-up and resulting fluidization of the bed which can then eroded without a need for high velocities greater than u_c, and E_2 is the classical Partheniades equation for erosion by excess shear stress that can occur without wave-induced pore pressure bed-up and fluidization of the bed,

$$E_1 = A_1 \ (W/W_o)^3 \ F(|V|/u_o)^n \qquad (8)$$

$$E_2 = \{A_2 \ (((|V|/u_o)^n - 1), \text{ if } |V| > u_o; \ 0 \text{ if } |V| < u_o\} \qquad (9)$$

where it was assumed that excess pore-pressure build-up is proportional to wave-induced pressure fluctuations on the seafloor so that (Kuo and Chiu, 1994; Tsai et al. 2005),

$$F = H_z \exp(-0.95 \ \omega^2 \ H/g - 0.0207) \qquad (10)$$

where ω is the wave frequency, H is the total depth, g is the acceleration due to gravity, and A_1 and A_2 are empirical constants that depend only on the characteristics of the fine sediment on the seafloor and not on the oceanography. The model was successful in reproducing the SSC observations at Middle Reef during tradewinds (Fig. 2b) and during cyclonic conditions (Fig. 4b), as well as correctly predicting no resuspension during calm weather conditions. The model also predicted a spatial distribution of SSC that qualitatively matched that of MODIS images (not shown), though a quantitative comparison is not feasible because there is no reliable method to convert MODIS light leaving radiance values to SSC values.

5. DISCUSSION

The fine sediment in Cleveland Bay was mobile in quantity only during a number of discrete events, namely during river floods, during tradewinds, and during cyclones. During calm weather conditions the bottom sediment was not resuspended. It was resuspended during strong tradewinds, although the waves were small and, from linear wave theory, only marginally increased the bottom shear stress. The classical Partheniades formula for bed erosion failed in such conditions. It is argued that this formula needs to be modified to parameterise wave-induced excess pore pressure build-up, so that ultimately the bed erodes only by wave-induced bed fluidisation during strong tradewinds, and by both excess shear stresses and wave-induced bed fluidisation under cyclonic conditions. Such a formula is proposed as Eqts. (7-10) that satisfactorily reproduces the observations across a wide range of oceanographic conditions without changing the two empirical coefficients (A_1 and A_2) between these different oceanographic conditions.

Based on the data and the model, the following fine sediment budget for Cleveland Bay is proposed. The Ross River gauging data during the 2007 river flood show a fine sediment discharge to Cleveland Bay of ~ 40000 tons, a value that greatly exceeds the long-term average sediment discharge of 250 tons y^{-1} estimated by Belperio (1983). This discrepancy may be due to the scarcity of data in the 1980s on which that estimate was based, as well as to increased land clearing in the Ross River catchment since that time. During windy days in the tradewind season the SLIM model suggests that a negligible amount of fine sediment is exported seaward from Cleveland Bay along the eastern shore of Magnetic Island and that fine sediment in suspension is exported longshore northward through West Channel at a rate of ~ 860 tons day^{-1}. As there are typically 20-30 days of strong tradewinds per year, the annual export is ~ 17200 - 25880 tons y^{-1}. Thus, in 2007, a year when there was no cyclone impacting the bay, fine sediment accumulated in Cleveland Bay at a rate of ~ 14000 – 22000 tons y^{-1}. A fraction of that sediment accumulated in the deeper waters of Cleveland Bay where tradewinds cannot resuspend it; the remaining sediment accumulated in areas where it was frequently resuspended by waves under tradewinds, thus increasing turbidity and stressing the seagrass and corals, and ultimately a fraction of that accumulated in sheltered areas such as the previously sandy and now muddy intertidal area between Hawkings Point and West Point (see Fig. 1a).

The data show (Fig. 2a) that fine sediment was resuspended in smaller quantity than at the beginning of the dry season, for the same wind/wave conditions This suggests that during the dry season the fine sediment was exported away to deeper waters and that the bed in shallow reefal waters was progressively armoured by minnowing.

For management this may be the most significant finding of this study, namely that reducing the amount of riverine fine sediment inflow into Cleveland Bay would reduce the length of time that high turbidity prevails, thus providing better quality water for seagrass and corals. Order of magnitude estimates suggest that if land-use management policies were implemented to reduce by a factor of 4 to 10 the Ross

River fine sediment discharge, approximating the historical pristine conditions of 4000 – 10000 tons y^{-1}, this fine sediment would be exported from Cleveland Bay in ~ 5 – 12 days of strong tradewinds. Since there are about 20 - 30 such days in a year, this sediment would be exported after typically ~ 90 - 160 days in the tradewind season. Therefore for the rest of the dry season clear waters would prevail even under tradewinds; in turn this would promote seagrass and reef growth.

Tropical cyclones are rare but their effect on the sediment budget is major. The model predicts that Cyclone Hamish exported Cleveland Bay fine sediment both through West Channel at a rate of ~ 34000 tons and seaward along the east coast of Magnetic island at a rate of ~ 16000 tons. The sediment in the deeper parts of Cleveland Bay that is not mobilised during tradewinds is mobilised during cyclones. Also, fine sediment from other bays further south may enter Cleveland Bay during a cyclone, as suggested by Belperio (1983); however no oceanographic data are available to estimate this effect.

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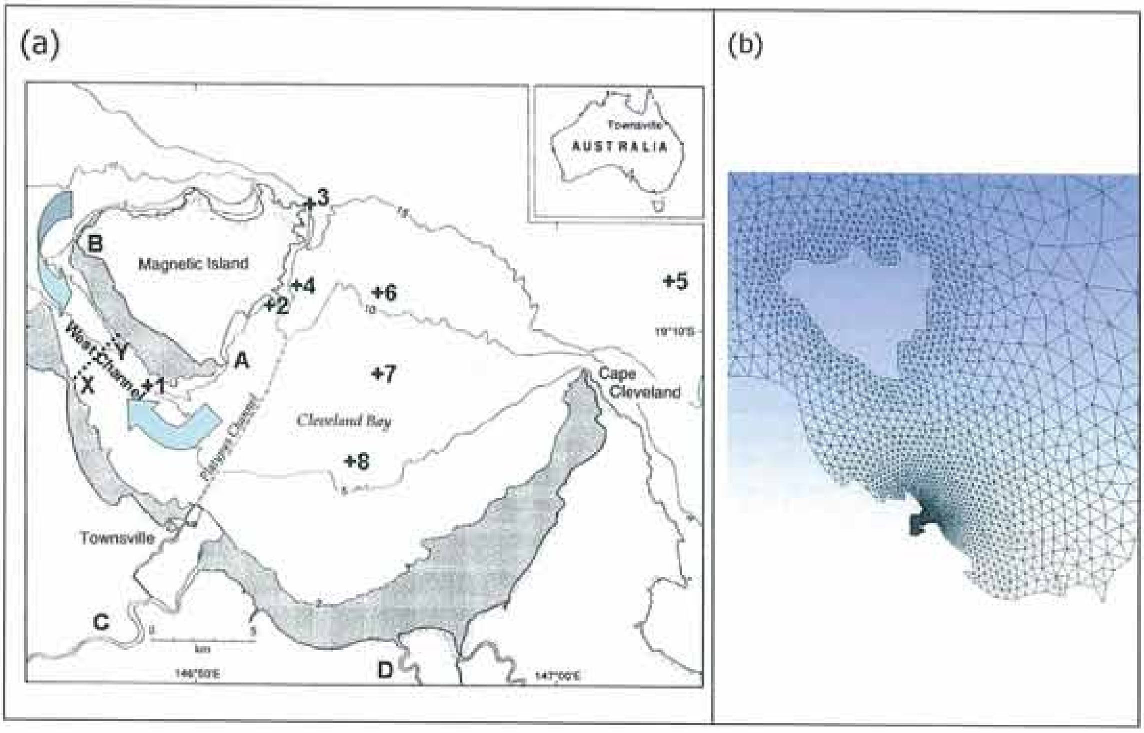
TEXT FOR FIGURES

Figure 1. (a) A chart of Cleveland Bay showing the location of the SSC measurements at sites 1-3, the weather station at site 4, the wave rider buoy at site 5, and the current meter moorings at sites 6-8. Depth is in m. (b) The near-field grid of the oceanographic model. The arrows show the flood tidal currents entering West Channel and converging at the stagnation line X-Y during calm weather. The ebb tidal currents during calm weather diverge from the same line. A= Hawkings Point, B= West Point, C= Ross River, D= Alligator Creek. Platypus Channel is a dredged navigation channel, West Channel is natural.

Figure 2. (a) Time-series plot of (a) dredging activities (1 = dredging; 0= no dredging), (b) Ross River discharge, and (c) observed and (d) predicted SSC at Middle Reef. A, B, and C refer to events nearer the end of the dry season where high SSC values were predicted but not observed. The Ross River discharge lasted only about 10 days during the wet season. (b) Time-series plot of the sea level, significant wave height H_s and period T_p, and observed and predicted SSC during the southeasterly wind event of day 609-612. Time is in day number from 1 January 2005.

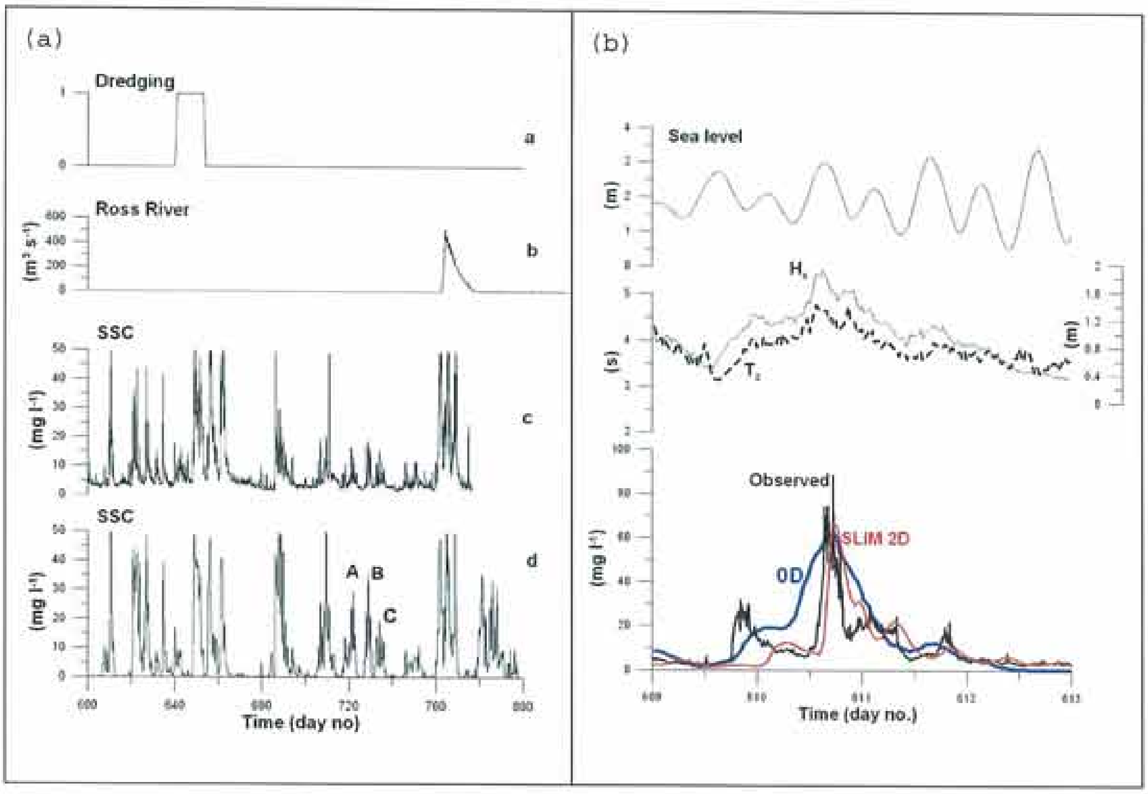
Figure 3. Distribution of the MODIS normalised water leaving radiance 645nm, at horizontal resolution of 250 m, on (a) July 27, 2009, at 1350 h, at slack high tide; (b) August 1, 2009, at 1410 h, 1 h into the rising tide. The black arrows show the wind speed and direction. The black bands along the coast are pixels that are suspected of being contaminated by the land signal.

Figure 4. (a) Time-series plot for the January 2009 storm of the sea level, the wind (using the oceanographic convention), the significant wave height H_s, wave period T_z, and wave direction, and the suspended sediment concentration (SSC) at the mooring sites. (b) Time-series plot of the observed and predicted SSC at Middle Reef. Time is in day number in 2009.



(a)
(b)
Townsville
AUSTRALIA
+3
B
Magnetic Island
+4
+6
+5
+2
A
19°10'S
West Channel
+1
Y
X
+7
Cape Cleveland
Cleveland Bay
Platypus Channel
+8
Townsville
C
D
km
146°50'E
147°00'E

Figure 1



(a)
Dredging
a
Ross River
(m³ s⁻¹)
b
SSC
(mg l⁻¹)
c
SSC
(mg l⁻¹)
d
A
B
C
Time (day no)
(b)
Sea level
(m)
Hs
Tz
(s)
(m)
Observed
SLIM 2D
0D
(mg l⁻¹)
Time (day no.)

Figure 2.

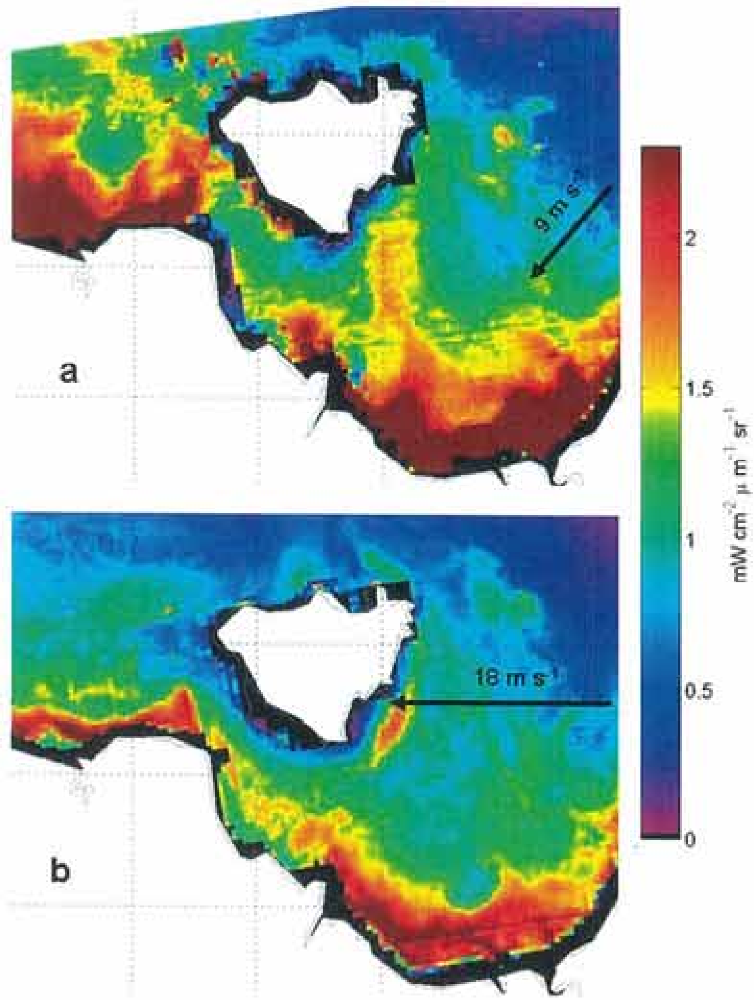
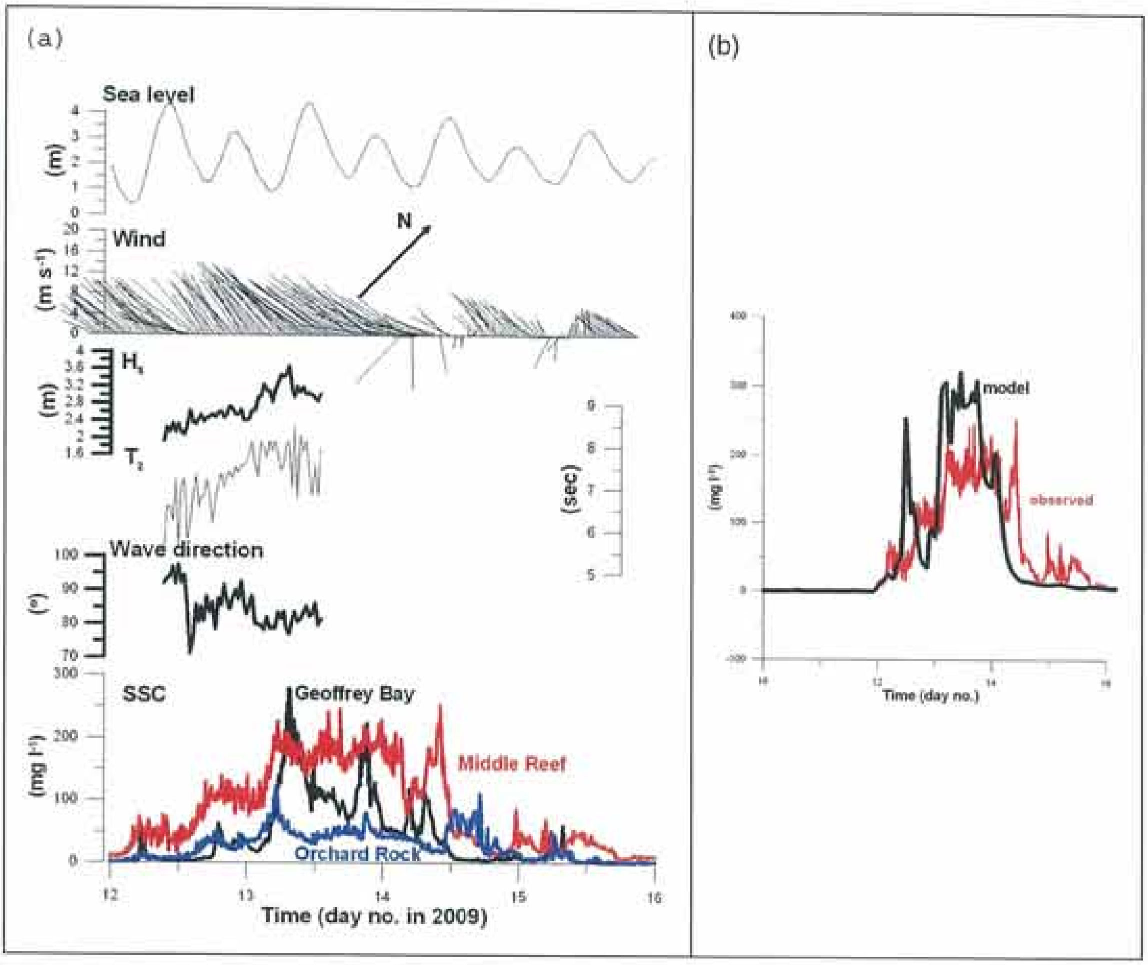


Figure 3



(a)
Sea level
(m)
Wind
(m s-1)
N
Hs
(m)
T2
(sec)
Wave direction
(°)
SSC
(mg l-1)
Geoffrey Bay
Middle Reef
Orchard Rock
Time (day no. in 2009)
(b)
model
observed
(mg l-1)
Time (day no.)

Figure 4

Table 1. The nephelometer mooring sites around Magnetic Island.

Site	Name	Location	Characteristics
1	Middle Reef	19° 11.972 S 146° 49.097 E	The logger was ~0.5 m above the seafloor made of soft, fine sediment. Maximum depth ~ 4.9 m below LAT
2	Geoffrey Bay	19° 09.29 0S 146° 52.111 E	The logger was located on the lower end of the reef slope, ~0.5 m above the seafloor made of ~50% hard substratum and 50% coral rubble Maximum depth ~ 5.5 m below LAT
3	Orchard Rocks	19° 06.655 S 146° 52.807 E	The logger was located on the island slope ~0.5 m above the seafloor that was a combination of coral outcrops, granitic bed rock, and fine sediment. Maximum depth ~ 6.4 m below LAT