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The effects of river run-off on water clarity across the central Great Barrier Reef

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ABSTRACT

Changes in water clarity across the shallow continental shelf of the central Great Barrier Reef were investigated from ten years of daily river load, oceanographic and MODIS-Aqua data. Mean photic depth (i.e., the depth of 10% of surface irradiance) was related to river loads after statistical removal of wave and tidal effects. Across the ~25,000 km^2 area, photic depth was strongly related to river freshwater and phosphorus loads ($R^2 = 0.65$ and 0.51, respectively). In the six wetter years, photic depth was reduced by 19.8% and below water quality guidelines for 156 days, compared to 9 days in the drier years. After onset of the seasonal river floods, photic depth was reduced for on average 6–8 months, gradually returning to clearer baseline values. Relationships were strongest inshore and midshelf (~12–80 km from the coast), and weaker near the chronically turbid coast. The data show that reductions in river loads would measurably improve shelf water clarity, with significant ecosystem health benefits.

1. Introduction

Water clarity or transparency is a key factor for marine ecosystems, affecting the resource supply for photosynthetic organisms and filter feeders. Coral reefs and seagrass meadows are built by photosynthetic organisms, and are therefore highly sensitive to changes in water clarity. Reduced water clarity leads to reduced coral biodiversity and increased macroalgal cover (De'ath and Fabricius, 2010), shifts in communities towards heterotrophic filter feeders (Birkeland, 1988), and a proliferation of filter-feeding macro-bioreordering organisms that weaken the structural integrity of coral reefs (LeGrand and Fabricius, 2011). Prolonged shading from reduced water clarity also limits the depth distribution of coral reefs, with an apparent threshold at ~6–8% of surface irradiance as absolute minimum for reef development (Cooper et al., 2007), and the lower depth limit of seagrasses (Duarte, 1991; Collier et al., 2012).

It is clearly established that the water clarity in shallow shelf seas is adversely affected by sediment resuspension from waves and currents (Larcombe et al., 1995; Wolanski et al., 2005; Piniak and Storlazzi, 2008; Storlazzi and Jaffe, 2008; Storlazzi et al., 2009; Fabricius et al., 2013). However it remains poorly understood for how long and by how much river runoff of sediments and nutrients will affect water clarity in shelf seas. For the Australian Great Barrier Reef (GBR), terrestrial runoff is of great concern (Brodie et al., 2011; Brodie and Waterhouse, 2012). Over 30 major rivers discharge sediments and nutrients from increasingly developed catchments into the shallow and wide continental shelf sea, which contains the >3000 coral reefs, ~40,000 km^2 of subtidal inter-reefal seagrass meadows and many other interreefal marine habitats that constitute this large World Heritage area. Rivers now discharge 17 million tonnes of suspended sediments, 80,000 tonnes of nitrogen, and 16,000 tonnes of phosphorus annually into the GBR, an 3–8-fold increase compared to pre-European times (Kroon et al., 2012). Satellite images derived from the Moderate Imaging Spectroradiometer (MODIS) document reduced water clarity within the river plumes, and show that long-shore currents transport their particulate loads (silt, clay, plankton and organic rich sediment flocs) for tens to hundreds of kilometers northwards away from the river mouths, and typically remain initially within ~5 km of the coast (Brodie et al., 2010; Bainbridge et al., 2012). After the plume has dissipated, these newly imported sediments continue to undergo repeated cycles of resuspension and deposition, until they eventually settle in wave-sheltered embayments or offshore beyond the depth of wave resuspension (Orpin et al., 2004; Wolanski et al., 2008; Bainbridge et al., 2012). Nepheloid flows and tropical cyclones can shift significant amounts of coastal sediments into deeper offshore waters (Gagan

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et al., 1990; Wolanski et al., 2003). Seafloor sediments are dominated by terrigenous materials from the shore to about 20 m depth, but consist mostly of biogenic carbonates further offshore (Belperio and Searle, 1988).

Substantial recent management efforts to reduce the terrestrial runoff of nutrients and sediments into the GBR have led to small but significant reductions in end-of-river sediment and nutrient loads (State of Queensland, 2013). However, both the intra- and inter-annual time-scale of burial or export of such newly imported fine sediments (with residency times beyond that of acute floods) remain poorly understood. Water clarity is typically low in the shallow coastal and inshore zone (De'ath and Fabricius, 2010; Weeks et al., 2012), but within that zone, it is up to 10-fold lower near, compared to away from river mouths, suggesting a long-term accumulation of river derived resuspendible sediments on the seafloor (Fabricius et al., 2013).

Newly imported materials are assumed to be retained on the shelf for decades to centuries, suggesting that the effects of water quality improvements may become measurable within the marine environment only at a time scale of decades (Brodie et al., 2012; The State of Queensland and Commonwealth of Australia, 2009). Fabricius et al. (2013) documented that water clarity in the GBR after floods returned to clear values within weeks to years, rather than years to decades. However, that study was limited to coastal and inshore waters and the three year-long instrumental record was too short to assess inter-annual variation in water clarity. The present study significantly expands this work, and used a novel approach (outlined below) to assesses the relationship between terrestrial runoff and daily changes in water clarity across the ~120 km wide continental shelf of the GBR over a period of 10 years.

'Photic depth' ($Z_{\%}$; unit: m) is a measure to quantify light availability (as photosynthetically active radiation, PAR) relative to the light at the water surface. For example, the water depth of the euphotic zone, $Z_{1\%}$, reflects the depth where PAR is 1% of its surface value, and $Z_{10\%}$ is the photic depth for 10% of surface PAR (Lee et al., 2007; Weeks et al., 2012). Photic depth depends on the light attenuation in the water column, which is traditionally quantified from remote sensing data as the diffuse attenuation coefficient of the downwelling spectral irradiance at 490 nm wavelength, K_{d490}, or the photosynthetically available radiation, K_{dPAR} (Saulquin et al., 2013). Light attenuation is diminished by suspended abiotic and biotic particulate matter (esp. clay- and fine silt sized particles) and some dissolved substances. Photic depth can therefore be used as a measure of water clarity (Lee et al., 2007).

In optically complex waters, semi-analytical algorithms typically provide better results than traditional empirical algorithms to convert the ocean color signal into biogeochemical quantities (IOCCG, 2006). Lee et al. (2002, 2007) derived photic zone depths ($Z_{1\%}$, $Z_{10\%}$ and $Z_{50\%}$) semi-analytically from spectral remote-sensing reflectance using a model based on the inherent optical properties of water and a suite of *in situ* measurements. $Z_{1\%}$ and $Z_{10\%}$ values were found to be, on average, within 14% of the *in situ* values, both within complex coastal and shelf waters as well as oceanic waters, and across different seasons. Historically, ocean transparency has been most often measured using Secchi disk as a useful index of water quality. Doron et al. (2011) adapted Lee's algorithm to estimate Secchi depth from satellite ocean color data using an extensive set of coincident satellite and *in situ* measurements (>400 matchups) from both coastal and oceanic waters. A recent study evaluated K_{dPAR}, $Z_{1\%}$ and K_{d490}, derived with three bio-optical algorithms applied to Moderate Imaging Spectroradiometer (MODIS) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) observations, using optical data from the coastal waters off South Florida and the Caribbean Sea (Zhao et al., 2013). The algorithm by Lee et al. (2007) showed the overall best performance, while empirical algorithms performed well for clear offshore waters but underestimated K_{dPAR} and K_{d490} in coastal waters. Zhao et al. (2013) suggested their findings lay the basis for synoptic time-series studies of water quality in coastal ecosystems, although more work is required to minimize bottom interference in optically shallow waters.

This study uses a new approach to assess the relationships between the terrestrial runoff of freshwater and its associated fine sediments and nutrients to the daily to inter-annual variation in water clarity, using the central section of the shallow GBR continental shelf as a model system. The study was based on 10 years of remote sensing and environmental data (2002–2012), a new GBR-validated photic depth algorithm for MODIS-Aqua data (Weeks et al., 2012) and statistical models. The study shows that annual mean water clarity in the central GBR is strongly related to discharges by the large Burdekin River. The study then assessed the spatial extent (inshore to ~120 km offshore) and the duration of reduction in water clarity beyond the duration of the flood plumes. The results suggest that reductions in the sediment and nutrient loads of the Burdekin River will likely result in significantly improved water clarity downstream of the river mouth and across much of the central GBR, both during the wet season and throughout the following dry season.

2. Methods

2.1. MODIS data: photic depth

Water clarity was calculated by applying a GBR-validated 'photic depth' algorithm to MODIS-Aqua, i.e., determining the depth where 10% of the surface light level is still available (GBR $Z_{10\%}$). The method is fully described in Weeks et al. (2012). In brief: GBR $Z_{10\%}$ was calculated with the algorithm of Lee et al. (2002, 2007) based on the regression coefficients of satellite data against GBR Secchi depth data. Many of the >5000 records of Secchi depth (collected by the Australian Institute of Marine Science and the Queensland Department of Primary Industries and Fisheries between 1994–1999 and 1992–2012) pre-dated the MODIS-Aqua satellite data (2002–2012), hence both MODIS-Aqua and SeaWiFS data (1997–2010) were used. Satellite to *in situ* "matchups" ($Z_{10\%}$) for the Secchi data were acquired from the NASA Ocean Biology Processing Group. Stations in optically shallow water, where the signal is affected by light reflection from the sea floor, were excluded. A Type II linear regression of log-transformed satellite and Secchi values was applied, to then estimate GBR $Z_{10\%}$ as:

$$\text{GBR } Z_{10\%} = 10 \wedge [(\log_{10}(Z_{10\%}) - a_0)/a_1] \quad (1)$$

where a_0 and a_1 are slope and intercepts of satellite data against Secchi (values: 0.518 and 0.811 for SeaWiFS, and 0.529 and 0.816 for MODIS-Aqua). GBR $Z_{10\%}$ was implemented into the NASA satellite processing software (SeaDAS) and applied to the full time series of MODIS-Aqua data (01 July 2002 to 21 November 2012).

The large Burdekin River with its 133,400 km^2 catchment area is the single greatest source of suspended sediments into the GBR lagoon (mean: 4 million tonnes yr^{-1}, representing ~25% of total loads entering into GBR; Kroon et al., 2012). A mask was generated for the continental shelf off the Burdekin Natural Resource Management region (~17.9–20.1°S and 146.3–149.3°E), extending from the shore to the 200 m depth contour, and excluding coral reefs (Fig. 1). To the best of our knowledge, grid points in optically shallow water were also excluded. The final data contained 25,621 grid points each covering a 1-km^2 area. Data availability varied greatly between days and months due to cloud cover.

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