Sediments flows in the Great Barrier Reef lagoon as revealed by MERIS satellite data

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Abstract – The total suspended sediment (TSS) concentrations obtained by the satellite remote sensing instrument MERIS were validated using in situ data acquired during a dry and a wet season in the vicinity of the Herbert River, central Great Barrier Reef region, Australia. The available MERIS imagery for the region covering 16 months in 2003-2004 was then compiled, and derived TSS distributions statistically analysed. The present study demonstrated that river-borne sediments discharged by a typical flood in the Herbert River are mostly precipitated or consumed within the first 20 km from the coast and therefore are unlikely to affect the mid-shelf coral reefs of this section of the Great Barrier Reef lagoon.

Key words: Great Barrier Reef, suspended sediments, satellite remote sensing.

1. INTRODUCTION

Coral reefs are sometimes referred to as "tropical rainforests of the deep" since they are one of the most diverse, productive, and beautiful marine ecosystems in the world (Spalding et al, 2001). The Great Barrier Reef (GBR) located in north eastern Australia is the largest coral reef in the world and is a natural heritage listed site. However, an increasing weight of evidence shows system-wide decline of coral reefs in the GBR over the past decades (Bellwood et al, 2004). One of the possible causes for the above is the increased sediment, nutrient and pollutant input associated with human activities (McCulloch et al, 2003). There is increasing evidence that certain levels of sediments are detrimental to corals. Suspended sediments contribute to water turbidity and attenuate light penetrating the water column, thus decreasing the availability of the primary source of energy for corals, their symbiont zooxanthellae, seagrass and benthic algae (Furnas, 2003; Telesnicki et al; 1995). At high suspended sediment levels and sufficient exposure time, direct deposition of sediments on underlying substrate might occur (Fabricius et al, 2003; Nugues et al, 2003; Philipp et al, 2003).

Nutrient-rich sediments, which support the productivity of ecosystems of the GBR, come from a variety of sources with terrestrial runoff being the largest source. Terrestrial input of sediments and nutrients mainly occurs via river discharge, especially during periods of intense rainfall typically associated with tropical cyclones. As a result, river discharge regimes in the GBR catchments are highly seasonal and usually episodic in nature. Thus, it is a combination of natural disturbances (floods) and human-enhanced nutrient and sediment inputs that produces the greatest threat to the GBR ecosystems.

The study region is the Herbert River and adjacent ocean located in the central part of the Great Barrier Reef (GBR) next to the Hinchinbrook Island (Fig. 1). The area is located in the semi-humid tropics of the central GBR zone, with pronounced dry and wet seasons. The Herbert River is the largest of the river systems (mean annual flow 5 x 10^6 ML) in the humid tropics region of northeast Australia and the fourth largest fluvial system draining into the GBR. The bulk of freshwater and fine sediment exports from the Herbert River most frequently comes as a single large event during the wet season (December to March). Therefore, flood events are the major factors of sediment and nutrient export, particularly from grazing lands laid bare after long periods of drought (Furnas, 2003).

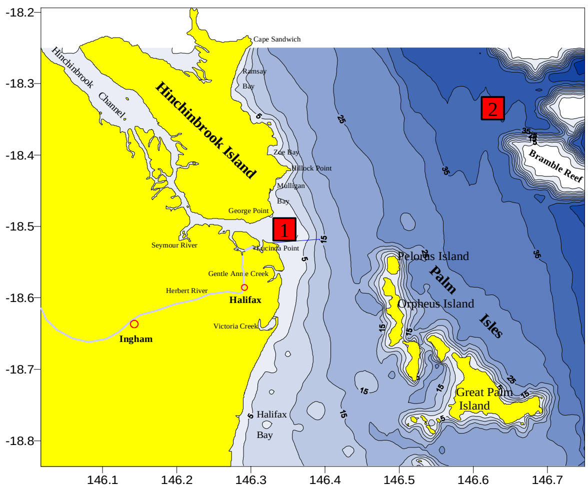

Figure 1. Study region in the vicinity of the Herbert River, central Great Barrier Reef, Australia. Boxes correspond to Herbert River Mouth (box 1) and Coral Reef region (box 2).

Given the natural temporal and spatial variability observed in river plume behaviour, real-time observations of plumes are highly desirable. Such opportunity is readily available with remote sensing technologies. Remote sensing is an appealing alternative approach to direct measurements because it provides non-invasive, synoptic, repetitive data for environmental parameters across broad spatial and temporal domains. These technologies are also cost-effective for regional studies because they eliminate the need to conduct expensive in situ monitoring programs. With the help of ocean colour remote sensing, this study looks at sediments discharged by a GBR river into the adjacent coastal ocean and examines their potential to reach and affect mid-shelf coral reefs.

2. DATA

2.1. Vertical homogeneity of TSS

The satellite sees through the water column up to a visibility depth. In order to check whether a surface value of Total Suspended Sediment (TSS) is representative of the water column suspended sediment concentration up to the depth, which is visible to the satellite, the turbidity vertical profiles were measured at the satellite validation stations on 20 February 2004. The Secchi depth was taken as a proxy of such visibility depth. The turbidity profiles with corresponding Secchi depths for validation stations are shown in Fig. 2. The results revealed vertical homogeneity of turbidity in the studied waters within the visibility layer. Since TSS is the major contributor to the water column turbidity in these waters (Ametistova, 2004), satellite-derived TSS concentrations can be considered a reasonably accurate representative of surface TSS in natural waters of the studied region.

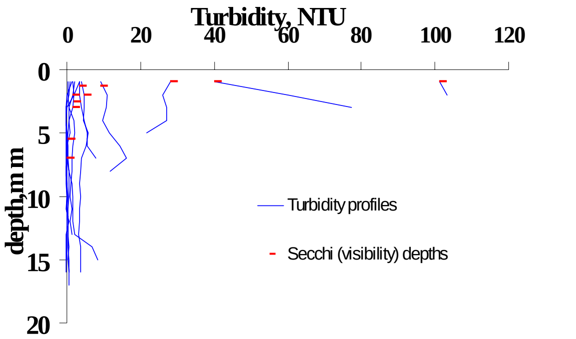

Figure 2. Turbidity profiles and Secchi depths in the coastal ocean in the vicinity of the Herbert River on 20 February 2004.

2.2. MERIS validation

The MERIS-hosting satellite ENVISAT was launched in 2002 and by July 2003 validated data was available for the region in question. MERIS provides ocean colour products, such as suspended sediments, yellow substance and chlorophyll concentrations, generated by the inverse neural network algorithm (Schiller et al, 1999). Therefore, direct comparison of these bio geophysical substances with in situ measurements is possible. This allowed direct comparison of ground truth and MERIS-derived data. In order to assess the feasibility of MERIS data for ocean colour studies in the studied area, in situ measurements of TSS (gravimetric filter analysis) were taken at the times coinciding with overpasses of MERIS. As a result, three days which corresponded to in situ measurements in October 2003 (dry season) and February 2004 (wet season) permitted comparison of satellite-derived and in situ measured values of suspended sediments.

A total of 33 stations, located both in coastal and open ocean waters of the region, were available for validation analysis. The concentrations of TSS obtained by MERIS were averaged for pixels within a 0.5 km radius of a validation station and were subsequently compared to corresponding in situ data (Fig. 3). The good correspondence between measured and satellite-derived TSS concentrations was observed. The correlation coefficient was 0.51 and there is at least 99.9 % confidence that the compared values are correlated. The MERIS tends to underestimate TSS in comparison to the in-situ observations. Overall, MERIS total suspended sediment product can be considered validated and therefore can be used for geophysical research.

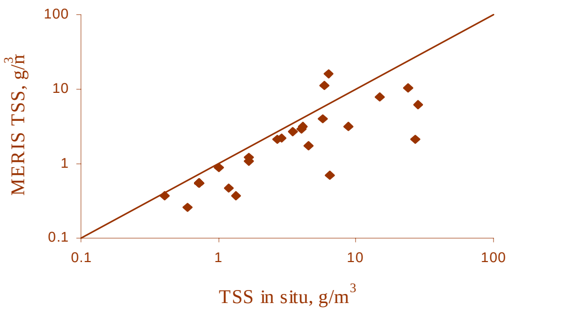

Figure 3. Comparison of in-situ and MERIS-derived total suspended sediment concentrations.

2.3. Available MERIS imagery

The available MERIS imagery for the region used in the subsequent analysis covered 16 months in 2003-2004. Over one hundred images have been processed from February 2003 till May 2004.

3. METHODS

3.1. Study regions

Two regions of 5 km x 5 km (approximately 20 pixels by 20 pixels) were chosen for analysis of temporal distribution of TSS. They are shown as box 1 and box 2 in Fig.1. Box 1 is located at the mouth of the Herbert River, while box 2 is situated close to the nearest mid-shelf coral reef.

3.2. Selection criterion

The studied region is characterised by frequent cloud-cover, which tends to contaminate remote measurements. Furthermore, areas with valid pixels around cloud areas often have erroneous values due to the specifications of the MERIS processing algorithm. Also, no considerations for cirrus clouds, which can be mistaken for high sediment laid waters, are provided for in the MERIS atmospheric correction procedure.

The ratio of the standard deviation divided by the mean, multiplied by 100, so that it is expressed as a percent, is called relative standard deviation or coefficient of variation. It measures the spread of a set of data as a proportion of its mean. This summary statistic is frequently employed in the natural sciences, where the standard deviation of measurement error is often proportional to the magnitude of the values being measured. Since the coefficient of variation provides a measure of relative variation and is scale-free, it is particularly useful in making comparisons between different samples.

The following selection criteria were exercised in the present study to select high-quality data for further analysis:

1. If an image exhibited more than 50% cloud cover in a box (region), the box was disregarded;
2. If coefficient of variation expressed in percentage was larger than 100%, the box was eliminated from further analysis.

4. RESULTS AND DISCUSSION

4.1. Spatial distribution of TSS

The TSS distribution on 22 October 2003 derived from the MERIS imagery is shown in Fig. 4. The image was taken during dry season and at the time of low tide. The map exhibits higher concentrations (darker coloured regions) along the coastline and consistently lower concentrations (lighter colouring) in the open oceanic regions. At the river mouth concentrations are high, mostly above 8 g/m^3, thus outlining the plume of sediment-rich river water. Extremely high concentration values above 20 g/m^3 (red pixels) are observed in shallow regions adjacent to the coast. There is a well-defined TSS gradient in the direction away from the river mouth, with suspended sediment concentration decreasing to less than one gram per cubic metre (g/m^3) at about 20 km and further eastwards from the coast. Shallow areas occupied by coral reefs can be clearly identified on the TSS distribution map as areas of elevated TSS concentrations.

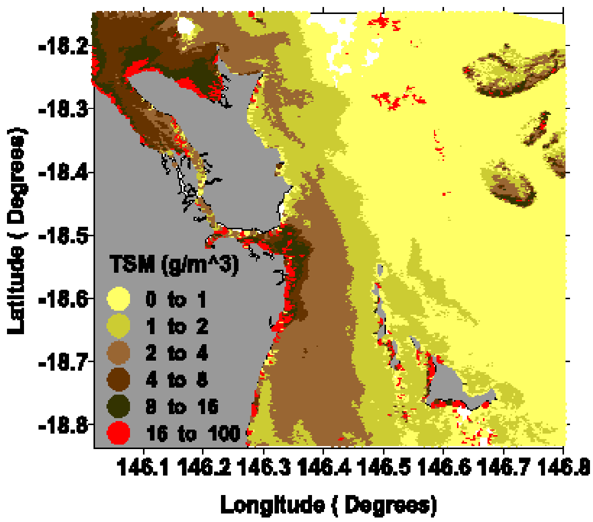

Figure 4. TSS distribution derived from MERIS on 22 October 2003

An interesting feature observed on the map of satellite-derived water property is elevated concentrations of TSS in the shallow zone along the coast south of the Herbert River mouth, with TSS above 5 g/m^3. These higher than image average concentrations are probably the result of resuspension of inorganic and organic sediments due to wind waves. Estuarine mangrove swamps covering the shoreline in the vicinity of the Hinchinbrook Channel supply organic matter to underlying soils, which is subsequently washed into the nearby coastal ocean by tidal forces and deposited as organic-rich sediments prone to further resuspension (Wolanski et al, 1990; Brunskil et al, 2002). When stirred, these sediments move into suspension and therefore can be detected using remote sensing tools. Unfortunately, no wind data were available on that day. However, a recent study showed that wave-induced bed stress is the most significant mechanism of sediment resuspension in the GBR (Orpin et al, 1999).

4.2. Temporal distribution of TSS

The data that survived the selection criteria outlined in section 3.2, were processed to get daily and monthly averages for 16 months in 2003-2004 for the regions representing river mouth and open ocean waters (i.e. box 1 and box 2, see section 3.1 and Fig. 1). The daily values for the small region at the Herbert mouth (box 1) range between 0.9 and 20.1 g/m^3, whereas the corresponding monthly results are between 3.1 and 8.1 g/m^3. The range and actual values of TSS concentrations in the open ocean region (box 2) are much smaller than that at the Herbert River mouth, with concentrations between 1.1 and 3.7 g/m^3 on a monthly scale, while daily results vary from 0.5 to 6.5 g/m^3.

Not surprisingly, daily TSS values are more scattered than monthly averages for both regions. For example, the peak on 17 February 2004 of 16.3 g/m^3 in the Herbert River mouth region translates into 6.70 g/m^3 monthly average of 5 TSS values available for February that year. Satellite-derived coastal TSS distribution exhibited significant variability in time (with a standard deviation of 2.4 g/m^3 at the mouth of the Herbert River) reflecting the effects of high intensity low frequency events characteristic of the region as well as wind-, and wave-induced resuspension patterns. In contrast, daily open ocean values were less scattered (with a standard deviation of 1.0 g/m^3 in the coastal region) thus indicating a minor effect of the Herbert River discharge and coastal driving forces on waters neighbouring the mid-shelf coral reefs.

These data were then compared with flood discharge measurements at the Herbert River mouth and are presented in Fig. 5. There is a distinct correlation between Herbert River discharge values and MERIS data for the coastal region in February 2004, during the medium-size flood caused by the tropical cyclone. Flood-induced peaks are observed in all time-series of water characteristics except for the open ocean region. It can be concluded then that river-borne sediments and nutrients released by a typical flood in the Herbert River are precipitated and/or consumed within the first 20 km from the coast and therefore are unlikely to reach and possibly affect the mid-shelf coral reefs of this section of the GBR lagoon. Coastal total suspended sediments responded to the Herbert River discharge in the studied period, whereas offshore TSS did not exhibit this pattern. Therefore, it can be concluded that a 15-year flood in the Herbert River and the resultant plumes of terrestrial substances in the adjacent coastal ocean do not affect mid-shelf and outer reefs in this section of the GBR.

Since the satellite overpass occurs at approximately the same time every day, satellite-retrieved data are expected to represent various tide phases. Apart from the flood-induced peak of TSS, which is well correlated with the Herbert River discharge, other peaks in the Herbert River mouth time-series relate to the low-tide situation whereas high sediment-laden river waters occupy the Hinchinbrook Channel and extend somewhat into the coastal ocean.

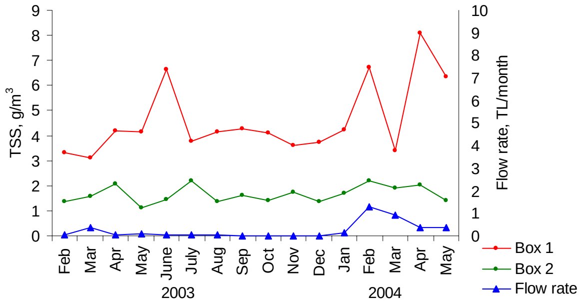

Figure 5. Monthly TSS for the Herbert River mouth (box 1), open ocean waters (box 2) and monthly Herbert River discharge.

From the observed dynamics of the satellite-derived TSS plume it can be concluded then that due to rapid settling, highly turbid sediment-rich riverine influxes are generally confined close inshore, thus providing little chance for detrimental amounts of sediments to reach mid-shelf and offshore coral reefs. This conclusion is in agreement with other sediment-related studies in the area, which show that terrestrial sediment deposition in the coastal waters off Hinchibrook Channel is largely restricted by a 20-m isobath (Woolfe et al, 2000). Therefore, significant quantities of riverine sediments are unlikely to be deposited on mid- and outer reefs in the central GBR lagoon (Larcombe et al, 1996; Orpin et al, 1999; Woolfe et al, 2000).

5. CONCLUSION

MERIS total suspended sediments are reasonably correlated with in situ measurements carried out in the GBR. Therefore, satellite data can be confidently used for geophysical research in the region. Furthermore, satellite-derived sediment maps are suitable for studying river impact on coral reefs. While remote sensing images provide synoptic views of geophysical regions, the statistical approach exercised in the present study allowed a more detailed specified analysis of the targeted areas.

Remote sensing data were capable of giving accurate locations of river plumes and providing overviews of a region in a synoptic perspective. The observed distributions of substances in the coastal waters adjacent to the Herbert River reveal that under favourable conditions for across-shelf plume dispersal, none of the plumes managed to carry harmfully significant amounts of inorganic and nutrient-rich sediments to mid-shelf reefs. River-borne sediments and nutrients released by a typical flood in the Herbert River are precipitated and/or consumed within the first 20 km from the coast and therefore are unlikely to reach and possibly affect the mid-shelf coral reefs of this section of the GBR lagoon. However, the same conclusion cannot be extrapolated to low-probability (> 15 years) significant flood events, and further research is required in this direction.

6. REFERENCES

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7. ACKNOWLEDGEMENT

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