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Terrestrial discharge into the Great Barrier Reef Lagoon: nutrient behavior in coastal waters

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Abstract

Pollution of coastal regions of the Great Barrier Reef World Heritage Area (GBRWHA) is dominated by river discharge associated with agricultural development of the adjacent catchments. Runoff of sediment, nutrients and pesticides has sharply increased since European settlement. Since 1991 plumes from river discharge entering the GBRWHA have been mapped by aerial mapping of plume edges and concentrations of contaminants in plumes measured. Plume dispersion is governed primarily by wind speed and direction. Most plumes spread in a band up to 50 km from the coast. Particulate material discharged in the plumes is trapped within 10 km of the coast. Dissolved nutrients disperse much further and elevated nutrient concentrations are measurable at distances of hundreds of kilometres from river mouths. This differential transport of particulate versus dissolved nutrients is important for the potential effects of these materials and management of their generation on the Great Barrier Reef catchment.

Keywords: Flood plumes; Great Barrier Reef; Land runoff; Nutrients; Suspended sediment; Water quality

1. Introduction

The Great Barrier Reef World Heritage Area (GBRWHA) lies adjacent to the Queensland coast, primarily on the continental shelf, between 9° S and 24° S (Fig. 1). The shelf varies in width from 50 km in the north to over 200 km in the south and can be arbitrarily divided into an inner shelf immediately adjacent to the coast, with depths to 20 m, a middle shelf with depths of 20–40 m and an outer shelf with depths of 40–100 m (Fig. 2). The inner shelf is significantly influenced by the adjacent coast with sediments dominated (greater than 80%) by terrestrial material (Maxwell, 1968). The middle shelf is a sediment starved area while outer shelf sediments are carbonate dominated. The open water of the Great Barrier Reef (GBR) in which the reefs are embedded is commonly known as the GBR lagoon.

Approximately 900 'inshore' reefs are found on the inner shelf along with large areas of seagrass (about 4000 km^2 in total, Lee Long et al., 1993) and mangrove forest (about 2070 km^2, Wachenfeld et al., 1998). The middle shelf has few reefs and relatively small areas of deepwater seagrass. Large areas of *Halimeda* algal banks (~2000 km^2) occur between 13° S and 15° S on the middle shelf (Drew and Abel, 1988; Wachenfeld et al., 1998). The outer shelf contains the majority of GBR reefs (~2000) with minor amounts of seagrass. One of the most important processes directly impacting the Great Barrier Reef (GBR) is the input of terrestrially derived nutrients and sediments to near shore regions. This mainly occurs via river runoff, especially during periods of intense rainfall typically associated with tropical cyclones. New nutrient (nitrogen and phosphorus)

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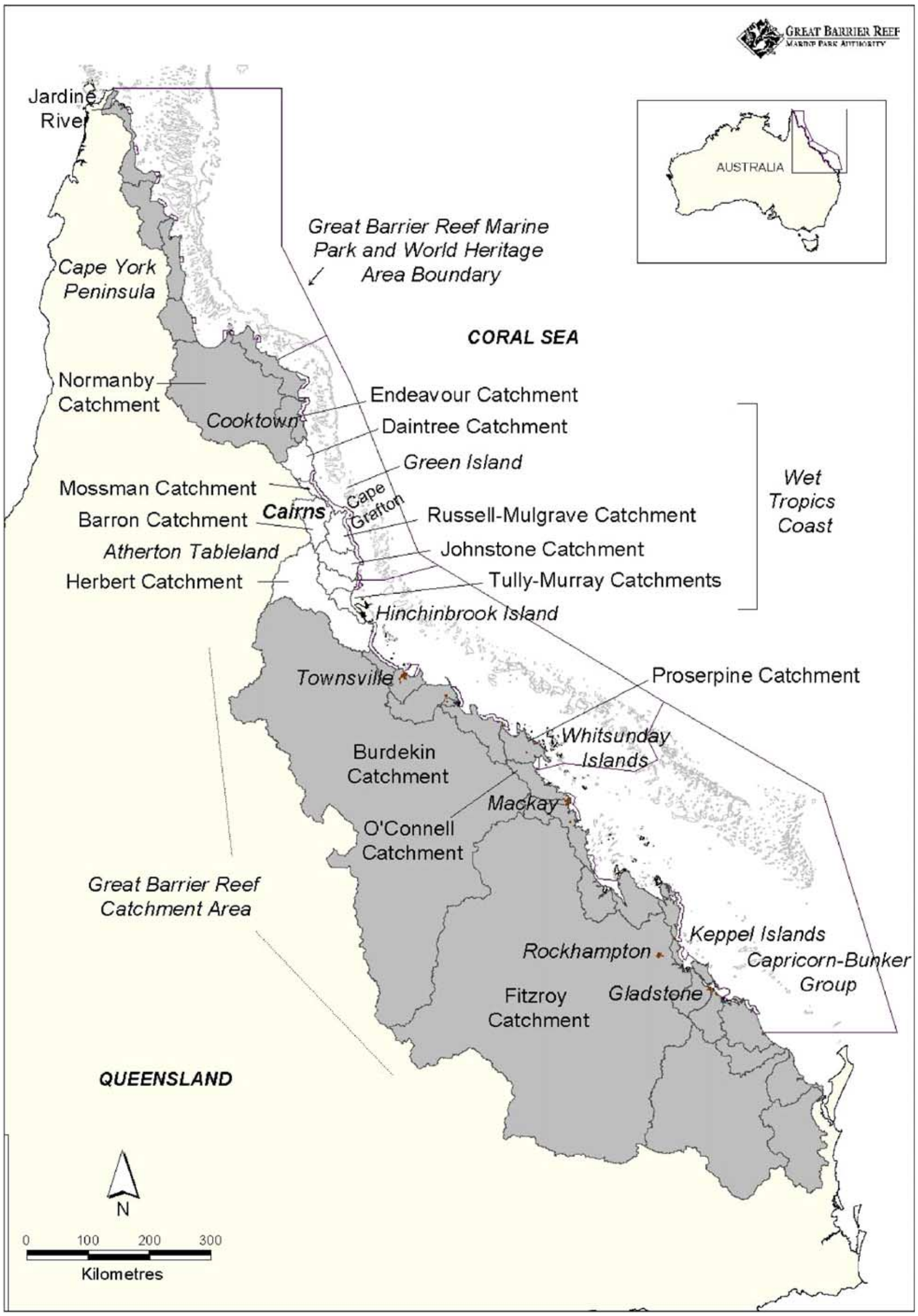

Fig. 1. The Great Barrier Reef and its catchments.

inputs to GBR ecosystems are dominated by river runoff which contributes on average 30% of the total N and 39% of P to the central GBR (Furnas et al., 1997). Other sources are Coral Sea upwelling (12% of N, 39% of P), rain (16% of N, 11% of P) and nitrogen fixation (38% of N). However nutrient usage in biological uptake is dominated by internal recycling with new inputs only comprising 27% of the demand for N and 18% for P (Furnas et al., 1997). On the inner shelf new inputs come primarily from terrestrial runoff while on the middle and outer shelf upwelling and nitrogen fixation are more important (Furnas and Mitchell, 2001).

The primary land uses on the catchment of the GBR are rangeland beef grazing (77%) and cropping, particularly sugarcane cultivation (1%), horticulture (0.2%) and cotton (0.2%) (Gilbert et al., 2003). The development of the GBR catchment since European settlement (≈1850) has led to large increases in the discharge of sediments and nutrients to the GBR (Moss et al., 1992; Furnas, 2003; Neil et al., 2002). Recent modelling studies have

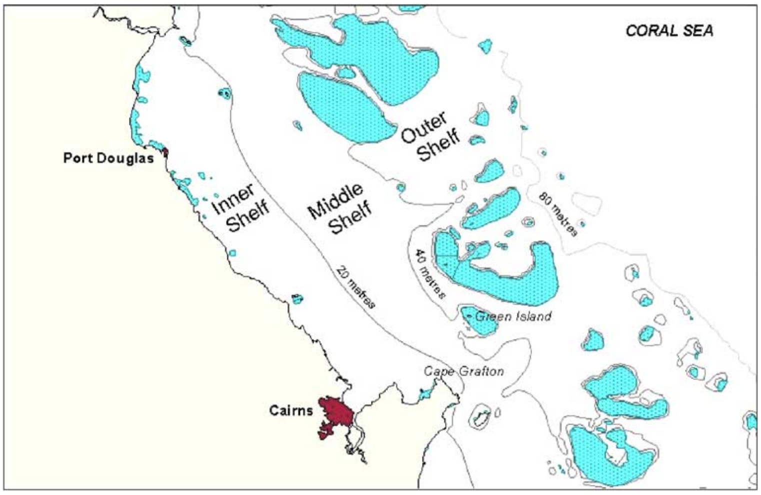

Fig. 2. Offshore Cairns, the three shelf divisions and reef areas.

estimated that sediment yield has risen by a factor of four, total nitrogen by a factor of three, nitrate and total phosphorus by 10 (Furnas, 2003; Brodie et al., 2003). The increased sediment and particulate nutrient flux is largely due to soil erosion, particularly on grazing lands, while increased dissolved nutrient flux is often associated with fertilizer use and loss (Johnson et al., 2001; Mitchell et al., 1997; Furnas and Mitchell, 2001; Mitchell et al., 2001). In rivers where there is enough monitoring data to show trends, the concentration of nutrient species such as particulate nitrogen (PN) and nitrate are significantly increasing. In the Tully River (Mitchell et al., 2001) mean baseflow PN concentrations have risen by 100% from about 100 to $200\,\mu\mathrm{g\,l}^{-1}$ in the period 1987–2000 while mean baseflow nitrate concentrations rose by 16% in the same period.

Discharge of terrestrial material to the GBR occurs predominantly during the major river floods generally associated with cyclonic rainfall events between November and May. The output from individual rivers varies from those such as the Tully which have multiple major flows each year, to those such as the Herbert and Pioneer which generally have one major annual flow, and those such as the Burdekin and Fitzroy in which major flows are separated by periods of 4–10 years. One of the defining features of the rivers is the sharp division between a wet season state, lasting a short period annually (one to eight weeks) and a prolonged dry season condition. In the dry season little or no freshwater discharge occurs and the estuary behaves as a tidal inlet with a sharp division between freshwater (zero salinity) and seawater (salinity −36‰). In the dry season reprocessing of materials occurs such as movement of sediments up the coast and subsequent trapping in north facing bays and mangroves (Larcombe et al., 1995; Wolanski, 1994). In the wet season, the estuaries are totally river dominated with the 'estuarine' mixing zone where the salinities range from 0‰ to 36‰, lying outside the river mouth on the continental shelf, i.e. an 'estuarine plume zone' or 'riverine plume' type (Dagg et al., 2004). A salt wedge exists but lies outside the river itself as the river flushes fresh throughout its depth profile completely to the sea. This estuarine behaviour, quite different to many temperate rivers (Eyre, 1998) has important consequences for delivery of materials from the land to the sea. All direct processing of materials discharged from the catchment occurs in the wet season when almost 100% of input of these materials takes place. This input of bio-relevant elements, along with the complex physical structure of river plumes, leads to strong gradients in concentrations of, and transformations among, biochemical constituents in plume environments. In general, the fate of the organic matter and its constituent nitrogen, phosphorus and carbon, is mineralisation, uptake, sinking and dilution. Nutrient cycling in plumes can not only change total nutrient loads but also modify ratios of one nutrient to another.

The distribution of flood plume waters in the GBR has been studied opportunistically over the last 30 years in some detail but observations of river water in the GBR lagoon were noted and documented at many times earlier in the 20th century. For example low salinity water was recorded at Low Isles (16 km offshore) during the 1928/1929 British Museum Great Barrier Reef Expedition coinciding with flooding in the adjacent Barron and Daintree Rivers (Orr, 1933). The effects of low salinity water on the reefs of the Whitsundays, associated with major cyclones near Mackay in 1918 were reported by Hedley (1925) and Rainford (1925). In the 1960s low salinity water was noted in the wet season well offshore in the Cairns area (Pearson and Garrett, 1978). Davies and Hughes (1983) noted terrigenous sedimentation in 1982 at Boulder Reef (15 km offshore) associated with flooding in the Endeavour River. Wolanski and associates led a period of more detailed study of flood plumes in the 1978–1983 period focussed on the Burdekin River. Plumes were tracked using salinity measurements in both the 1979 (Wolanski and Jones, 1981) and 1981 Burdekin floods (Wolanski and van Senden, 1983). Burdekin plume water was shown to move north from the river mouth and was detectable up to 300 km from the mouth (Wolanski and van Senden, 1983). Plume water distribution was governed by geostrophic forces—particularly the wind regime and Coriolis effect (Wolanski, 1994).

The effects of the major 1991 flood in the Fitzroy River on reefs impacted by the river plume was dramatic. Low salinity, high suspended solids and nutrient-rich water surrounded reefs of the Keppel Islands group (20 km offshore) for a period of three weeks (Brodie and Mitchell, 1992; O'Neill et al., 1992) and reached the northern reefs of the Capricorn-Bunker group (75 km offshore) for a few days (Devlin et al., 2001). Coral mortality in the Keppels was high (van Woesik et al., 1995) with some mortality in the Capricorn-Bunkers (Devlin et al., 2001). In the same cyclonic rainfall the Burdekin River plume was detected 30 km off Townsville (100 km from the river mouth) with a frontal area of high productivity and larval fish abundance (McKinnon and Thorrold, 1993; Thorrold and McKinnon, 1995). Low salinity water containing elevated nutrient concentrations have also been recorded during long-term biological oceanographic studies of the GBR lagoon (Brodie and Furnas, 1996). In recent studies the increase in suspended sediments discharged from the Burdekin River due to the effects of beef grazing on the catchment has been measured. Elevated barium concentrations in corals from reefs almost 200 km from the river mouth were used as a signal for increased discharge (McCulloch et al., 2003). Studies of the evolution and dynamics of the Herbert River flood plume using an airborne salinity mapper have shown how the plume developed in response to tidal currents, the wind and boundary current forcing (Burrage et al., 2002). Modelling of river plumes from the Burdekin, Herbert, Tully and Johnstone Rivers has recently shown how inner-shelf reefs in this area are exposed to low salinity water on a regular basis (King et al., 2002).

Following the 1991 Fitzroy flood a more formal investigation of flood plumes in the GBR lagoon was instituted (Steven et al., 1996; Devlin et al., 2001) with the objective of mapping the spatial limits of the influence of river water, quantifying the concentrations of key parameters in plume water at various times in the life of the plume and determining the fate of materials discharged from the rivers. Results reported in this paper focus on the spatial extent of plumes in the period 1991–2000 and the processes which occur in the plumes. The results are compared to evidence from benthic sediment chemical composition and isotope signatures in corals and sediments to confirm the spatial extent of direct terrestrial runoff influence in the GBR. The concentrations of chemical constituents in plume water are directly related to the degree of mixing between the fresh and salt water. Where the changes in concentration result only from the dilution associated with mixing, the constituents are said to behave conservatively (Boyle et al., 1974). Processes occurring in addition to mixing i.e. non-conservative behaviour can include, the biological uptake from dissolved to a particulate stage, sedimentation of particulate matter and the mineralisation or desorption of particulate to dissolved species (Dagg et al., 2004).

2. Methods

2.1. Plume mapping

River plumes were mapped using aerial survey. Over the monsoonal season, weather reports were monitored closely and when plumes formed aerial surveys were conducted once or twice during the event. Plumes were readily observable as brown turbid water masses contrasting with cleaner seawater. The visible edge of the plume (Fig. 3) was followed at an altitude of 1000–2000 m in a light aircraft and mapped using GPS. Where individual rivers flooded simultaneously, as often happens in the Wet Tropics, adjacent plumes merge into a continuous area. In these cases efforts were made to distinguish the edge of the individual river plumes through colour differences. The vertical distribution of plume water and depth stratification was studied in a limited number of cases by depth sampling (Taylor, 1997). The results of each mapping exercise were transferred to a Geographic Information System on which subsequent spatial analysis was based. Flood plumes associated with Cyclone Joy (1991), Cyclone Sadie (1994), Cyclone Violet (1995), Cyclone Ethel (1996), Cyclone Justin (1997), Cyclone Sid (1998) and Cyclone Rona (1999) were mapped. The rivers studied were between the Fitzroy River (mouth at 23°30′ S) and the Daintree River (at 16°15′ S) (Fig. 1).

2.2. Water sampling

Water samples were collected from multiple sites within the flood plume. Location of samples were dependent on which rivers were flooding and the areal extent of the plume but generally samples were collected in a series of transects heading out from the river mouth, with additional samples taken in between river mouths if more than one river was in flood. Time of sampling was also dependent on the type of event and how quickly boats were mobilised. Sampling in these plumes requires a short response time strategy as a detailed pre-

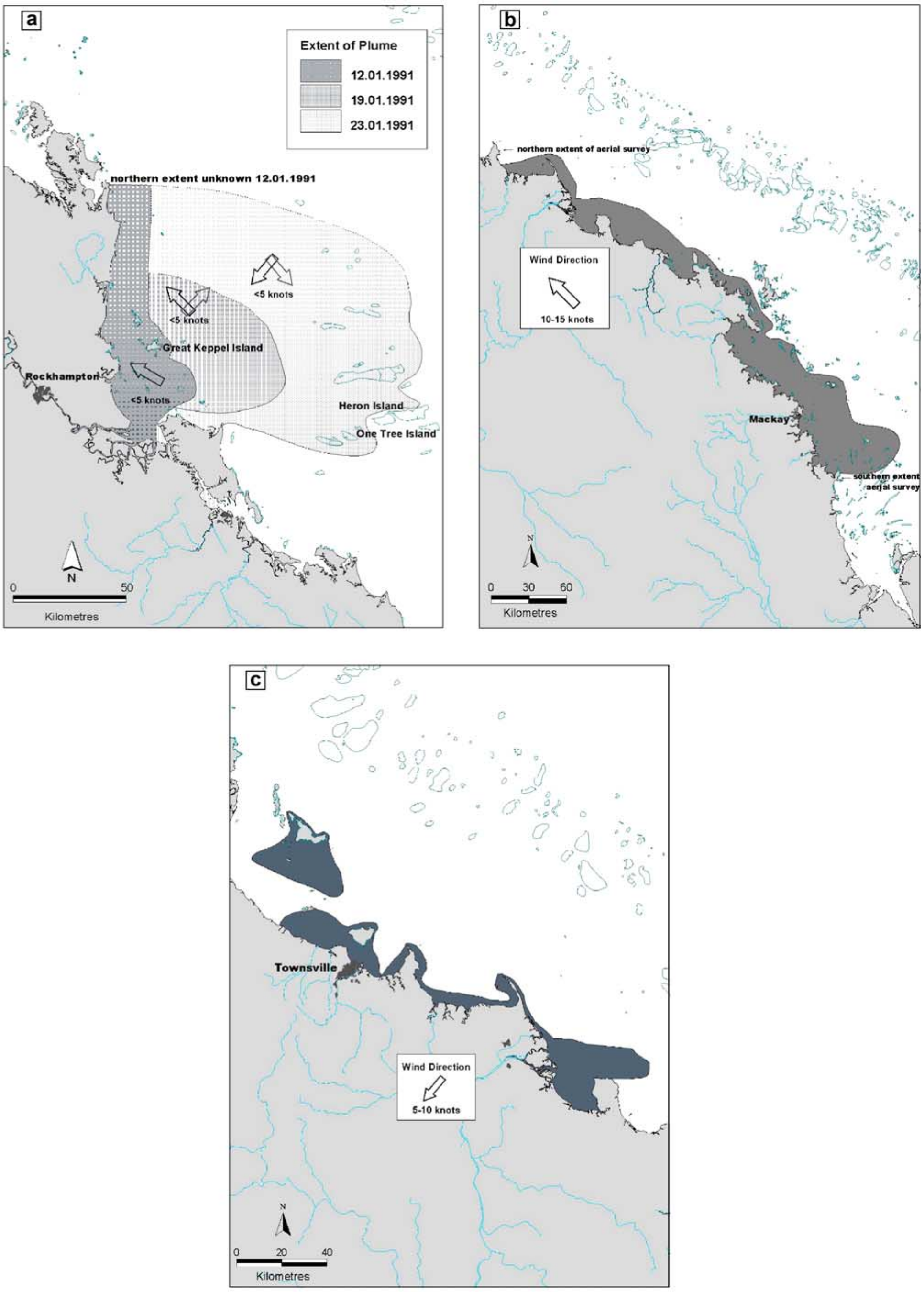

Fig. 3. Flood plumes in the 'dry' tropics associated with (a) Cyclone Joy (1991), (b) Cyclone Justin (1997) and (c) Cyclone Sid (1998).

planned schedule is not possible due to the unpredictability of the river flood events. The need for a responsive, event-driven sampling strategy to sample plumes from small to medium sized rivers has been noted previously (Wheatcroft, 2000). The majority of samples were collected inside the visible area of the plume, though some samples were taken outside the edge of the plume for comparison. Surface samples were collected at 0.5 m below the surface, with either a reversing thermometer Niskin bottle or a rinsed clean sampling container with temperature measured by thermometer. Samples taken at depth were collected with Niskin bottles. Salinity and temperature profiles were measured at all sites with a YSI salinity meter. Secchi disk clarity was determined at each station. Water samples for nutrient and chlorophyll analysis were collected, filtered and stored for further analysis. Volumes filtered for all analyses were dependent on the turbidity of the water. Subsamples were filtered through GF/F (glass fibre) filters for chlorophyll and phaeophytin, the filter and retained algal cells were wrapped in aluminum foil and frozen. The second subsample was filtered through pre-weighed 0.45 μm membrane filters for suspended solids. The third subsample was filtered through pre-combusted GF/F for particulate nutrient analysis, wrapped in aluminum foil and frozen.

Dissolved nutrient samples were collected using sterile 50-ml syringes, pre-rinsed three times with the seawater to be sampled. A 0.45 μm disposable membrane filter was then fitted to the syringe and a 10-ml sample collected in tubes pre-rinsed in filtered water. Tubes were placed upright in tube holders which were then stored either on ice in an insulated container or in a freezer dependent on the sampling vessel. Further samples were taken in tubes for silicate analysis and stored at room temperature. Samples were analysed for dissolved inorganic nutrients (NH_4, NO_2, NO_3, $NO_2 + NO_3$, PO_4 and Si) and total dissolved nitrogen and phosphorus (TDN, TDP). Analytical methods are described in detail in Devlin et al. (2001).

2.3. Data analysis

Assessment of the behaviour of materials in the plume was done by plotting the concentration of each species versus salinity. This mixing curve plot has been commonly used to analyse processes occurring in flood plumes (Boyle et al., 1974) but problems of interpretation may arise when changes in river concentrations of parameters change rapidly (Loder and Reichard, 1981). Conservative or non-conservative mixing processes can be estimated from the shape of the plot and analysis of the processes occurring in the plume made if care is used in interpretation in the low salinity area (Eyre, 2000). In most cases limited samples were taken due to constraining weather conditions and timing. Only the most complete plots are shown in the figures. Complete data from this study is available in Devlin et al. (2001).

3. Results

The results of each mapping exercise are shown in Figs. 3–5 for the nine plumes mapped in this study. Fig. 3a–c shows individual plumes from large rivers (Burdekin and Fitzroy in the 'dry' catchment areas) while Figs. 4 and 5 show the combined plumes typical of the situation in the Wet Tropics (Herbert, Tully, Johnstone, Russell-Mulgrave, Barron and Daintree Rivers) and Mackay Whitsunday (Plane Creek, Pioneer, O'Connell, Proserpine Rivers) regions. Plumes in the Wet Tropics region normally merge into a continuous area. However the individual river contributions can still be distinguished visually through differences in colour and turbidity. This is not shown in Figs. 4 and 5.

The area of the shelf covered by plume water and its spatial distribution pattern is governed by river discharge volume, Coriolis forcing and wind stress (Chao, 1988a). In the absence of wind stress plumes move in a northerly direction from the river mouth in accordance with Coriolis forcing. In times of low wind stress the plumes spread well offshore and can reach beyond the main barrier reefs on the outer shelf into the Coral Sea (e.g. Fig. 4a, Cyclone Sadie).

In periods of stronger winds, wind stress may be a greater forcing function than the Coriolis effect (Chao, 1988b; Wolanski, 1994). If the wind forcing is opposed to the Coriolis effect in direction, i.e. north or north east winds, the overall plume movement may be to the south e.g. the Burdekin plume associated with Cyclone Justin (Fig. 3b). However the most common situation from the data sets presented in this study is when winds are from the south east. South-easterly trade winds dominate for most of the year in the GBR and produce a strong north west longshore movement of inner shelf waters (Wolanski and Ruddick, 1981; Brinkman et al., 2002). Under these conditions wind and Coriolis effect act in the same direction to drive plumes to the north (Fig. 4b). In addition plumes tend to be held closer to the coast in these conditions than in periods of light winds or north/north east winds (Fig. 4b). These observations are in agreement with the modelling studies on the Burdekin plume of King et al. (2001) which also show the northern movement and coastal nature of this plume.

Plumes most commonly extend into the GBR lagoon to a distance of about 20 km perpendicular to the coastline i.e. over the inner shelf. Of the nine plumes mapped in the present study only two (Figs. 3a and 4a) spread significantly beyond this distance onto the outer shelf and thus may have had direct effects on outer shelf reefs. In contrast to other outer shelf reefs, Green Island Reef, on the outer shelf off Cairns, was covered by plume water in five occasions of the six plumes which occurred in the Wet Tropics during this study. This high frequency appears due to the steering effect of Cape Grafton. Plume water from the Johnstone and Russell-Mulgrave Rivers moving north is steered offshore by the prominent Cape Grafton (Figs. 4b, c and 5c). The plume then intersects and covers Green Island Reef and frequently parts of Arlington, Upolu, Oyster and Vlassof Reefs as well. These reefs are thus the only outer shelf reefs in the central and southern GBR observed in this study to regularly and directly experience river influence.

The frequency with which inner shelf ecosystems experience plume water varies greatly with location on the GBR coast. The frequency observed is a direct function of prolonged, high intensity rainfall frequency on the adjacent coast. Plumes occur in inner shelf waters of the Wet Tropics coast (Herbert to Daintree Rivers) at least annually and often twice a year. Plumes occur

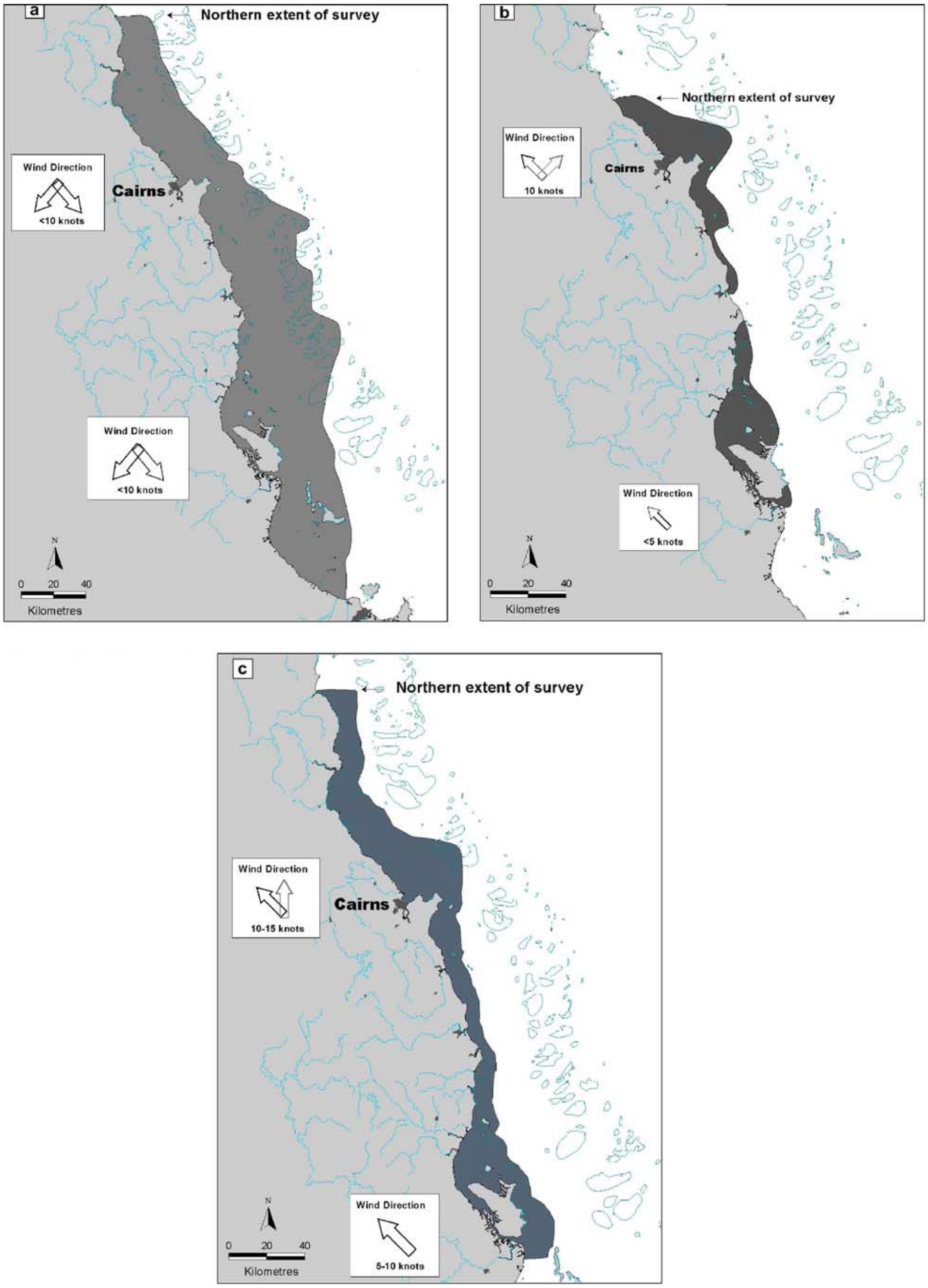

Fig. 4. Flood plumes in the wet tropics associated with (a) Cyclone Sadie (1994), (b) Cyclone Violet (1995) and (c) Cyclone Ethel (1996).

in inner shelf waters from Mackay to the northern Whitsundays (Pioneer to Proserpine Rivers) approximately once every two years while the Burdekin River produces a significant plume approximately at 3–4 year intervals and the Fitzroy River on average at 10 year intervals. The intervals for Cape York rivers is probably 3–4 years but plumes in this area have not been studied.

NO_x, DIP, and NH_4 values are plotted against individual flood events within each catchment (Fig. 6). The inorganic nutrients demonstrate initial high concentrations in low salinity waters, with decreasing concentrations over the mixing zone. Mixing patterns are variable over catchment and cyclonic event, though there are strong similarities between events. NO_x concentrations generally follow a conservative mixing process in the lower salinity ranges, diluting in a linear pattern in relation to the salinity concentrations. River concentrations are variable between catchments and events and as a result, plume concentrations also vary. However, the majority of NO_x mixing curves show non-conservative behaviour at the higher salinity ranges (25–35‰) indicating biological uptake as shown

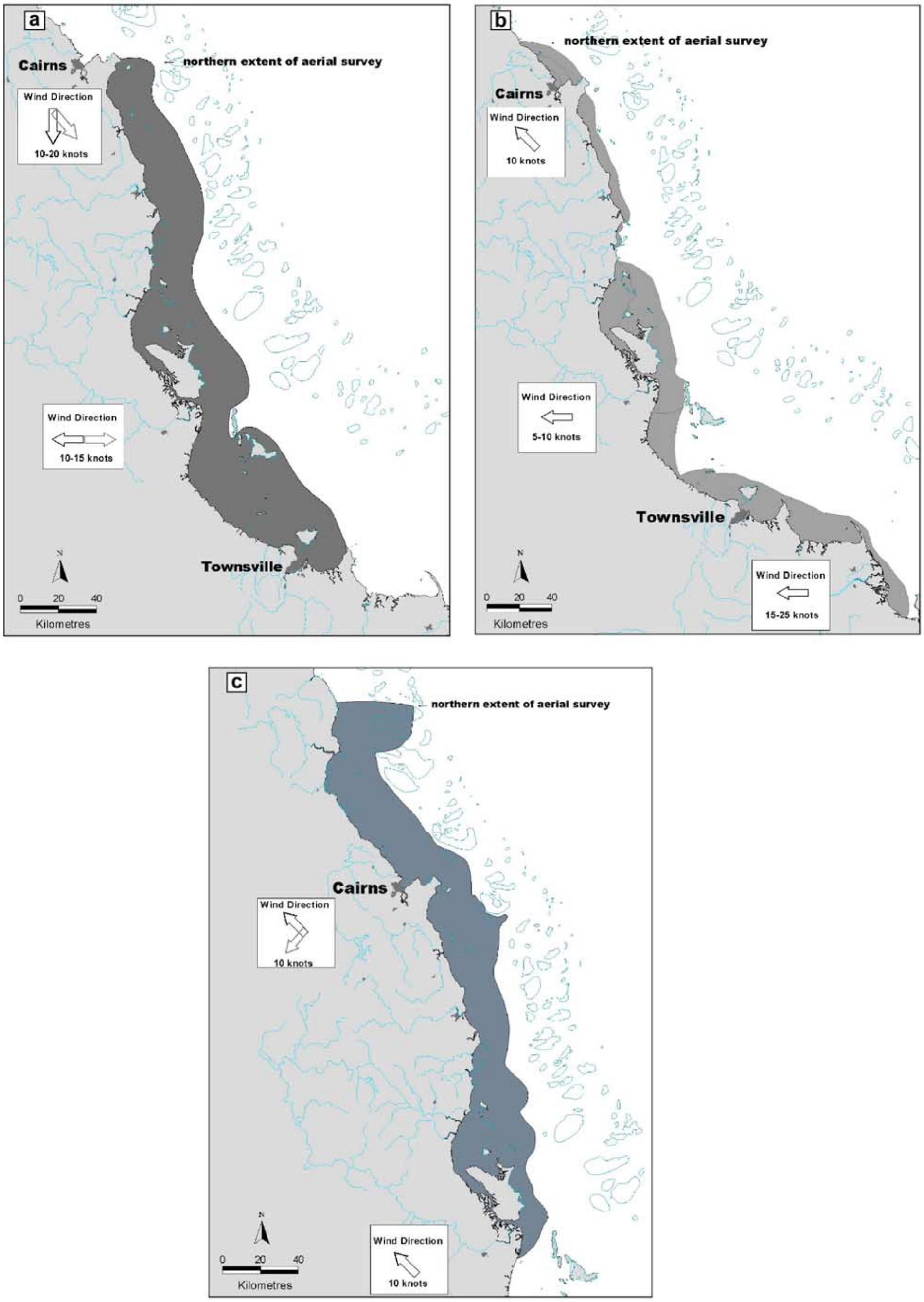

Fig. 5. Flood plumes in the wet tropics associated with (a) Cyclone Justin (1997), (b) Cyclone Sid (1998) and (c) Cyclone Rona (1999).

in Fig. 6 in the Barron plume during Cyclone Sadie and Burdekin catchment for Sid. The conservative behaviour indicates that NO_x is not utilised or released by chemical or biological processes as the freshwater initially moves into the coastal zone. The area of non-conservative behaviour is the area of high productivity where uptake of nutrients by phytoplankton occurs. DIP concentrations over the mixing curves show similar patterns to NO_x, with conservative behaviour at salinities to 25‰ and biological uptake at salinities above 30‰. There is little evidence from the mixing diagrams of release of phosphate from particulate matter in the early stages of the mixing process. This is an important mechanism for transport of phosphate to the ocean in other rivers e.g. in the Amazon more than half of the phosphate reaching the ocean is released from particulate matter during plume mixing (DeMaster and Pope, 1996). Little desorption of phosphate was found from Herbert River soils when mixed with marine waters in studies assessing this process in the GBR region (Edis et al., 2002).

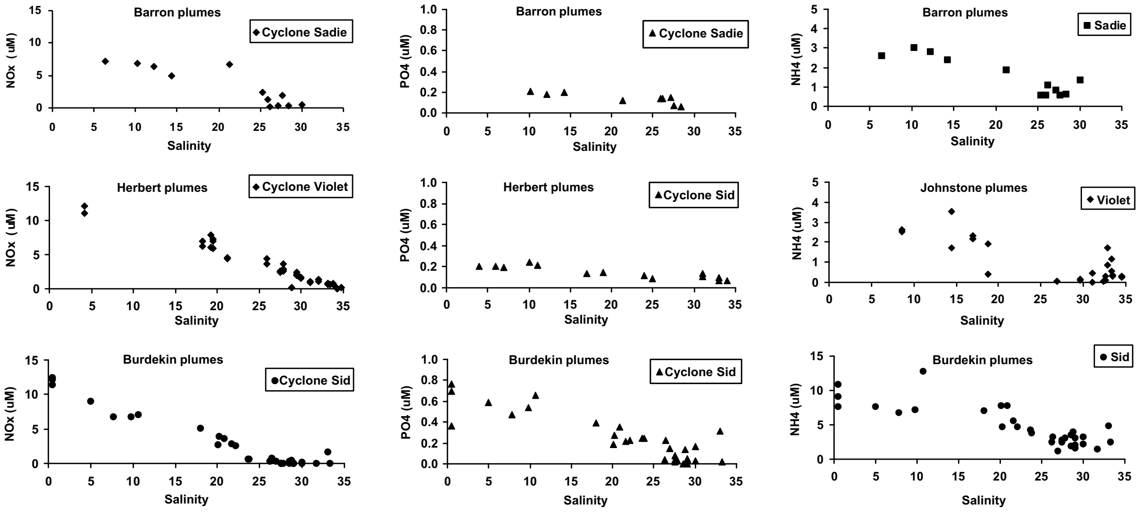

Fig. 6. Nitrate, phosphate and ammonia concentrations plotted against salinity.

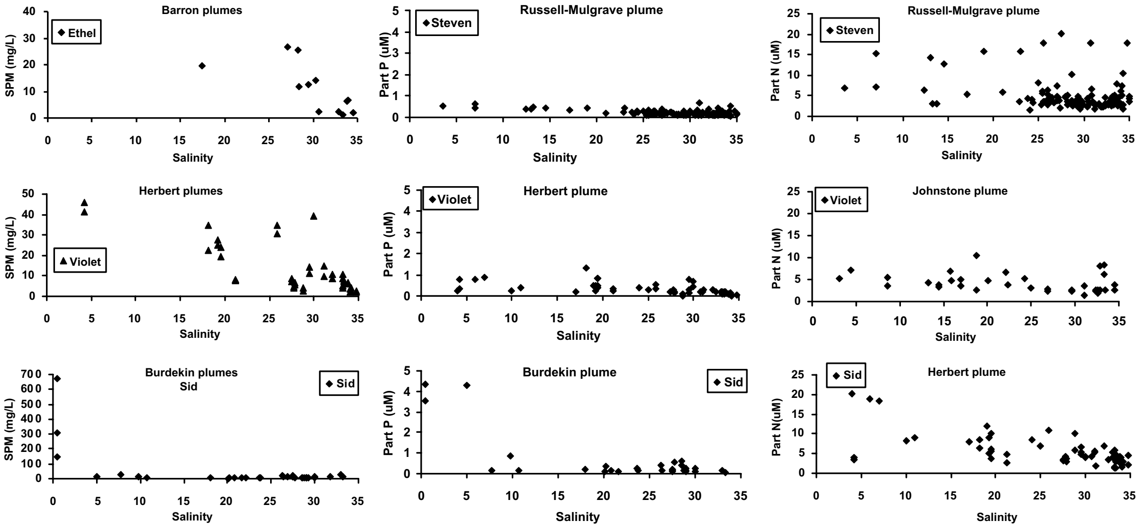

Fig. 7. Suspended particulate matter, particulate phosphorus and particulate nitrogen concentrations plotted against salinity.

Ammonium concentrations are far more variable reflecting both variations in supply, uptake and release from biological processes in the plume. Concentrations of ammonium remain elevated in the higher salinities suggesting sources of ammonia in the plume, for example, excretion by zooplankton. Straight dilution processes in the mixing curves are more evident in the Burdekin plume data, specifically for NO_x and NH_4. The higher turbidity associated with the Burdekin plumes may limit the ability of the phytoplankton to uptake the 'new' nitrogen and biological uptake may not occur till much later in the plume process.

In the initial mixing zones (low salinity ranges) water velocity is reduced as the freshwater mixing with the higher salinity coastal water. This reduction in velocity allows the river derived particulate matter to settle from the plume. Flocculation is also enhanced due to a combination of physical and chemical changes in this region (Geyer et al., 2004). This is most clearly shown in the results from the Burdekin for Cyclone Sid (Fig. 7) where suspended solid and particulate phosphorus concentrations drop to very low levels only a few kilometres from the river mouth at salinity of approximately 10‰. However, sediment distribution information (Maxwell, 1968) shows that the area off the mouth of the Burdekin River has a low proportion of fine sediments. This apparent inconsistency is best explained by the resuspension and northward transport and deposition in northerly facing bays of fine sediments which occurs throughout the year under the influence of the south-east wind regime on the inner-shelf (Woolfe and Larcombe, 1998). Reductions in suspended sediment with increasing salinity in the plume

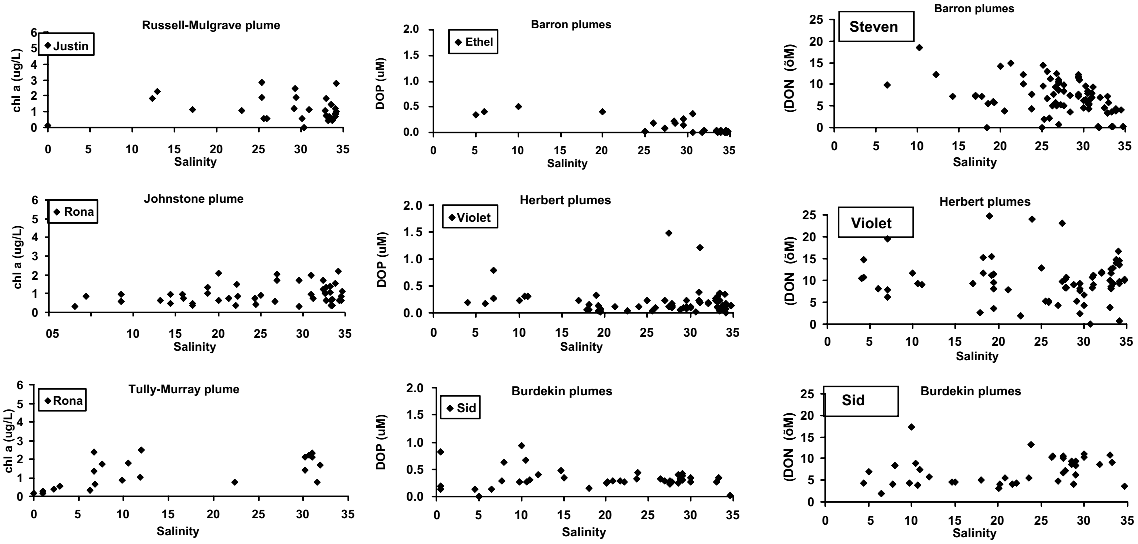

Fig. 8. Chlorophyll *a*, dissolved organic phosphorus and dissolved organic nitrogen concentrations plotted against salinity.

are less clear in some of the other plumes reported but this is complicated by the resuspension during the plume event in stronger wind conditions on these occasions.

Particulate nutrient concentrations decline rapidly across the mixing zone, falling from 8 to 20 μM in the river for PN to about 1 μM at salinities above 5‰ and from 1.0 μM to 0.1 μM for PP. Conversely there can be an increase in the particulate nutrients at a greater distance and time in the plume reflecting the formation of particulate nitrogen and particulate phosphorus in algal biomass from the dissolved nutrient component. DON and DOP (Fig. 8) concentrations stay relatively constant throughout the plumes as concentration in river water and shelf seawater are similar. Dissolved organic nitrogen and phosphorus are also not readily available for phytoplankton uptake. Increased chlorophyll *a* in the higher salinity ranges (25–36‰) in plume waters (Fig. 8) reflect biological uptake into phytoplankton in this region.

4. Discussion

The fate of materials suspended or dissolved in plumes can be partially understood from studies of the concentration changes occurring in the plume as mixing with seawater progresses (Dagg et al., 2004). Generally most suspended solids and the associated particulate nutrients and pesticide residues sediment from the plume quickly and are deposited within a few kilometres of the river mouth. This process is common in many large rivers e.g. the Mississippi (Trefry et al., 1994). In the salinity mixing diagrams of the Burdekin plume suspended solids concentrations drop from >1000 mg l^{-1} in the river at zero salinity to <50 mg l^{-1} at salinities near 5–10‰. The zone of salinity 5–10‰ occurs about 5 km from the river mouth in active large plume conditions. This fine benthic sediment is then continuously resuspended, as it has been deposited in depths of generally less than 10 m, by the prevailing south-east wind regime and transported north along the coast (Larcombe et al., 1995; Woolfe and Larcombe, 1998; Lambeck and Woolfe, 2000). This behaviour of initial short-term deposition of fine sediments near the river mouth and final deposition in a different area as the result of wind-driven resuspension and transport over a longer time period is characteristic of many global river systems. A well-studied example is the Atchafalaya River, a distributary part of the Mississippi system, and its discharge to the Gulf of Mexico (Allison et al., 2000). The final fate of sediment from most GBR rivers is to be trapped in northward facing bays where the south-east wind regime is attenuated and minimal further resuspension occurs (Larcombe and Woolfe, 1999). Dissolved fractions in the plume are transported far further than the suspended solids and particulate fractions. Dissolved inorganic nutrient concentrations are relatively high in peak flow conditions in the rivers involved in the present study. Typically DIN (mostly nitrate) concentrations lie in the range 300–1000 μg l^{-1} (20–70 μM) and DIP in the range 5–40 μg l^{-1} (0.15–1.3 μM) in flood conditions in rivers such as the Burdekin, Herbert, Tully and Johnstone (Furnas, 2003). This can be compared to the large rivers and their plume behaviour reviewed by Dagg et al. (2004) where three temperate rivers (Changjiang, Mississippi and Huanghe) have DIN concentrations in the range 40–134 μM and DIP, 0.6–3 μM but three tropical rivers (Amazon, Zaire and Orinoco) have much lower concentrations in the range 6–12 μM for DIN and 0.2–0.8 μM for DIP. High concentrations of dissolved nutrients, 10–100 times non-flood ambient concentrations, are measurable in the plumes in the GBR at distances of 10–200 km from the river mouth. Dissolved nutrients move conservatively through the estuarine plume in the lower salinity ranges, indicating very little biological uptake in the initial stages of the plume. However, in the higher ranges of salinity (25–36‰), there is increased biological processing. Nutrient levels stay elevated throughout the plume, with dissolved inorganic nutrient levels exceeding ambient concentrations through all salinity ranges. Dissolved inorganic nutrients are not taken up in the early stages possibly due to light limitations on phytoplankton growth due to plume turbidity. This effect has been commonly observed in many rivers including the Amazon (Smith and DeMaster, 1996), Mississippi (Lohrenz et al., 1999), Changjiang (Tian et al., 1993), Pearl (China) (Cai et al., 2004) and Brantas (Indonesia) (Jennerjahn et al., 2004). Suspended matter concentrations appear to need to be reduced below 10 mg l^{-1} to allow sufficient light for strong phytoplankton growth (Turner et al., 1990). This lack of uptake allows the inorganic nutrients to be transported away from river mouth, exposing inshore reefs to high inorganic nutrient concentrations. Coupled with this, inshore reefs are exposed to elevated concentrations of fine particulate matter, both river-derived clay materials and phytoplankton. After the large initial sedimentation stage there is little sedimentation at higher salinities with suspended particulate matter concentrations averaging between 10 and 30 mg/l in the higher salinity levels (26–35‰). The particulate matter concentrations are reduced in the higher salinity ranges, but the variability suggests that resuspension of the finer particulate matter may be occurring. Concentrations in the later stages of the plume are still elevated and may suggest an increase in fine colloidal matter as the larger particulate matter sediments out of the plume.

The high variability between catchments is due to the different source concentrations in the different rivers, the different stages of sampling through the existence of the plume and flow variability. High spatial variance of nutrient concentrations in the plumes is related to plumes constrained and broken up by islands and reefs, with the complexity directed by the multiple rivers and streams acting as source water for the plume and resuspension processes resulting from rough weather conditions.

Most flood plumes in the GBR spread to the north of the river mouth for distances of up to 200 km but not more than approximately 20 km from the coast. Material in the plume will initially be deposited within this zone either directly as particulate matter from the river or, if dissolved, eventually as organic particulate matter after uptake into biological organisms. Thus, if little further transport of the terrestrial material in an offshore direction occurs, we could expect to see evidence of the material in benthic sediments in a band along the coast on the inner shelf. Further offshore, on the middle and outer shelf, we would expect to see little terrestrial derived material in benthic sediments. With a few exceptions this pattern has been verified in studies of benthic sediment and biota composition. In transects across the GBR, terrestrial biomarker chemicals (Currie and Johns, 1989; Johns et al., 1994), higher plant materials (Shaw and Johns, 1985), land-sourced trace metals (Brady et al., 1994), δ^{13}C in corals (Risk et al., 1994) and sediments (Gagan et al., 1987), δ^{15}N in corals (Sammarco et al., 1999) and coral skeletal densities (Risk and Sammarco, 1991) change from a terrestrially influenced signal inside 20 km to almost no terrestrial influence beyond 20 km. On the other hand evidence of movement of fine sediment as a nepheloid layer from inshore to almost 30 km offshore in strong wind conditions has been reported near Cairns (Wolanski and Spagnol, 2000). Pesticide residues, particularly of the herbicide diuron and the insecticide dieldrin, are also found in intertidal and subtidal sediments, primarily in a band close to the coast (Haynes et al., 2000) adjacent to those catchments with a history of use of the particular pesticide. The effects of variability in river influence on inner shelf ecosystems is not well understood. However correlations between relative distance from the coast or relative distance across the shelf and diversity and/or abundance in taxa such as soft corals (Alcyonaria) (Fabricius and De'ath, 2001a) and crustose coralline algae (Fabricius and De'ath, 2001b) are known. Such correlations are attributed to turbidity and sedimentation gradients with distance across the shelf.

The group of middle shelf reefs off Cairns is the area in which all three waves of crown-of-thorns starfish (*Acanthaster planci*) outbreaks on the Great Barrier Reef were first recorded. Outbreaks were recorded at Green Island in 1962 (Pearson, 1972), at Green Island in 1979 (Moran, 1986) and at Hastings Reef in 1993 (Wachenfeld et al., 1998). It has been postulated that *A. planci* population outbreaks are initiated by enhanced larval survivorship due to phytoplankton blooms on which the larvae feed (Lucas, 1973; Birkeland, 1982; Brodie, 1992; Brodie et al., in press). The phytoplankton blooms may be caused by increased nutrient runoff from adjacent catchments due to anthropogenic catchment modification (Englehardt and Lassig, 1997). The results presented in this paper are supportive of such a causal connection in showing the correlation of the *A. planci* outbreak initiation area on the GBR with the only outer shelf area of the GBR regularly affected by high nutrient content river waters.

5. Conclusions

Most SPM deposits from the plume close to the river mouth, often within a few kilometres of the mouth. Thus most of the particulate nutrient material will also be lost from the water column in this zone and not transported any great distances in the plume. In contrast there is almost no loss of dissolved nutrients, except by dilution, in the plumes until salinities rise to above 25‰ which is generally 50–200 km from the river mouth. The main reason for lack of biological uptake and phytoplankton growth appears to be the elevated turbidity in the early stages of the plume and the consequent light limitation. The implications of the contrasting behaviour of particulate nutrients and dissolved nutrients are that nutrients discharged from rivers in dissolved form are transported great distances in the plume. They thus have the ability to influence biological activity on much of the inner-shelf of the GBR. Nutrients discharged in a particulate form are trapped near the coast and probably do not have a major influence on, for example, most of the inner-shelf coral reefs. These results have important implications with respect to the degree of exposure of inner-shelf ecosystems to river-sourced nutrients and suspended particulate matter. As different forms of nutrients are exported from different land uses on the catchment the results can also help decide on priorities for management to reduce export from specific land uses. In general it is very clear that the primary area where flood plumes are common is the inner shelf and that ecosystems in this area are at most risk from pollutants contained in river discharge (Brodie et al., 2001; Brodie, 2002; Furnas, 2003; Fabricius and De'ath, 2004).

Long-term effects of eutrophication on some inner shelf coral reefs of the GBR are now evident. In the Whitsundays, a nutrient/suspended sediment gradient from the Proserpine River has been correlated with reduction in coral cover, species richness and abundance combined with increased coral recruit mortality (van Woesik et al., 1999). Synergistic effects of nutrients and sediment (Fabricius and Wolanski, 2000) in association with the acute effects of cyclones, bleaching and crown of thorns starfish (Fabricius and De'ath, 2004, Fabricius et al., in press) are the cause of the widespread reef degradation in inner shelf areas of the central GBR. At Green Island off Cairns the large expansion in the area of seagrass meadows on reefal areas normally without seagrass has been shown to be a result of increased nutrient supply from mainland river discharge (Udy et al., 1999). Knowledge of the transport of land-derived materials on the GBR shelf and hence the exposure of GBR ecosystems to this material allows us to better understand the changes which are occurring in these ecosystems.

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