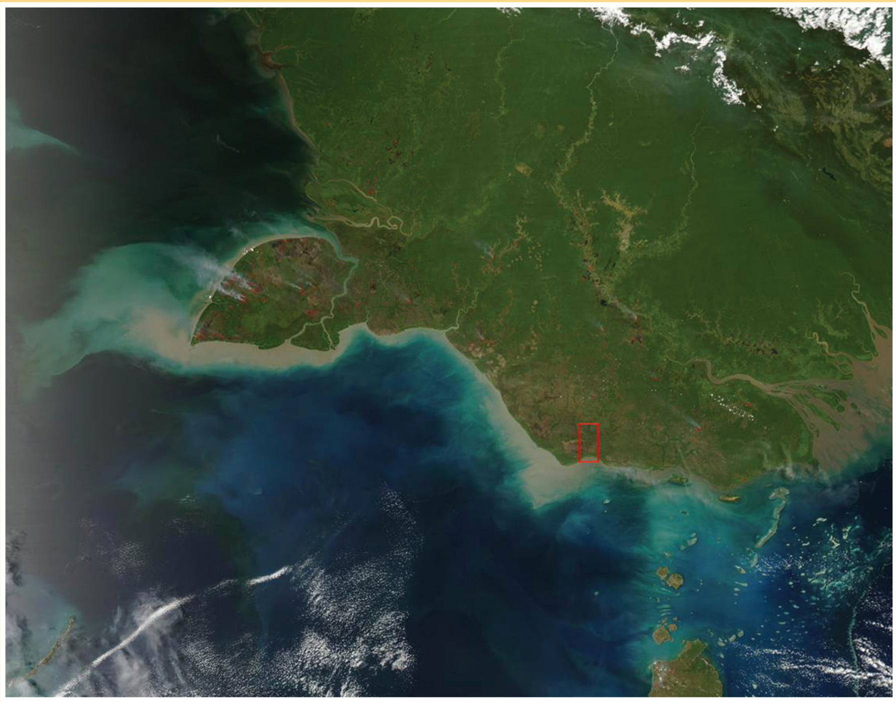
National Environmental Research Program

TROPICAL ECOSYSTEMS hub

Technical Report

Application of MODIS remote sensing imagery for monitoring turbid river plumes from Papua New Guinea in the Torres Strait Region: a test study



Caroline Petus

Australian Government

Department of the Environment

TropWATER

Centre for Tropical Water and Aquatic Ecosystem Research

JAMES COOK UNIVERSITY AUSTRALIA

Reef & Rainforest RESEARCH CENTRE

Application of MODIS remote sensing imagery for monitoring turbid river plumes from Papua New Guinea in the Torres Strait Region: a test study

Caroline Petus[1]

[1]Catchment to Reef Group, Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), James Cook University

Australian Government

Department of the Environment

Supported by the Australian Government's
National Environmental Research Program
Project 4.4 Hazard Assessment for water quality threats to Torres Strait marine waters, ecosystems and public health

TropWATER
Centre for Tropical Water and Aquatic Ecosystem Research

JAMES COOK UNIVERSITY
AUSTRALIA

National Library of Australia Cataloguing-in-Publication entry:

This report should be cited as:

Petus, C. (2013). Report to the National Environmental Research Program. Application of MODIS remote sensing imagery for monitoring turbid river plumes from the Papua New Guinea in the Torres Strait Region: a test study Reef and Rainforest Research Centre Limited, Cairns (20pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's National Environmental Research Program (NERP) Tropical Ecosystems (TE) Hub.

The Tropical Ecosystems Hub is part of the Australian Government's Commonwealth National Environmental Research Program. The NERP TE Hub is administered in North Queensland by the Reef and Rainforest Research Centre Limited (RRRC). The NERP Tropical Ecosystem Hub addresses issues of concern for the management, conservation and sustainable use of the World Heritage listed Great Barrier Reef (GBR) and its catchments, tropical rainforests including the Wet Tropics World Heritage Area (WTWHA), and the terrestrial and marine assets underpinning resilient communities in the Torres Strait, through the generation and transfer of world-class research and shared knowledge.

This report is available for download from the NERP Tropical Ecosystems Hub website:

http://www.nerptropical.edu.au/research

July 2013

Contents

List of Figures

List of acronyms

Note that comprehensive remote sensing glossaries can be found online on the UNESCO website: http://www.unesco.org/csi/pub/source/rs15.htm and the European Space agency: https://earth.esa.int/handbooks/meris/CNTR4-2-6.htm.

CDOM: Coloured Dissolved Organic Matter

MODIS: Moderate Resolution Imaging Spectroradiometer: URL: http://modis.gsfc.nasa.gov/index.php

MYD09GQ: MODIS Surface Reflectance lance product Daily L2G Global 250m. MYD09GQ provides Bands 1 and 2 at a 250-meter resolution in a daily gridded L2G product in the Sinusoidal projection:
https://lpdaac.usgs.gov/products/modis_products_table/myd09gq

NERP: National Environmental Research Program

PNG: Papua New Guinea

R(λ): surface reflectance measured at the wavelength λ

Rrs(λ): remote sensing reflectance measured at the wavelength λ

TC: True Colour. MODIS TC composites show objects and water masses in the same colours that eyes would normally see

TSM: total suspended matter

Executive Summary

Surface turbidity distribution in the Torres Strait results from the combined action of tides, wind, waves, currents, resuspension and turbid river discharge. Complemented with in-situ water quality data and hydrodynamic models, MODIS satellite images are useful tools to map the distribution of turbid river plumes in the Torres Strait region because of their synoptic coverage and spatial resolution. These images are freely distributed and are available from 2002. This study successfully tested the application of MODIS true colour imagery in combination with land surface reflectance products to observe turbid (sediment-dominated) river plumes from PNG and surface turbidity distribution in the Torres Strait region. These first analyses and comparisons with true colour composites show that MODIS land surface reflectance product can help to map the plumes and turbidity levels in the Torres Strait region.

Our preliminary dataset of MODIS satellite images suggests that high turbidity levels along the PNG coast are constrained to the coast, and that intrusions of the Fly River plumes in the Torres Strait region and protected area are limited. High turbidity levels recorded along the south-western PNG coast suggest a combined influence of turbid outflows from the several rivers draining the southern New Guinea margin, enhanced by bottom resuspension in the shallow coastal zone.

It is evident that cloud levels in the Torres Strait study region are important consideration for future applications, as the area is regularly masked by dense and developed clouds. This can limit the number of images available, particularly during the Northwest monsoon season (November to April) when most of the annual rainfall occurs in the region. The limited number of images processed for this study gave only snapshots of surface turbidity dynamic in the Torres Strait. More images should be acquired for a more comprehensive study of the dynamic of surface turbidity in Torres Strait and of PNG turbid river plumes.

1. Introduction

The influence of turbid river plumes within the Torres Strait region from the adjoining areas of Papua New Guinea (PNG) is potentially important for water quality conditions in the Torres Strait. Concerns have been expressed regarding sediment transported from Papua New Guinea, where increasing catchment development, mining and deforestation have affected river sediment loads (e.g. Harris et al., 2008, Heap and Sbaffi, 2008) and might affect the pollutant load to the Torres Strait area. Potential water quality issues include discharge of metal (and other pollutants in future), pollution from the Fly River associated with mining and future projects involving oil palm plantation development, the port at Daru, other mines in PNG or West Papua and other land clearing (Waterhouse et al., 2013).

This report is part of a project of the National Environmental Research Program (NERP) Tropical Ecosystems Hub. *Project 4.4 "Hazard Assessment for water quality threats to Torres Strait marine waters and ecosystems*" was undertaken to assess the potential threats to water quality in the Torres Strait region (see Waterhouse et al., 2013). As part of this study, we undertook a supplementary test study to evaluate the potential of MODIS data to map turbid (sediment-dominated) river plumes from PNG and thus potential pollutant transport from adjacent sources to the Torres Strait region.

We developed an initial data base of satellite images documenting the behaviour of these plumes and their areal extents within the Torres Strait and discussed surface turbidity distribution in the Torres Strait region. This test study allowed recommendations to be made for future application of remote sensing imagery in the Torres Strait Region. In combination with in-situ turbidity information the spatial data would help developing a monitoring program reporting on the status of water quality in the Torres Strait.

2. Study area

Torres Strait is a shallow shelf region located between the southern Papua New Guinea (PNG) coast and the north-eastern end of the Queensland state (Harris et al., 2008) (Figure 1a). The shelf of Torres Strait extends just over 150 km from north to south covering some 48000 km^2, is a productive area, and has numerous continental and volcanic islands, coral cays, mangroves, coral reefs as well as extensive seagrass beds (Coles et al., 2003) sheltering a large population of endangered dugongs (Marsh and Kwan, 2008).

Torres Strait is situated in a wet tropical region and has two wind regimes; the Northwest monsoon season from November to April and the Southeast trade-wind season from May to October. Most of the annual rainfall occurs during the Northwest monsoon wet season (Harris et al., 2008). Tropical cyclones are infrequent in Torres Strait, with a return period of approximately 10 years (Lourensz, 1981).

Several rivers drain our study area (Figure 1). The Fly River is the 17th largest river in the world in terms of sediment discharge (Galloway, 1975; Milliman and Syvitski, 1992). The Fly River accounts for about half the PNG discharge (~ 6000 $m^3\ s^{-1}$; Wolanski et al., 1995a) and is the largest single sediment source, with about 85 million tonnes year-1 of sediment discharged by the Fly (Harris et al., 1993). In spite of the strongly seasonal rainfall, the rate at which the sediment is delivered to the south coast of New Guinea is relatively invariant throughout the year (Walsh et al., 2004; Wolanski et al., 1995a). Mining at the headwaters of the Ok Tedi and Strickland (principal tributaries of the Fly River), started in 1985 and 1991, respectively and is estimated to have caused a 40% increase in the sediment discharge (Eagle and Higgins, 1990; Wolanski et al., 1995). A large proportion of sediments in the Fly River is retained in the estuary through e.g. flocculation dynamics (Wolanski et al., 1995a; Wolanski and Gibbs, 1995). Sediment concentrations at the mouth of the estuary have been estimated up to 70 $mg.l^{-1}$

(Robertson et al., 1993, Ayukadi and Wolanski, 1997) and rapidly reduced to a few milligrams per litre in the area where salinity was still as low as 26 (Ayukadi and Wolanski, 1997). To our knowledge, little information exists about sediment discharge rates of the rivers located south-west of the Fly River (Morehead, Wassi Kussa and Mai Kussa rivers).

As described in Wolanski et al., (2013), the Torres Strait is a complex hydrodynamic system. Modelling studies indicated that the most energetic current patterns are strongly dominated by the barotropic tide and its spring-neap cycle (Saint-Cast, 2008). Longer-term transport through the strait is mainly driven by seasonal prevailing winds: a dominant westward drift developed in summer over the south-easterly trade winds season, which then weakened and reversed in winter over the north-westerly monsoon winds season (Saint-Cast, 2008). High-energy swells generated in the Coral Sea are blocked by the northern most extension of the Great Barrier Reef (Hemer et al., 2004).

The winnowing and transport of sediments occur constantly throughout Torres Strait under the combined action of tides, wind and waves. Strong currents and waves maintain an extremely high-energy environment in Torres Strait and cause frequent resuspension of sediments resulting in a semi-permanent area of turbid water (Figure 1b) located in central Torres Strait (e.g. Harris and Baker, 1991; Margvelashvili et al., 2008; Saint-Cast, 2008). Hydrodynamic and sediment transport models as well as field observations for the region suggest predominant water and sediment movements oriented east–west which disperses sediments parallel to the coast (Margvelashvili et al., 2008; Saint-Cast, 2008) These currents form a hydraulic barrier to sediment transport southwards from New Guinea to central and southern Torres Strait (Heap and Sbaffi, 2008). The transport pathways along PNG coast remains thus strongly streamlined through-strait and restricted to within ~10 km of the coast (Heap and Sbaffi, 2008; Saint-Cast, 2008). Intrusions of the Fly River plumes in the Torres Strait region are limited and of the 85 million tonnes year-1 of sediment discharged by the Fly, less than 2% have been estimated to be deposited in Torres Strait (Harris et al., 1993). Under persistent (> 10 days) south-westward currents in the Great North East channel, Fly River plume waters have been detected over the northern Torres Strait both east and west of the Warrior Reefs (Figure 18; Wolanski et al., 1995b, 1999, this report, and Figure 1).

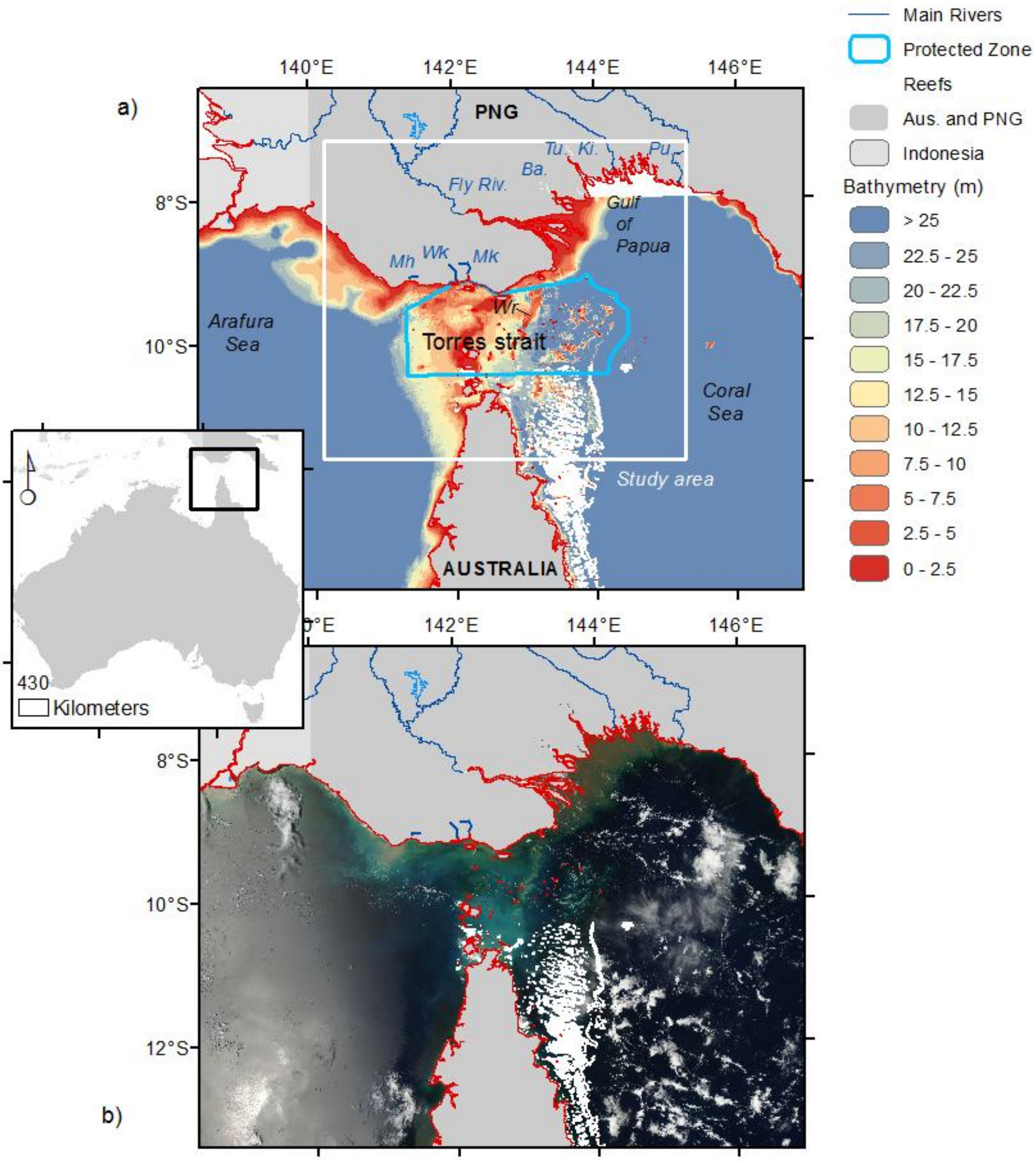


Figure 1: Maps of the study area. a) Bathymetry of Torres Strait (Geosciences Australia). Torres Strait is a shallow (<20 m) narrow shelf separating Australia and PNG, as well as the Coral Sea and the Arafura Sea. Wr: Warrior reef. List of rivers: Pu: Purari Ki: Kikori, Tu: Turama, Ba: Bamu, Mk: Mai Kussa, Wk: Wassi Kussa and Mh: Morehead River. (b) MODIS True color composite of February 8th, 2013 showing high surface turbidity levels in the study area (brownish to beige areas).

3. MODIS satellite data

Moderate Resolution Imaging Spectroradiometer (MODIS) imagery is a free satellite data with a medium spatial resolution (250 m for bands 1 and 2) and sufficient revisit times (at least once a day) available for monitoring turbid river plumes regularly and over multi-annual time periods

(since 2000). MODIS images have been used for monitoring turbid river plume plumes worldwide (e.g. Miller and Mckee 2004; Petus et al. 2010; Devlin et al., 2012).

For this initial Torres Strait database, we used the MODIS-Aqua 'surface reflectance' land product (MYD09GQ) in combination with MODIS True Colour composites (TC).

3.1 MODIS surface reflectance land product

The MODIS surface reflectance land product has been initially developed for land applications and the atmospheric correction procedure used to derive the surface reflectance is not accurate enough for open ocean applications. However Doxaran et al. (2009) demonstrated that this product can be a priori appropriate in the case of highly reflective turbid waters, as the PNG coastal waters. This product is relatively easy to process (see Doxaran et al., 2009) and, for a practical and operational point of view, was considered the most adapted within the short time frame of this project. Surface reflectance data are geolocated and are provided by the NASA (http://reverb.echo.nasa.gov/reverb/) in a Sinusoidal Grid (SIN) projection with standard tiles representing 10 degrees by 10 degrees. The Torres Strait protected area is located at the cross-junction between tiles h31v09, h32v09, h31v10, h32v10 (Figure 2a). It means that for each day of satellite acquisition, these 4 tiles must be downloaded in order to product maps of our study area.

We used the MODIS bands 1 'surface reflectance' land product centred at 645 nm (R645) as a proxy for the turbidity (sediment-dominated) levels. Chen et al. (2007) and Hu et al. (2004) demonstrated that the quality of the medium resolution MODIS land band 250 m resolution is adequate for producing remote sensing products of coastal waters. There is a strong correlation between the suspended sediment concentrations in turbid environments and the MODIS band 1 (e.g. Miller and Mckee, 2004; Doxaran et al. 2009; Petus et al. 2010; Ondrusek et al.., 2012). Radiance or reflectance values measured in the band 1 have been used as qualitative proxy for amounts of total suspended matter (TSM) (e.g. Lahet et al. 2010) or integrated in empirical bio-optical algorithms to quantify the concentrations of TSM ($mg.l^{-1}$) or the turbidity levels (NTU) in marine waters (e.g. Miller and McKee, 2004, Petus et al. 2010). MODIS Bands 2 'surface reflectance' land product centred at 858 nm (R(858)) was complementary processed as this product at 250 m resolution can be useful to identify cloud contaminations in satellite observations (Wang and Shi, 2006).

There is no universal algorithm available to map TSM concentrations in coastal waters. Furthermore, no in-situ TSM or turbidity data were available to develop a regional empirical algorithm to calibrate the MODIS surface reflectance data of the Torres Strait. In order to produce complementary quantitative information about the TSM concentrations in our study area, we used the TSM empirical algorithm (Equation 1) developed specifically for the MYD09GQ product by Petus et al. (2010).

$$TSM\ (mg.l^{-1}) = 12450*Rrs(645)^2 + 666.1*Rrs(645)+0.48 \qquad \text{Equation 1}$$

With Rrs(645), the remote sensing reflectance at 645 nm and Rrs(645) = R(645)/pi. Note that this algorithm has been developed from optical and TSM in-situ measurements collected in French turbid waters (Petus et al., 2010). This algorithm could be unadapted to the Torres Strait area, particularly if the size, shape, composition and optical properties of the suspended matter discharged through the PNG rivers differ significantly from the properties of the French suspended particles (Petus et al., 2010). Underestimation of suspended matters concentrations higher than 30 mg l^{-1} is furthermore expected (Petus et al., 2009). Thus, without further comparison with TSM data measured in situ, the TSM maps of Torres Strait should only be considered as informative.

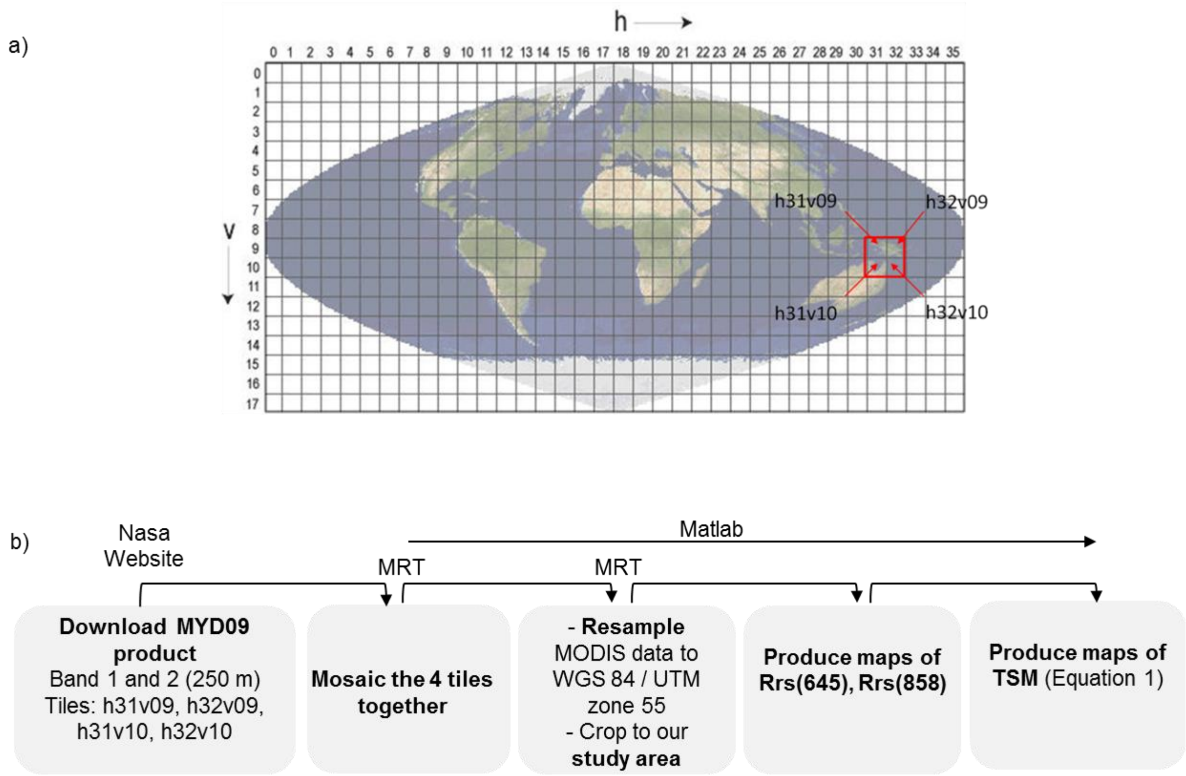


Figure 2: a) location of the study area on the MODIS sinusoidal grid. Torres Strait is located at the cross-junction between MODIS tiles h31v09, h32v09, h31v10, h32v10, b) flow chart illustrating major image processing steps of MODIS surface reflectance land product.

MODIS 'surface reflectance' imagery were downloaded between the 1st of October, 2009 and the 19th of June, 2010 (292 days * 4 tiles = 1168 MODIS scenes downloaded). A Matlab script was developed to mosaic the 4 MODIS tiles together; resample the data to WGS 84 / UTM zone 55, mask out land areas, convert reflectance satellite data to remote sensing reflectance values (Rrs(645)=R(645/pi and Rrs(858)=R(858/pi), in nm), and finally produce maps indicative of the turbidity in our study area (Figure 1b). This Matlab program use the Modis Reprojection Tool (MRT: https://lpdaac.usgs.gov/tools/modis_reprojection_tool) distributed freely by the Land Processes Distributed Active Archive Center (LDAAC).

3.2 MODIS true colour images

Following a request from our project team, a subset for the Torres Strait area has been added by the NASA to the LANCE website where NASA displays true colour images for different areas around the world (http://lance-modis.eosdis.nasa.gov/imagery/subsets/?subset=TorresStrait/). True colour images of our area of interest are now freely available since May 2008 and on a daily basis. Images can be downloaded in e.g. jpeg, kmz and geotiff formats and at resolutions of 250 m, 500 m and 1000 m.

A selection of cloud free true colour images (between 2008 and 2012) was downloaded from the NASA lance website. True colour images were exported to Google Earth and maps centred in our study area were produced.

4. Using MODIS data to map PNG turbid river plumes

Figure 3 presents a selection of TC images of our study area recorded between 2008 and 2012. Clouds (white areas on the true colour images) regularly cover about 20 to 50% of the sky but turbid water masses in the region are clearly detectable in clear sky areas by their differences in colour (brownish to beige) from ambient marine waters (navy blue). Turbidity patterns observed in the selection of TC images are in agreement with those described from hydrodynamic and sediment transport models and field observations in the region (e.g. Heap and Sbaffi, 2008; Margvelashvili et al., 2008; Saint-Cast, 2008, Wolanski et al., 2013):

- An area of turbid water is regularly located in central Torres Strait (Figure 4a);
- Figure 4b suggest turbid water movements parallel to the coast and orientated east–west in central and south TC;
- High turbidity levels along the PNG coast are mainly constrained to the coast, even during the monsoon season (Figure 4c).
- Excursions of turbid water from the Fly River drainage basin (Figure 1) are spatially limited in Torres Strait (Figure 4d).

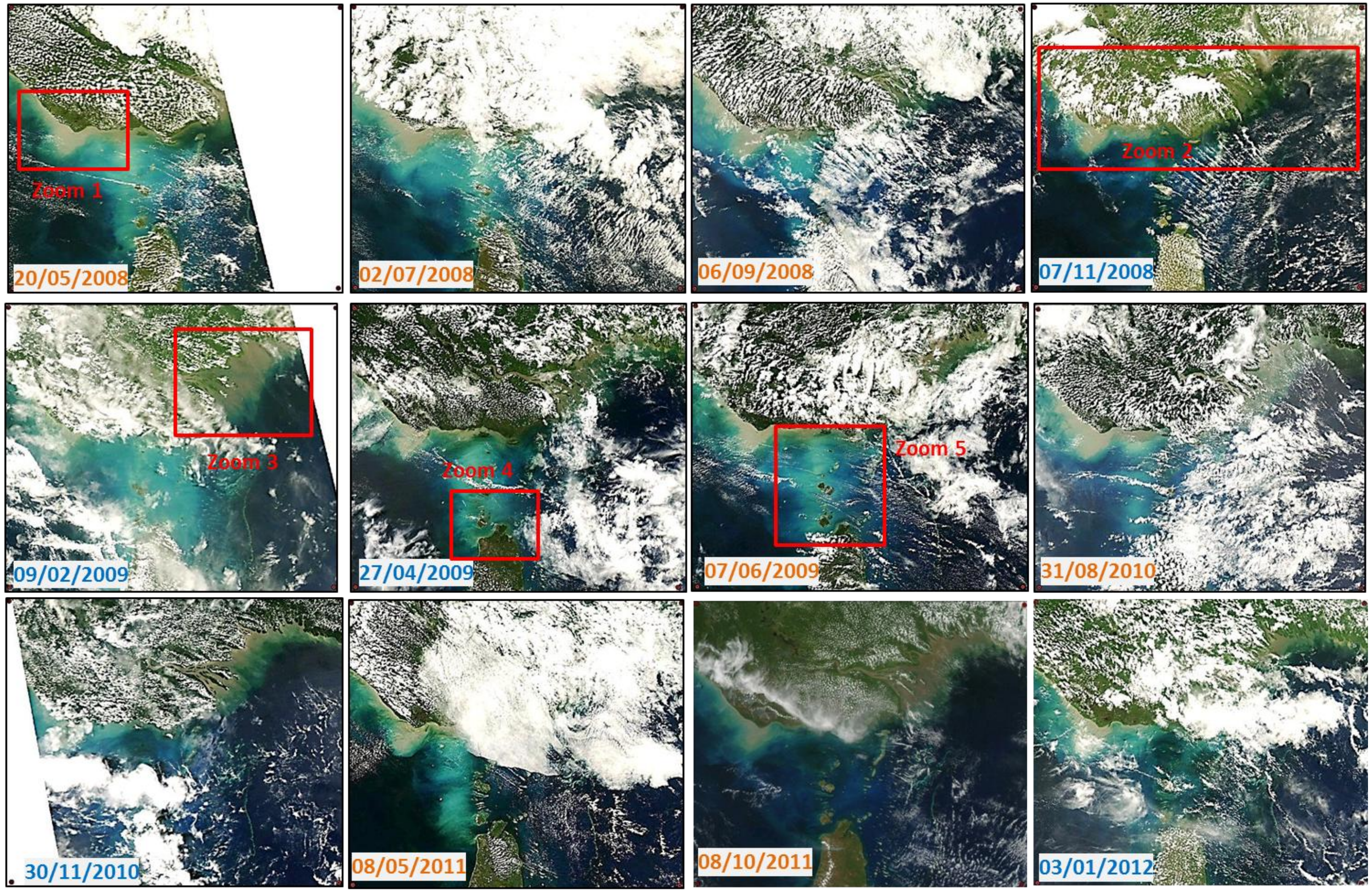


Figure 3: Selection of MODIS True Colour images of our study area recorded between 2008 and 2012 (NASA Lance website) during the Southeast trade-wind season (May to October, blue labels) and the Northwest monsoon season (November to April, orange labels). This dataset of images illustrate the strong spatial, temporal and sedimentary variability of the PNG turbid plumes. Enlargements are presented in Figure 4.

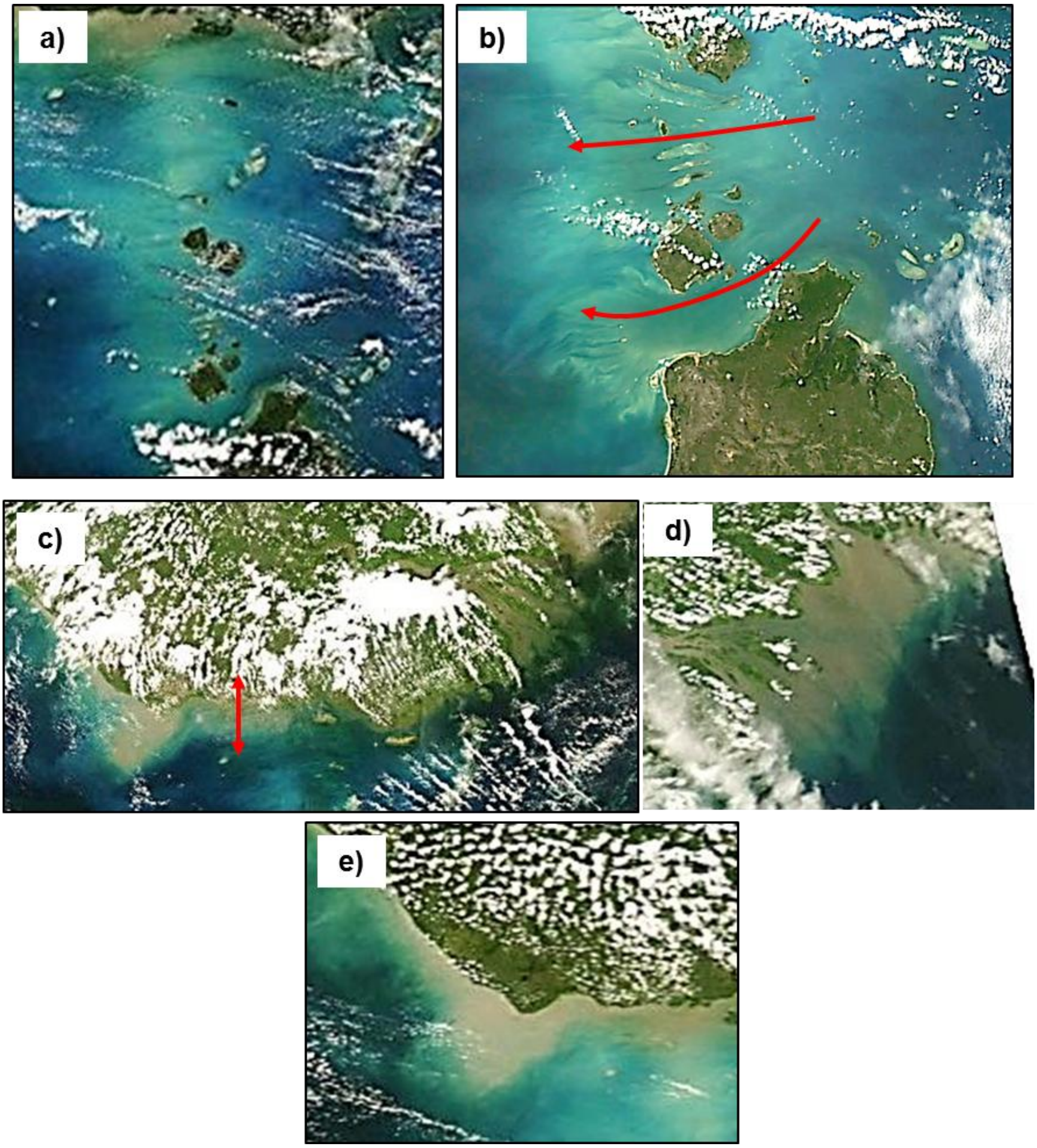


Figure 4: Enlargement of MODIS true colour composites (see Figure 3): a) turbid waters in central Torres Strait (Figure 3, zoom 5); b) turbid water movements parallel to the coast (Figure 3, zoom 4); c) high turbidity levels constrained to the coast along the PNG coast (Figure 3, Zoom 2); d) turbid river plumes monitored in the Gulf of Papua during the monsoonal season of 2009 (Figure 3, zoom 3) and e) turbid plumes in western PNG (Figure 3, zoom 1).

Turbid river plumes in the Gulf of Papua (Figure 1) are dynamic oceanographic features characterized by varying areal extents (Figure 3). In our TC dataset, maximum plume extent is recorded the 9th of February, 2009 (Figure 3 and 4d), in the middle of the wet season. High turbidity levels recorded along the south-western PNG coast suggest a combined influence of turbid outflows from the rivers draining the south-western New Guinea margin, enhanced by bottom resuspension in the shallow coastal zone (Figure 1a). Turbid areas systematically observed at the western corner of our study area (Figure 3 and Figure 4e) seem related to the

presence of the Morehead River and a shallow submarine cap in this zone (Figures 1a). Note that the limited number of images processed for this study gives only snapshots of turbidity dynamic in the regions. More images should be acquired for a more comprehensive study of the dynamic of surface turbidity in Torres Strait and of PNG turbid river plumes.

Comparisons between reflectance maps obtained and true colour composites (Figure 5) confirm the potential of the 'surface reflectance' MODIS land band 1 (Rrs(645)) to map the suspended solids discharged through the PNG river mouths. The PNG and Morehead turbid plumes aerial extents are well defined as well as turbid areas in the central part of the study area. MODIS satellite products allow representing movements of surface suspended solids within the Torres Strait region. However, clouds cover (Figure 5, white areas on the true colour images) make MODIS surface reflectance data unusable for this study and location of cloud contaminations must be done carefully when using Rrs(645) maps to monitor turbid river plumes of PNG. Similarly to the TSM concentration, clouds also increase the remote sensing reflectance in the MODIS band 1 (645 nm) and 2 (858 nm). They are identifiable by visual interpretation by their particular shapes and locations. However, when clouds are located above the turbid coastal areas, there signatures can mix with the optical signature of turbid river plumes (Figure 5, red circles) making their identification more complex. Clouds are more reflective than turbid areas in the infrared wavelengths (MODIS band 2, 858 nm; Figure 5).

Finally TSM levels retrieved (Figure 5b, right panel) seems in agreement with Robertson et al. (1993) and Ayukadi and Wolanski, (1997). TSM maps suggest TSM concentrations > 30 mg.l-1 at the mouth of the Fly estuary and rapidly reduced to a few milligrams per litre in the Gulf of Papua. Highest turbidity levels (> 15 mg.l-1) are constrained to coast in the south western coastal waters, except on the western side of the Morehead River. Note that equation 1 must be validated with in-situ TSM measurements before an operational application in the Torres Strait region. Concentrations values given in this section must be taken with caution.

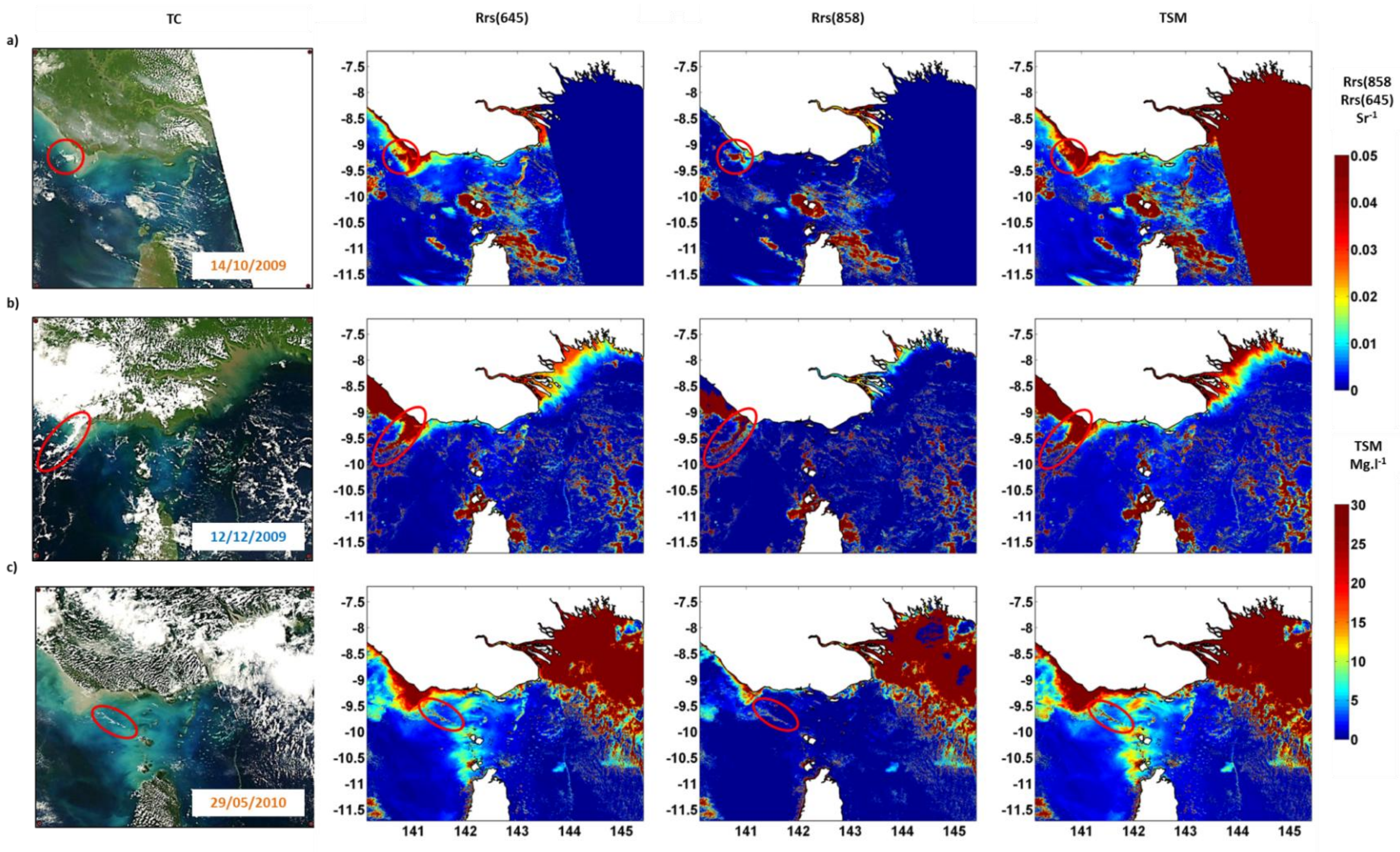


Figure 5: Comparison between and MODIS true colour composites, MODIS Rrs(645), MODIS Rrs(858) and TSM maps measured on a) October 14th, 2009. December 12th, 2009 and May 05th, 2010. True colour images are from the NASA Lance website. Images recorded during the Southeast trade-wind (May to October) and the Northwest monsoon (November to April) seasons are indicated with blue and orange labels, respectively. Rrs(645) values are proportional to the TSM concentrations (red and blue areas correspond to the most and less turbid waters, respectively). However cloud contaminations also increase the remote sensing reflectance values at 645 and 858 nm.

5. Conclusions and recommendations

The following conclusions can be made from our study which tested the application of MODIS true colour imagery in combination with land surface reflectance products to observe turbid (sediment-dominated) river plumes from PNG and surface turbidity distribution in the Torres Strait region.

- The Torres Strait zone is a very complex hydrodynamic system due to the complex bathymetry, the separate forcing by the Coral Sea and the Arafura Sea, as well as local forcing by the tide, wind, waves and rivers including the Fly River.
- Surface turbidity distribution in Torres Strait result from the combined action of tides, wind, waves, currents, resuspension and turbid river discharge.
- First analyses and comparisons with true colour composites show that MODIS land surface reflectance product can help to map the plumes and turbidity levels in the Torres Strait region. The surface reflectance measured in the MODIS band 1 can be used as proxy for surface turbidity levels in our study area.
- Complemented with in-situ water quality data and hydrodynamic models, MODIS satellite images are useful tools to map these dynamic oceanographic structures because of their synoptic coverage and spatial resolution. These images are freely distributed and cover more than a decennial period (2000 – 2012).
- Our preliminary dataset of MODIS satellite images suggests that high turbidity levels along the PNG coast are constrained to the coast, and that intrusions of the Fly River plumes in the Torres Strait region and protected area are limited.
- High turbidity levels recorded along the south-western PNG coast suggest a combined influence of turbid outflows from the several rivers draining the southern New Guinea margin, enhanced by bottom resuspension in the shallow coastal zone.
- Cloud levels in the study area are important and the Torres Strait area is regularly masked by dense and developed clouds. This can limit the number of images available, particularly during the Northwest monsoon season (November to April) when most of the annual rainfall occurs in the region.
- Clouds are more reflective than turbid areas in the infrared wavelengths (see Figure 5). A remote sensing reflectance ratio test using the MODIS 858 band divided by 645 band (Rrs(858/Rrs(645)) could be implemented to delineate and mask thick clouds. This test makes use of the fact that the spectral reflectance at these two wavelengths must be similar over thick white clouds (ratio near 1) but different over water masses (Ackerman et al., 2006). However, this ratio test would not be efficient to mask thin semi-transparent cirrus clouds. Particles inside these clouds affect the scattering properties of the upper troposphere and lower stratosphere regions (Thampi, 2012) and thus might affect the surface reflectance values of MYD09GQ products.
- The limited number of images processed for this study gave only snapshots of surface turbidity dynamic in the Torres Strait. More images should be acquired for a more comprehensive study of the dynamic of surface turbidity in Torres Strait and of PNG turbid river plumes.

Several recommendations are made for future application of the remote sensing imagery in the Torres Strait region:

- Extend the temporal coverage of the satellite database of MODIS True colour images and MODIS band 1 surface reflectance. For example, assess historic PNG river flow data to

select key satellite images over peak and low river flow periods (intra and inter-annually) would help to identify extreme and 'typical' plume incursions in the Torres Strait region.

- Implement on MODIS reflectance data of the study area cloud masks using, for example, the remote sensing reflectance ratio (Rrs(858/Rrs(645).
- Local turbidity (NTU) or TSM (mg.l^{-1}) measurements would help assessing the validity of the TSM algorithm (equation 1) used in this study. Combined with in-situ optical measurement (radiance and irradiance sensors), these turbidity data would help developing a local empirical algorithm to calibrate the band 1 surface reflectance values (Petus et al., 2009).
- This study has focused on using backscattering properties of sediment to map turbidity levels (sediment-dominated) in the Torres Strait. This method doesn't allow distinguish between turbidity from rivers runoff and resuspension. Light absorption data like satellite coloured dissolved organic matter absorption (CDOM) products could be complementary investigated to map PNG river flood plume extents (Schroeder et al., 2012) and disentangle resuspension from runoff in the satellite signal. However, the retrieval of CDOM absorption remains complex in the optically complex coastal environment (Odermatt et al., 2012), and a regionally adapted aCDOM algorithm for the Torres Strait must be used;
- Mask reefs and shallower waters in the studied area.
- Finally, satellite data with higher resolution (e.g. Digital Globe) or repetitivity (MTSAT, half hourly image intervals) could be investigated to complete the long-term, frequent and free spatial information available thought MODIS images.

6. Bibliography

Ackerman, S., Strabala, K., Menzel, P., Frey, R., Moeller, C., Gumley, L., Baum, B., Wetzel Seemann, S., Zhang, H., 2006. Discriminating clear-sky from cloud with MODIS. Algorithm theoretical basis document (MOD35), Version 5.0, 129 pp. Nasa technical report, available online at: http://modis-atmos.gsfc.nasa.gov/_docs/atbd_mod06.pdf.

Ayukai, T., and Wolanski, E., 1997. Importance of Biologically Mediated Removal of Fine Sediments from the Fly River Plume, Papua New Guinea. Estuarine, Coastal and Shelf Science, 44, 629–639.

Chen, T., Hu, C., & Muller-Karger, F. (2007). Monitoring turbidity in Tampa Bay using MODIS/Aqua 250-m imagery. Remote Sensing of Environment 109 207–220.

Coles, R.G., McKenzie, L.J., Campbell, S.J., 2003. The seagrasses of eastern Australia. In: Green, E.P., Short, F.T., Spalding, M.D. (Eds.). The World Atlas of Seagrasses.

Devlin, M.J., McKinna, L.W., Álvarez-Romero, J.G., Petus, C., Abott, B., Harkness, P., Brodie, J., 2012b. Mapping the pollutants in surface riverine flood plume waters in the Great Barrier Reef, Australia, Marine Pollution Bulletin, 65(4-9), 224-35.

Doxaran D., Froidefond, J.M., Castaing, P. and Babin, M., 2009. Dynamics of the turbidity maximum zone in a macrotidal estuary (the Gironde, France): Observations from field and MODIS satellite data. Estuarine, Coastal and Shelf Science, 81 321-332.

Eagle, A. M., and R. J. Higgins, 1990. Environmental investigations on the effects of the Ok Tedi copper mine in the Fly River system, in Proceedings of the Torres Strait Baseline Study Conference, Workshop Series No. 16, edited by D. Lawrence and T. Cransfield-Smith, pp. 97–118, Great Barrier Reef Marine Park Authority, Queensland, Australia

Galloway, W. E., 1975, Process framework of describing the morphologic and stratigraphic evolution of deltaic depositional systems, in Deltas: Models for Exploration, edited by M. L. Brossard, pp. 87–88, Houston Geological Society, Houston, Texas.

Harris, P.T., Baker, E.K., Cole, A.R., Short, S.A., 1993. A preliminary study of sedimentation in the tidally dominated Fly River Delta, Gulf of Papua. Continental Shelf Research, 13, 441-472.

Harris, P.T., Butler, A.J., Coles, R.G., 2008. Marine resources, biophysical processes, and environmental management of a tropical shelf seaway: Torres Strait, Australia– Introduction to the special issue. Continental Shelf Research, 28, 2113-2116.

Heap, A. D. and Sbaffi, L., 2008. Composition and distribution of seabed and suspended sediments in north and central Torres Strait, Australia. Continental Shelf Research, 28, 2174-2187

Hemer, M.A., Harris, P.T., Coleman, R., Hunter, J., 2004. Sediment mobility due to currents and waves in the Torres Strait—Gulf of Papua region. Continental Shelf Research, 24, 2297-2316.

Hu, C., Chen, Z., Clayton, T., Swarzenski, P., Brock, J., &Muller-Karger, F. (2004). Assessment of estuarine water-quality indicators using MODIS medium-resolution bands: Initial results from Tampa Bay, FL. Remote Sensing of Environment, 93, 423-441.

Lahet, F., Stramski, D., 2010. MODIS imagery of turbid plumes in San Diego coastal waters during rainstorm events. Remote Sensing of Environment, 114, 332–344.

Lourensz, R.S., 1981. Tropical cyclones in the Australian region: July 1909 to June 1980. Bureau of Meteorology, Melbourne, 94pp.

Marsh, H., Kwan, D., 2008. Temporal variability in the life history and reproductive biology of female dugongs in Torres Strait: The likely role of sea grass dieback? Continental Shelf Research, 28, 2152-2159.

Miller, R.L. and McKee, B.A., 2004., Using MODIS Terra 250 m imagery to map concentrations of total suspended matter in coastal waters. Remote Sensing of Environment, 93, 259-266.

Milliman, J. D., and J. P. M. Syvitski, 1992. Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers, Journal of Geology, 100, 525–544.

Odermatt, D., Gitelson, A., Vittorio Ernesto Brando, V.E., Schaepman, M. 2012. Review of constituent retrieval in optically deep and complex waters from satellite imagery. Remote Sensing of Environment 118: 116-126.

Ondrusek, M., Stengel, E., Kinkade, C.S., Vogel, R.L., Keegstra, P., Hunter, C., Kim, C., 2012. The development of a new optical total suspended matter algorithm for the Chesapeake Bay. Remote Sensing of Environment 119: 243–254

Petus, C., Chust, G., Gohin, F., Doxaran, D., Froidefond, J.M., Sagarminaga, Y., 2010. Estimating turbidity and total suspended matter in the Adour River plume (South Bay of Biscay) using MODIS 250-m imagery. Continental Shelf Research, 30 379-392.

Robertson, A. I., Daniel, P. A., Dixon, P., Alongi, D. M., 1993. Pelagic biological processes along a salinity gradient in the Fly delta and adjacent river plume (Papua New Guinea). Continental Shelf Research, 13, 205–224.

Saint-Cast, F., 2008. Multiple time-scale modelling of the circulation in Torres Strait—Australia. Continental Shelf Research, 28, 2214-2240.

Schroeder, T., Devlin, M.J., Brando, V. E., Dekker, A. G., Brodie, J. E., Clementson, L.A., McKinna, L., 2012. Inter-annual variability of wet season freshwater plume extent into the Great Barrier Reef lagoon based on satellite coastal ocean colour observations. Marine Pollution Bulletin, 65, 4-9, 210-223.

Thampi, B. V., Parameswaran, K., Sunilkumar, S. V., 2012. Semitransparent cirrus clouds in the upper troposphere and their contribution to the particulate scattering in the tropical UTLS region. Journal of Atmospheric and Solar-Terrestrial Physics, 74, 1-10.

Walsh, J.P., Nittrouer, C.A., Palinkas, C.M., Ogston, A.S., Sternberg, R.W., Brunskill,

G.J., 2004. Clinoform mechanics in the Gulf of Papua, New Guinea. Continental Shelf Research, 24, 2487–2510.

Wang, M., Shi, W., Cloud Masking for Ocean Color Data Processing in the Coastal Regions. IEEE Transactions On Geoscience And Remote Sensing, 44, 11, 3196-3205.

Waterhouse, J., Brodie, J., Wolanski, E., Petus, C., Higham, W., Armstrong, T., (2013). Hazard assessment of water quality threats to Torres Strait marine waters and ecosystems. Report to the National Environmental Research Program. Reef and Rainforest Research Centre Limited, Cairns (88pp.).

Wolanski, E., Lambrechts, J., Thomas, C.J., Deleersnijder, E. (2013). A high resolution model of the water circulation in Torres Strait. Report to the National Environmental Research Program. Reef and Rainforest Research Centre Limited, Cairns (31pp.).

Wolanski, E., Spagnol, S., King, B., 1999. Patchiness in the Fly River plume, Papua New Guinea. Journal of Marine Systems, 18, 369-381.

Wolanski, E. & Gibbs, R. J., 1995. Flocculation of suspended sediment in the Fly River estuary, Papua New Guinea, Journal of Coastal Research, 11, 754–762.

Wolanski, E., Norro, A., King, B.,1995b. Water circulation in the Gulf of Papua. Continental Shelf Research, 15, 185-212.

Wolanski, E., King, B., Galloway, D., 1995a. Dynamics of the turbidity maximum in the Fly River estuary, Papua New Guinea. Estuarine, Coastal and Shelf Science, 40, 321-337.

Wolanski, E. 1991, A review of the physical oceanography of Torres Strait, In: D Lawrence and T Cansfield-Smith (eds) Sustainable Development for Traditional Inhabitants of the Torres Strait Region, Great Barrier Reef Marine Park Authority, Townsville, pp. 133-141.